National Park Service
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Natural Resource Stewardship and Science

Indiana Dunes National Park

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2020/2196

The production of this document cost $ 24,748 including costs associated with data collection, processing, analysis, and subsequent authoring, editing, and publication.

ON THE COVER
Photograph of an inland wetland area near West Beach.
Photograph by Katie KellerLynn (Colorado State University) taken in summer 2010.

THIS PAGE
Photograph of wind ripples on the face of a dune.
Photograph by Todd Thompson (Indiana and Water Geological Survey) taken in summer 2010.

Indiana Dunes National Park

Geologic Resources Inventory Report

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The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics. These reports are of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

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All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner. This report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data.

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Executive Summary

The Geologic Resources Inventory (GRI) provides geologic map data and pertinent geologic information to support resource management and science-informed decision making in more than 270 natural resource parks throughout the National Park System. The GRI is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The Geologic Resources Division of the NPS Natural Resource Stewardship and Science Directorate administers the GRI.

This report synthesizes discussions from a scoping meeting held in 2010 and a follow-up conference call in 2018 (see Appendix A). Chapters of this report discuss the geologic setting, distinctive geologic features and processes within Indiana Dunes National Park, highlight geologic issues facing resource managers, describe the geologic history leading to the present-day landscape, and provide information about the previously completed GRI map data. A poster illustrates these data.

Vast piles of wind-whipped sand rise dramatically from the shores of Lake Michigan along the 24 km (15 mi) of shoreline contained in Indiana Dunes National Park. For nearly 2.6 million years, the Laurentide ice sheet that originated in the Arctic advanced and retreated multiple times over the Great Lakes region in response to climatic variability. The movements of ice, along with the sediment and meltwater they produced, blocked and rerouted river systems, scoured the Great Lakes basins, and left a complex glacial geologic record on the local landscape. During the last glacial episode and following each glacial advance, an ancestral version of the modern Lake Michigan formed between the glacier's terminal moraine and the ice margin. Relic shorelines exist as a geologic record of changes in Lake Michigan through time and are brilliantly preserved at the park, which has provided a natural scientific laboratory for more than 100 years. Earth surface processes continue to modify and affect the Indiana Dunes landscape. These include the famous dunes but also meandering streams, bogs, marshes, pannes (a type of wetland), beaches, and hardwood forests. Geology and geologic processes affect nearly every facet of the natural environment of the park as well as its long and rich human history.

This report is supported by one GRI–compiled map of the surficial and glacial geology of Indiana Dunes National Park. The compiled map coverage (4-letter code: indu) encompasses vast portions of Lake and Porter Counties, including the entirety of the park lands. The surficial and glacial map coverage differentiates the units deposited by the Pleistocene glaciers from those more recent paralic (of and pertaining to the coast) units being reworked and accumulating on the modern landscape by Earth surface processes. The map data poster (see "GRI Map Poster") is the most important figure of this GRI report showing the GRI GIS data draped over aerial imagery of the park. Individual surficial and glacial units are included in the poster's legend.

This report outlines and describes the park's geologic features, processes, and resource management, including

- Shoreline Erosion
- Disturbed Lands
- Geologic Hazards: Slope Movements, Sand Collapses, and Earthquakes
- Coastal/Lacustrine Features and Processes
- Eolian Features and Processes
- Fluvial Features and Processes
- Glacial Features and Processes
- Paleontological Resources

Following general descriptions, the main table of the report (table 2) provides a detailed look at which features, processes, and/or issues pertain to each map unit included in the GRI GIS data. The table presents the units in relative stratigraphic order with the oldest units on the bottom and the youngest units on the top. The table is supplemented by a discussion of geologic resource management that includes relevant references and links to data and resources for park managers to provide guidance in making science-based decisions. Another table (table 3) highlights the GRI GIS data layers for the map products: indu_geology.mxd.

Products and Acknowledgments

The NPS Geologic Resources Division partners with the Colorado State University Department of Geosciences to produce GRI products. The Indiana Geological and Water Survey developed the source map, and along with Indiana University Northwest staff, reviewed GRI content. This chapter describes GRI products and acknowledges contributors to this report.

GRI Products

The GRI team undertakes three tasks for each park (fig. 1) in the Inventory and Monitoring program: (1) conduct a scoping meeting and provide a summary document, (2) provide digital geologic map data in a geographic information system (GIS) format, and (3) provide a GRI report (this document). These products are designed and written for nongeoscientists.

Scoping meetings bring together park staff and geologic experts to review and assess available geologic maps, develop a geologic mapping plan, and discuss geologic features, processes, and resource management issues that should be addressed in the GRI report. Following the scoping meeting, the GRI map team converts the geologic maps identified in the mapping plan to GIS data in accordance with the GRI data model. After the map is completed, the GRI report team uses these data, as well as the scoping summary and additional research, to prepare the GRI report. The GRI team conducts no new field work in association with their products.

The compilation and use of natural resource information by park managers is called for in the 1998 National Parks Omnibus Management Act (§ 204), 2006 National Park Service Management Policies, and the Natural Resources Inventory and Monitoring Guideline (NPS-75). The "Additional References" chapter and Appendix B provide links to these and other resource management documents and information.

Additional information regarding the GRI, including contact information, is available at http://go.nps.gov/gri.

Acknowledgments

The author and GRI team thanks the participants of the 2010 scoping meeting and 2018 conference call (see Appendix A) for their assistance in the production of this report. Thanks very much to the Indiana Geological and Water Survey for their map of the area. This report and accompanying GIS data could not have been completed without them. Thanks to Michael Barthelmes (Colorado State University), Todd Thompson (Indiana Geological and Water Survey), and Erin Argyilan (Indiana Northwest University) for their invaluable input during review. Thanks to Katie KellerLynn (Colorado State University) and Rebecca Port (NPS Geologic Resources Division) for their final polishing.

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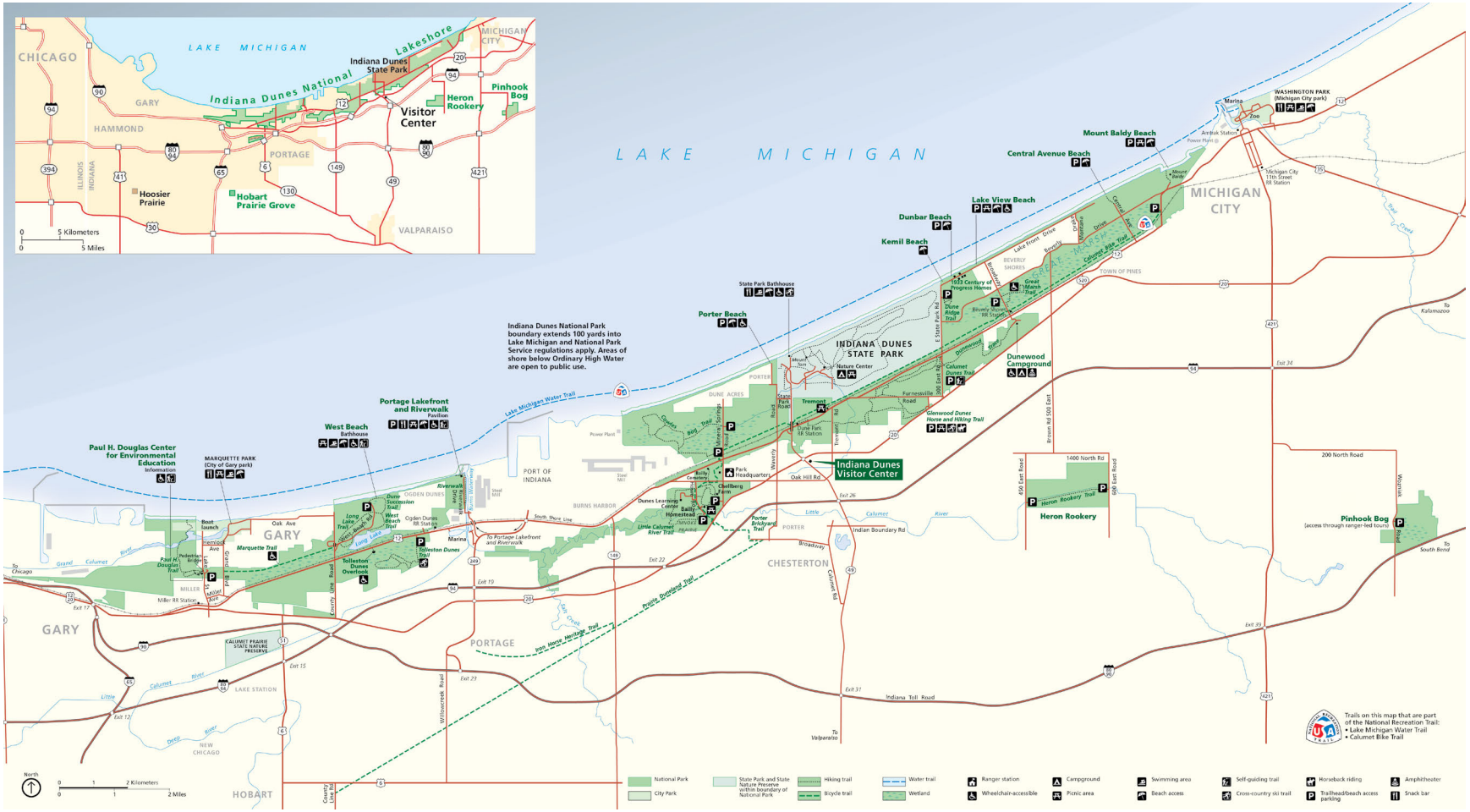

Figure 1. Park map and regional map (inset).
Hugging the southern shore of Lake Michigan, the park encompasses more than 6,000 ha (15,000 ac) spread over several units; it includes one national historic landmark (Joseph Bailly Homestead), four national natural landmarks (Pinhook Bog, Cowles Bog, Dunes Nature Preserve, and Hoosier Prairie), and the Heron Rookery area and trail. Indiana Dunes State Park, Calumet Prairie State Nature Preserve, and Hoosier Prairie State Nature Preserve are also located within the national park's designated boundaries. NPS maps are available at https://www.nps.gov/hfc/cfm/carto-detail.cfm?Alpha=INDU.

Geologic Setting, History, and Significance

This chapter describes the regional geologic setting and history of the park and summarizes connections among geologic resources, other park resources, and park stories.

Park Establishment and Purpose

Gracing 24 km (15 mi) of southern Lake Michigan's shoreline, Indiana Dunes National Park (prior to 2019, Indiana Dunes National "Lakeshore") preserves beaches, dunes, oak savannas, swamps, bogs, marshes, prairies, rivers, and forests amidst urban-disturbed landscapes (fig. 1). After a lengthy preservation campaign that began in early 1900s, the park was finally authorized in 1966, to protect the lake front and dunes from encroaching development from the east (Michigan City, Indiana) and from the west (Gary, Indiana). Today, the park encompasses more than 6,000 ha (15,000 ac) spread over several units; it includes one national historic landmark (Joseph Bailly Homestead), four national natural landmarks (Pinhook Bog, Cowles Bog, Dunes Nature Preserve, and Hoosier Prairie), and the Heron Rookery area and trail. In addition, Indiana Dunes State Park, Calumet Prairie State Nature Preserve, and Hoosier Prairie State Nature Preserve are located within the national park's designated boundaries; however, those areas are owned and managed by the Indiana Department of Natural Resources. Collectively, these natural areas of the southern shore of Lake Michigan are known as the Indiana Dunes. The major east and west units along the shoreline are separated by a large industrial complex (National Park Service 1997). At only 80 km (50 mi) from the third largest metropolitan area in the country (Chicago, Illinois), the park attracts nearly two million visitors each year for recreation and natural and cultural enrichment (National Park Service 2016).

The park's stated purpose includes preserving certain portions of the Indiana Dunes and other areas of scenic, scientific, and historic interest. The Lake Michigan shoreline, dunes, scientific study, and biological diversity are among the park's identified fundamental resources, that is, those features, systems, processes, and experiences that are essential to maintaining the park's significance (National Park Service 2016).

The park's beaches and primary dunes are created at the interface between the waters of Lake Michigan and the sandy coast. Much of the coast is fronted by dunes and the dune system, which includes beach ridges, swales, pannes, and intradunal wetlands. The park's geologic features and processes harbor and create significant biodiversity. Dune habitats evolve, transitioning from marram-grass covered foredunes along the shoreline to forested dunes farther inland.

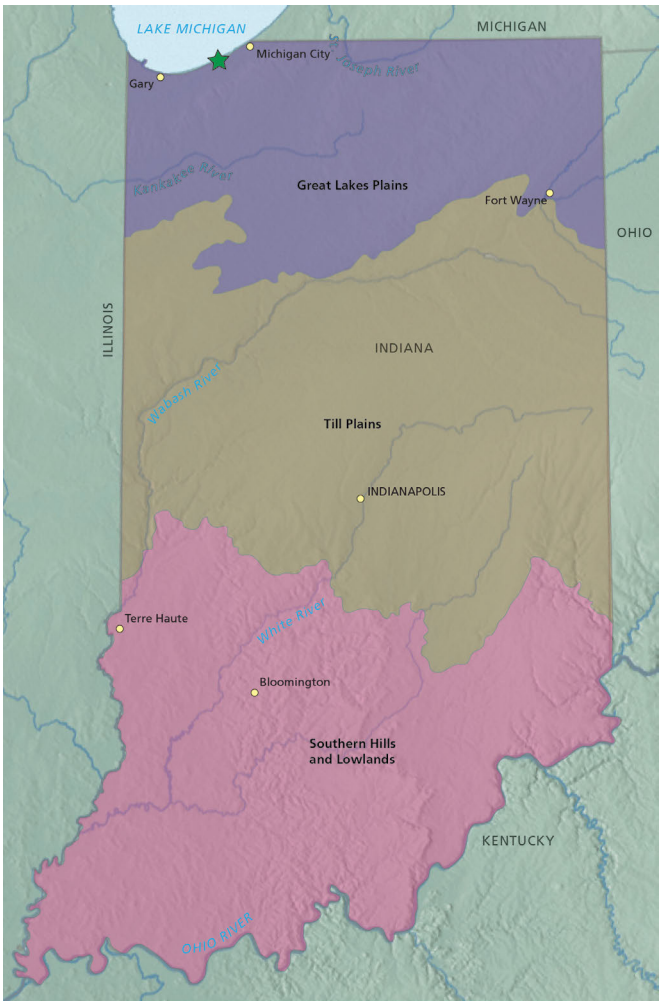

Figure 2. Physiographic province map. Indiana Dunes National Park (green star) is within the Great Lakes Plains province. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after Gray (2001). Shaded relief base map courtesy of Tom Patterson (National Park Service).

For more than a century, the Indiana Dunes has functioned as a natural laboratory. Today, scientific study informs resource management decisions, including plans for restoring and preserving habitats and landscapes (National Park Service 2016).

Geologic Setting and History

Located along the southern edge of the modern Lake Michigan basin, Indiana Dunes National Park is part of the Great Lakes Plains province (figs. 2 and 3). During

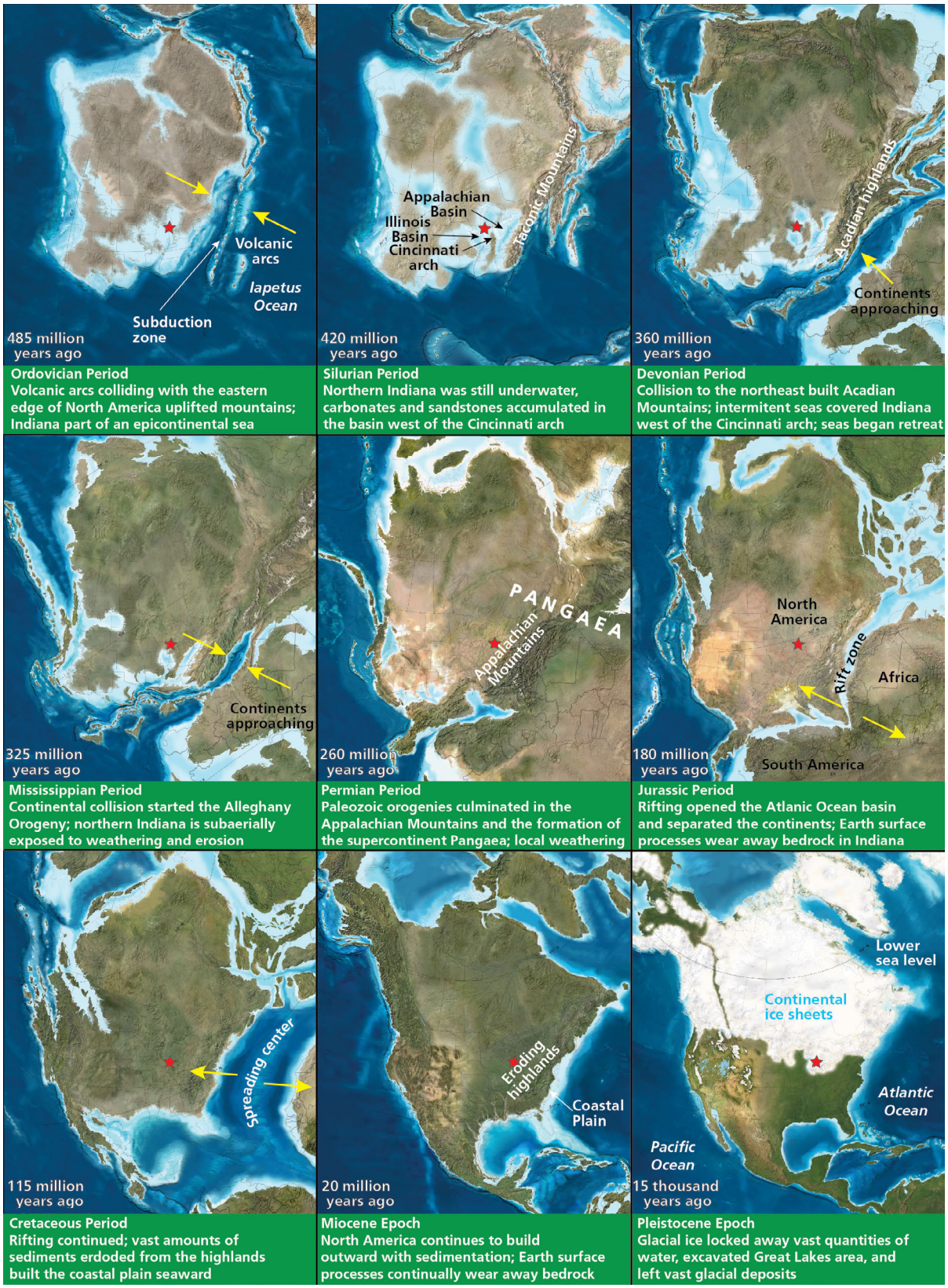

Figure 3. Paleogeographic maps of North America.
The red star indicates the approximate location of Indiana Dunes National Park. Base paleogeographic maps created by Ron Blakey (North American Key Time Slices © 2013 Colorado Plateau Geosystems Inc.), additional information is available at https://deeptimemaps.com/. Annotated by Trista L. Thornberry-Ehrlich (Colorado State University).

the Pleistocene Epoch (2.6 million to 11,700 years ago), this province experienced multiple advances and retreats of the Laurentide ice sheet and has since been affected by the fluctuating levels and extents of the Great Lakes. The ice sheet plowed over the preexisting bedrock, which dates to the Silurian and Devonian Periods of the Paleozoic Era (fig. 3). Buried beneath the park are the Wabash Formation (limestone and dolomite), Muscatatuck Group (dolomite, sandstone, and limestone), Antrim Shale (noncalcareous shale), and New Albany Shale (shale with limestone lenses) (Shaver 1974; Shaver et al. 1986; Hunt et al. 2008). Bedrock is buried beneath surficial deposits and is not part of the GRI GIS data.

The geologic history recorded in the mapped units at the park is relatively recent (table 1). During the Pleistocene Epoch (2.6 million to 11,700 years ago), the glacial ice sheet descended from the north and covered whatever surface and bedrock features existed in the Lake Michigan area. The southernmost terminus of glacial extent is recorded by a series of terminal moraines (a mound, ridge, or other distinct accumulation of unsorted, unstratified glacial drift, predominantly till, deposited mostly by direct action of a glacier) that stretch across south-central Indiana. As the ice sheet waxed and waned throughout the Pleistocene Epoch, it deposited vast amounts of sediment across the landscape. Upon each retreat, glacial lakes and outwash streams accumulated and reworked the glacial sediments. Different moraines, including the Valparaiso, Tinley, and Lake Border, mark the former positions of the ice sheet's margin in northwest Indiana and can be observed at locations within the park.

Table 1. Geologic time scale.

The divisions of the geologic time scale are organized stratigraphically, with the oldest divisions at the bottom and the youngest at the top. GRI map abbreviations for each time division are in parentheses. Only geologic units mapped within the park are included. Age ranges are millions of years ago (MYA). The Quaternary and Tertiary periods are part of the Cenozoic Era. The Triassic, Jurassic, and Cretaceous periods are part of the Mesozoic Era. The periods from Cambrian through Permian are part of the Paleozoic Era. Colors are US Geological Survey suggested colors for each geologic time unit. National Park Service graphic using dates from the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale).

MYA	Geologic Time Unit	Geologic Map Units	Local Geologic Events
0.01–today	Quaternary (Q) Period: Holocene (H) Epoch	**Qlmm** emplaced. **Qlma2**, **Qlmts**, **Qlmtd**, **Qlmtl** deposited and reworked.	Shoreline development of Lake Michigan. Fluvial meandering, incision, and deposition by rivers.
2.6–0.01	Quaternary (Q) Period: Pleistocene (PE) Epoch	**Qlmcn**, **Qlmcd**, **Qlmcl**, **Qlmgd**, **Qlmgs**, **Qlmgp** deposited. **Qlbl1**, **Qlbl2**, **Qlbm1** deposited. **Qvr2**, **Qvm1**, **Qvm2b** deposited.	Ice age glaciations; glacial outburst floods; glacial lakes impounded. Shoreline development.
5.3–2.6	Tertiary (T): Neogene (N) Period: Pliocene (PL) Epoch	None mapped.	Ongoing erosion and weathering. Fluctuating sea levels. Meandering rivers.
23.0–5.3	Tertiary (T): Neogene (N) Period: Miocene (MI) Epoch	None mapped.	Ongoing erosion and weathering. Fluctuating sea levels. Meandering rivers.
33.9–23.0	Tertiary (T): Paleogene (PG) Period: Oligocene (OL) Epoch	None mapped.	Ongoing erosion and weathering. Fluctuating sea levels. Meandering rivers.
56.0–33.9	Tertiary (T): Paleogene (PG) Period: Eocene (E) Epoch	None mapped.	Ongoing erosion and weathering/ Fluctuating sea levels. Meandering rivers.
66.0–56.0	Tertiary (T): Paleogene (PG) Period: Paleocene (EP) Epoch	None mapped.	Ongoing erosion and weathering. Fluctuating sea levels. Meandering rivers.

Table 1, continued. Geologic time scale.

MYA	Geologic Time Unit	Geologic Map Units	Local Geologic Events
145.0–66.0	Cretaceous (K) Period	None mapped.	Global mass extinction, including dinosaurs, at end of the Cretaceous Period.
201.3–145.0	Jurassic (J) Period	None mapped.	Atlantic Ocean opened; sediments began building out the coastal plain.
251.9–201.3	Triassic (TR) Period	None mapped.	Global mass extinction at end of Triassic Period. Breakup of the supercontinent Pangaea begins.
298.9–251.9	Permian (P) Period	None mapped.	Global mass extinction at end of Permian. Supercontinent Pangaea intact. Increased sedimentation in the Appalachian basin. Appalachians may have rivaled height of modern Himalayas.
323.2–298.9	Carboniferous: Pennsylvanian (PN) Period	None mapped.	Alleghany Orogeny (Appalachian mountain building).
358.9–323.2	Carboniferous: Mississippian (M) Period	None mapped.	Appalachian basin collected sediment and subsided.
419.2–358.9	Devonian (D) Period	Bedrock from the Devonian underlies the park, but was not included in the map data.	Global mass extinction at end of Devonian Period; Appalachian basin collected sediment and subsided.
443.8–419.2	Silurian (S) Period	Bedrock from the Silurian underlies the park, but was not included in the map data.	Appalachian basin collected sediment and subsided. Neo-Acadian Orogeny.
485.4–443.8	Ordovician (O) Period	None mapped.	Global mass extinction at end of Ordovician Period. Uplift and erosion Taconic Orogeny.
541.0–485.4	Cambrian (C) Period	None mapped.	Extensive oceans covered most of proto-North America (Laurentia).
1,000–541	Proterozoic Eon: Neoproterozoic (Z) Era	None mapped.	Supercontinent Rodinia rifted apart.
1,600–1,000	Proterozoic Eon: Mesoproterozoic (Y) Era	None mapped.	Formation of early supercontinent. Grenville Orogeny.
2,500–1,600	Proterozoic Eon: Paleoproterozoic (X) Era	None mapped.	None reported.

Table 1, continued. Geologic time scale.

MYA	Geologic Time Unit	Geologic Map Units	Local Geologic Events
~4,000–2,500	Archean Eon	None mapped.	Oldest known Earth rocks.
4,600–4,000	Hadean Eon	None mapped.	Formation of Earth approximately 4,600 million years ago.

When the glaciers finally left the Lake Michigan basin, the lake itself changed levels and created shorelines through various phases as the retreating glacier opened and closed outlets in the Great Lakes basin and land rebounded from the weight of the now-missing glacial ice (Todd Thompson Indiana and Water Geological Survey, director, written communication, 9 May 2019). The park's landscape beautifully records this shoreline evolution and is considered significant in the park's foundation document (National Park Service 2016). Three major coastal geomorphic features dominate the park: the Glenwood, Calumet, and Tolleston beaches (Capps et al. 2007). They correlate to highstands (an interval of time during one or more cycles of relative lake-level change when lake level is relatively elevated in a given area) of Lake Michigan. About 14,800 to 12,400 years ago, Glenwood beach formed during the Glenwood phase, the highest phase of ancestral Lake Michigan. Today's shoreline hovers around 176 m (577 ft) in elevation (Wright 2006). Water levels during the Glenwood phase were likely as high as 195 m (640 ft) in elevation and as low as 190 m (625 ft) during the beach's development. The high waters of the Glenwood phase were followed by a low period known as the Two Creeks phase, which lasted from 12,400 to 11,800 years ago. A return to high-water conditions, which ranged from as high as 189 m (620 ft) to as low as 184 m (605 ft) in elevation, lasted until about 10,000 years ago and is recorded by the Calumet beach shoreline (Thompson 1990; Capps et al. 2007; KellerLynn 2010). An extreme low-water phase, the Chippewa phase, caused the abandonment of Calumet beach. The lowest elevation of the Chippewa phase is not exactly known but may have been as low as 116 m (381 ft) (Todd Thompson, Indiana Geological and Water Survey, senior scientist, written communication, 20 October 2010; KellerLynn 2010). Following this extreme low, lake level rapidly rose associated with the glacial isostatic rebound (upward flexing of Earth's crust after the melting of heavy glacial ice that caused the crust to be depressed) of the North Bay outlet exiting Lake Huron through Georgian Bay. Lake level reached the elevation of the modern shoreline of the park about 6,000 years ago and continued to rise to a peak elevation of 183 m (601 ft) at 4,500 years ago (Argyilan et al. 2018). This maximum elevation was short lived, and lake level immediately fell 4 m (13 ft) (fig. 4). This highstand also formed the landward part of Tolleston beach, which was a beach complex consisting of beach ridges, dunes, and wetlands as opposed to a singular shoreline feature associated with a high lake phase. By 3,500 years ago, a lowered lake level exposed sand all along the shoreline that was swept up into a series of parabolic dunes that migrated roughly parallel to the modern shoreline. A systematic wind shift from westerlies to northerlies caused a reorientation of the shoreline and the development of parabolic dunes now oriented onshore, like Mount Baldy (fig. 5; Todd Thompson Indiana and Water Geological Survey, director, written communication, 9 May 2019). Today's shoreline and dunes are a continuation of the Tolleston beach landscape that started forming during the Nipissing phase of ancestral Lake Michigan (figs. 4 and 5).

Geologic Significance and Connections

The park's landscape begins with geology and Earth surface processes, which continue to shape the landforms that support the development of distinctive ecosystems and underpin human activities.

Human History Connections

The park's cultural resources document a wide range of human use and occupation for more than 10,000 years (National Park Service 2016). The park has 200 listed archeological sites, most of which are American

Indian sites that predate European contact. Notably, Renner (2013) developed a model for using GIS to predict the locations of archeological sites using slope, elevation, and distance to water. The remaining sites are associated with early immigration and homesteading in the area (National Park Service 2016). The park's administrative history (Cockrell 1988) documented recent human activities through 1987.

The southern shore of Lake Michigan has been a center of transportation and industry for well over 100 years, and today the park reflects a national struggle

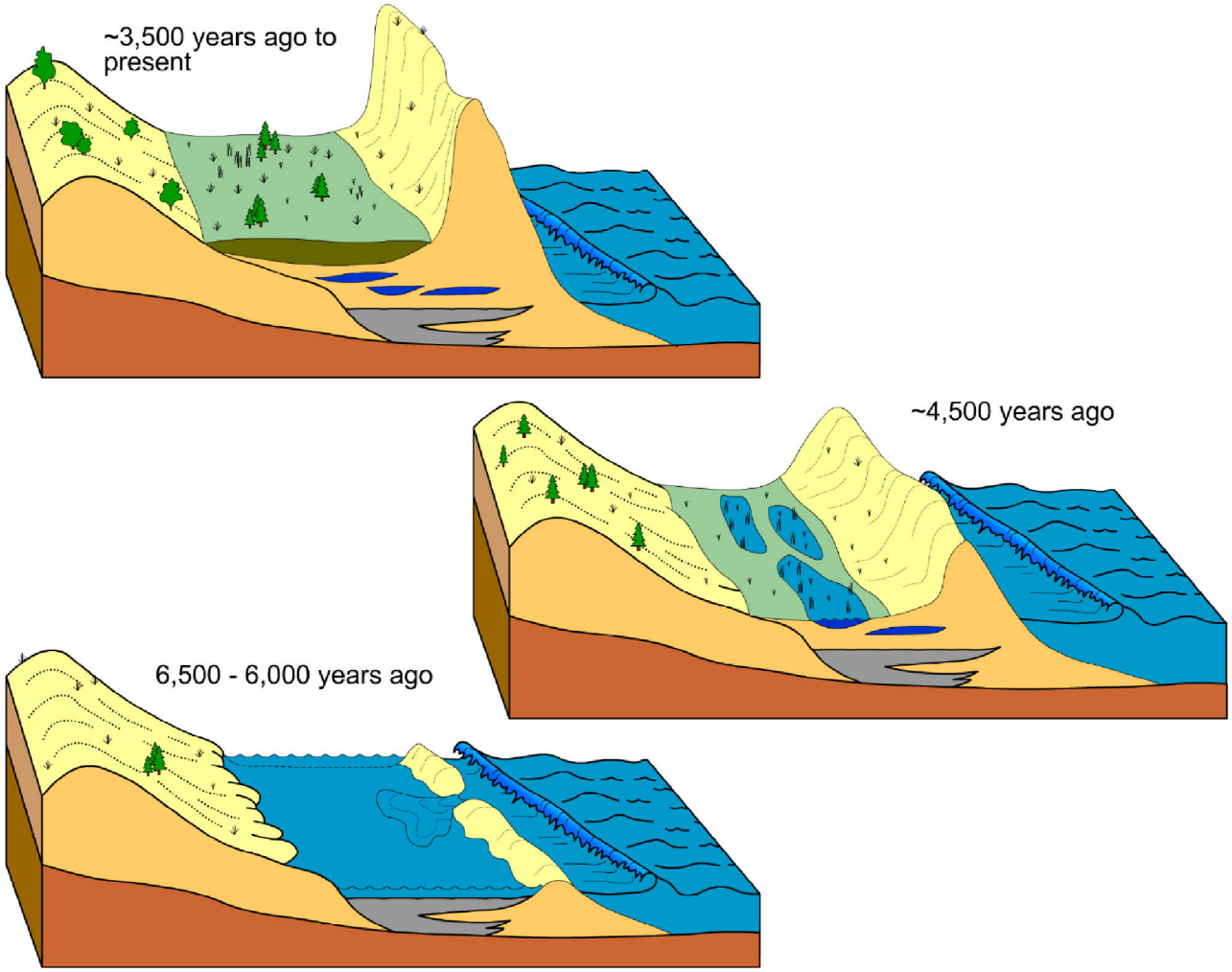

Figure 4. Three-dimensional block diagrams showing three stages of development of Tolleston beach. Lake levels rose and began to stabilize, starting about 6,500 years ago, developing an incipient Tolleston beach. As sand was added to the beach from wind and waves, the shoreline vertically aggraded and dunes were developed on the coastal sediment that migrated inward. By 4,500 years ago a wetland with ponds formed in the former back-barrier lacustrine area. A rapid lake-level fall and continued lake-level change permitted the dunes to grow in quantity and size and the wetland to expand. Graphic presented by Todd Thompson (Indiana Geological and Water Survey) at the GRI scoping meeting, 2010.

to balance urbanization, industry, and conservation (National Park Service 2016). Beyond the lake itself, the primary natural resource of the area has been quartz sand. Enterprises such as the Ball Company of Muncie, Indiana, mined away entire dunes (e.g., "Hoosier Slide") to make canning jars. Dunes from the once 13-km (8-mi) Long Lake area were mined and transported away to create lakefront property in Illinois before and after the Chicago World's Fair of 1893 (Garza et al. 2002; KellerLynn 2010). Much local sand and gravel from the beaches of southern Lake Michigan was incorporated in cement used to build Chicago and other nearby cities in the late 1800s to early 1900s. At that time, coarse sediment was raked from shallow water by hand and carted above the storm-wave line to be used in Chicago for roofing and concrete pavements (KellerLynn 2010).

Ecosystem Connections

Geology forms the foundation for myriad habitats that occur throughout Indiana Dunes National Park. The tightly packed set of ecosystems supports biodiversity that is among the highest per unit area in the entire National Park System (Renner 2013). More than 1,100 native plant species grow across the park's fragmented landscape including some in globally imperiled plant communities. More than 350 bird species have been observed in the park; it is part of a major migration corridor. About 70 native and nonnative fish species

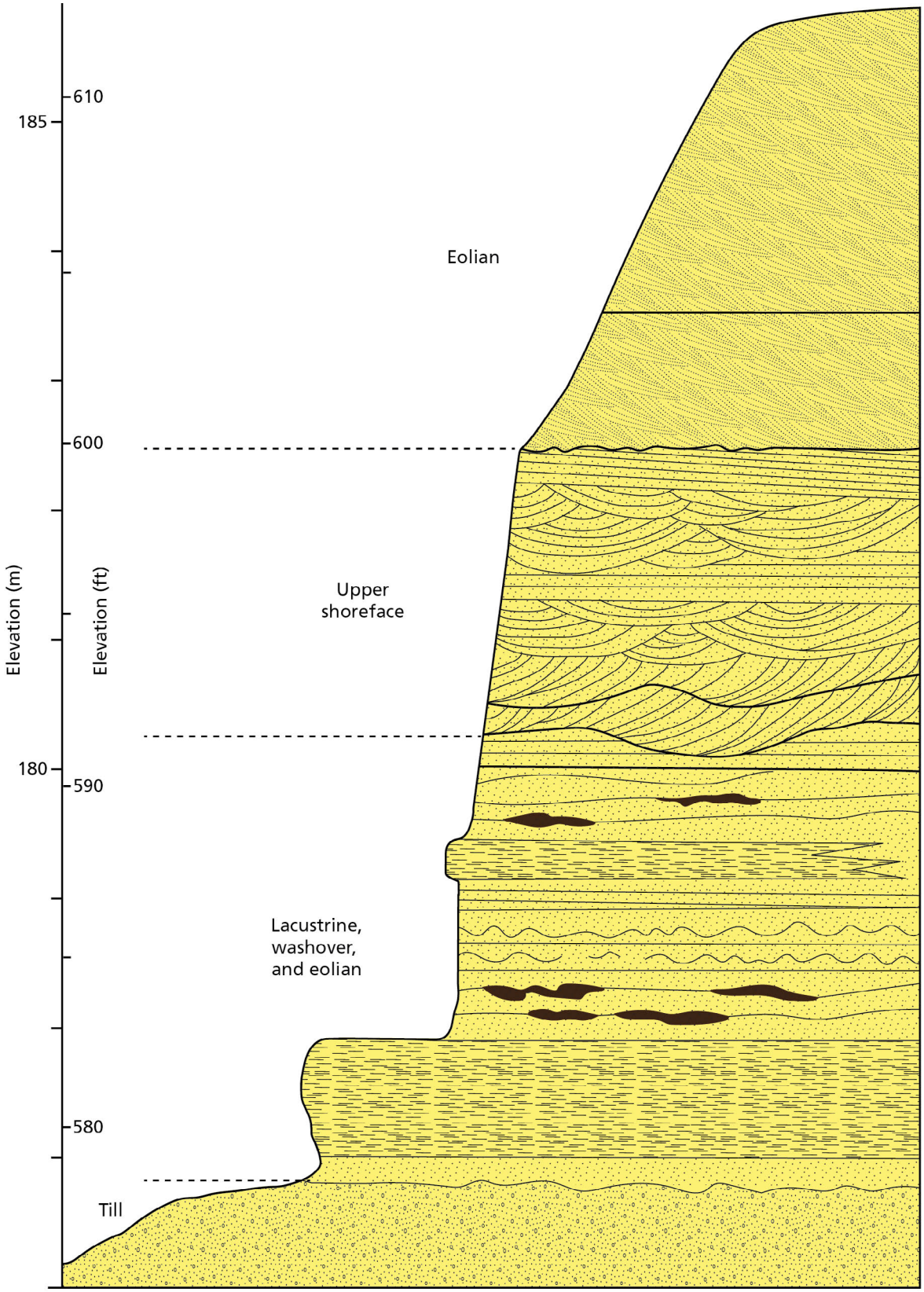

Figure 5. Stratigraphic column at Mount Baldy.
Sediments in part of the Tolleston beach are shown representing the landward migration of the earth Tolleston beach into a back-barrier lake.Glacial till deposits were covered by various lakeshore-associated deposits during the migration, including eolian sand and lacustrine silt, sand, and clay. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after figure 47 in Thompson (1987).

live in the park's streams, rivers, ponds, and lakes. A species list for the park, containing 1,964 species, is available at https://irma.nps.gov/DataStore/Reference/Profile/2205731.

The park has notable distinct coastal and dune systems dating to the late Pleistocene Epoch, mid-Holocene Epoch, and recent past. The ecology is linked to the geology because the landscape chronology established by post-glacial, coastal development provides the opportunity to observe the correlation of plant communities with landform age (Renner 2013). For more than 100 years, the dunes and plant communities in the park were natural field laboratories wherein the theory of ecological succession was developed by Henry Chandler Cowles. Geologic processes that create the park's dynamic landscapes (e.g., dunes, wetlands, beach ridges, and dune and beach complexes) define local hydrology; interact with climate and weather; and form the conditions that support the park's mix of eastern deciduous forest, prairies, oak savanna, wetlands, pannes, rivers, and remnants of boreal forests, which were identified as significant in the park's foundation document (National Park Service 2016).

Dunes and nearshore units (geologic map units **Qlmtl**, **Qlmcn**, **Qlmcl**) underlie modern and former wetland areas such as Great Marsh and Cowles Bog. Great Marsh is the largest interdunal wetland on Lake Michigan's southern shoreline (Government Printing Office 2006; KellerLynn 2010; Thompson and Johnson 2014). The general stratigraphy of these wetland areas, in descending order from the ground surface, is organic peat, sand, and calcareous sand to clayey marl. These sedimentary deposits are frequently water saturated. Lagoons and wetlands, harboring distinct flora and fauna, form in the dune complexes. The modern Great Marsh, located between the Glenwood and Tolleston dunes, began to form when the lake level dropped about 3,500 years ago exposing abundant sands that were reworked by winds into the modern dune field nearest the modern shoreline (KellerLynn 2010). Where shallow groundwater conditions exist, natural depressions that form in the blowouts of parabolic dunes become unique wetland ecosystems called "pannes," which harbor habitats for many state-listed species (KellerLynn 2010).

Pinhook Bog, a glacial kettle underlain by clay-rich sediments (geologic map unit **Qvm1)**, supports an unusual array of plants, including some carnivorous species (National Park Service 1997; Thompson and Johnson 2014). As a glacial feature, its origins are unique within the park (Erin Argyilan, Indiana University Northwest, geologist, written communication, 14 May 2020).

Other Natural Resource Connections

Additional information about other natural resources is provided in the following references:

- Soil resource inventory for the park (geospatial data): National Park Service (2012)
- Delineated landscape disturbances (geospatial data): Kirschbaum (2017)
- Vegetation mapping: Hop et al. (2009)
- Biotic stressors: Fisichelli et al. (2015)
- Water resources: NPS Water Resources Division (http://go.nps.gov/waterresources)
- Coastal bathymetry: Glase et al. (2015)
- Inventories and monitoring reports about natural resources such as climate, amphibians, diatoms, inland lake water quality, land birds, land cover and land use, large river water quality, persistent contaminants, and vegetation: NPS Great Lakes Network (https://www.nps.gov/im/glkn/index.htm).
- Metapopulation theory and recovery of rare plants (Pitcher's thistle): McEachern et al. (1994)
- Ecological characterization of Long Lake: Garza et al. (2002)
- Great Lakes aquatic studies: Lafrancois and Glase (2005) with considerations for monitoring.

Geologic Features, Processes, and Resource Management Issues

These geologic features and processes are significant to the park's landscape and history. Some geologic features, processes, or human activities may require management for human safety, protection of infrastructure, and preservation of natural and cultural resources. The NPS Geologic Resources Division provides technical and policy assistance for these issues.

During the 2010 scoping meeting (see GRI scoping summary by KellerLynn 2010) and 2018 conference call, participants (see Appendix A) identified the following geologic features, processes, and resource management issues. This chapter provides a description for each and, where available, suggests additional resources for monitoring and management. In addition, table 2 makes connections among the GRI GIS data (map units) and these geologic features, processes, and resource management issues.

- Shoreline erosion
- Disturbed lands
- Geologic hazards: slope movements, sand collapses, and earthquakes
- Coastal/lacustrine features and processes
- Eolian features and processes
- Fluvial features and processes
- Glacial features and processes
- Paleontological resources

Shoreline Erosion

Lake Michigan's shoreline is never static because wind, waves, currents, and ice continually move sand throughout the year. Sand is naturally transported along the east and west margins of Lake Michigan through longshore currents that converge along the southern shoreline. This ongoing delivery of sand is the fundamental reason why coastal features continued to develop north of morainal features to form a prograding (built forward or outward into water) shoreline in the context of lake level change. In the area of Indiana Dunes National Park, the majority of sand moving in the nearshore zone as longshore drift is transported in an east-to-west direction. Historically, however, development and installation of navigational harbors and shoreline stabilization structures such as jetties, revetments, groins, breakwaters, and bulkheads have altered the natural system of sediment transport. The result is an overall lack of sand at important lakeshore sites within the park, including Mount Baldy, Lakeview and Kemil Beaches, and Portage Lakefront Park, as significant accretion of sands occurs east (updrift) of harbors (fig. 6; Watkins et al. 2010; KellerLynn 2010; Erin Argyilan, Indiana University Northwest, geologist, written communication, 14 May 2020).

Coburn et al. (2010) inventoried coastal engineering structures at the park. The inventory identified 40 erosion-control structures (revetments, seawalls, breakwaters, jetties, and bulkheads), three dredging areas, and three beach/dune construction projects. The shoreline protection features impact approximately 11,300 m (37,000 ft) of the lakeshore (Coburn et al. 2010). In addition, dredging occurs at the Bailly Generating Station water intake structure, Burns International Harbor, Burns Waterway small boat harbor, and Michigan City Harbor, and beach/dune construction projects are taking place at Michigan City Harbor/Mount Baldy, Ogden Dunes/Beverly Shores, and Burns Waterway small boat harbor (Coburn et al. 2010).

Because extreme shoreline erosion is a major issue at the park, a shoreline management plan was completed in 2012 and finalized in 2014 (National Park Service 2014). Areas of primary concern include the Mount Baldy-Crescent Dune and Portage Lakefront-Ogden Dunes areas, as well as riprap stretches between Dune Acres and Indiana Dunes State Park. At Mount Baldy alone, roughly 137 m (450 ft) of shoreline was lost between 1932 and 1980 (KellerLynn 2010).

Coastal structures protruding into the lake have segmented the two natural littoral cells (coastal compartments that contain a complete cycle of sedimentation: sources, transport paths, and sinks) of southern Lake Michigan into multiple smaller cells. Four primary cells now exist along the Indiana shore, two of which impact the park: (1) the "eastern Indiana cell" from the Michigan-Indiana state line to Michigan City Harbor and (2) the "Indiana Dunes" cell from Michigan City Harbor to the US Steel lakefill/Gary Harbor. The latter cell is further subdivided into several secondary cells: Michigan City Harbor to Burns Waterway Harbor, Burns Waterway Harbor to US Steel lakefill/Gary Harbor, and two more cells to the west (Chrzastowski et al. 1994; KellerLynn 2010; Erin Argyilan, geologist, Indiana University Northwest, written communication, 14 May 2020). In addition to littoral drift, natural sources of sediment include deposition at the mouths of rivers (deltas) and ice rafting. Because of the anthropogenic manipulation of the system, these natural sources are interrupted and/or diverted (Chrzastowski et al. 1994; KellerLynn 2010).

Table 2. Geologic features, processes, and associated resource management issues in Indiana Dunes National Park.

alluvium—Stream-deposited sediment.

clay—Minerals and sedimentary fragments that are less than 1/256 mm (0.00015 in) across.

diamictite—Nonsorted or poorly sorted, noncalcareous, terrigenous sedimentary rock that contains a wide range of particle sizes, such as a rock with sand and/or larger particles in a muddy matrix. The term implies no origin.

diamicton—The nonlithified equivalent of diamictite.

gravel—An unconsolidated, natural accumulation of typically rounded rock fragments resulting from erosion; consists predominantly of particles larger than sand; that is, greater than 2 mm (1/12 in) across.

hummocky—Said of topographic land or ice forms that are abounding in small hills and depressions meters to tens of meters across.

loam—A rich, permeable soil composed of relatively equal proportions of clay, silt, and sand particles, and usually containing organic matter. It usually implies fertility and is sometimes called topsoil.

marl—loose, earthy deposits consisting of a mixture of clay and calcium carbonate, formed under marine or freshwater conditions.

moraine—A mound, ridge, or other distinct accumulation of glacial drift, predominantly till, deposited by direct action of glacier ice

peat—An unconsolidated deposit of plant remains in a water-saturated environment

proglacial—Immediately in front of or just beyond the outer limits of a glacier or ice sheet.

sand—A clastic particle smaller than a granule and larger than a silt grain, with a diameter ranging from 1/16 to 2 mm (0.0025 to 0.08 in).

silt—Clastic sedimentary material intermediate in size between fine-grained sand and coarse clay, 0.0039 to 0.063 mm (0.00015 to 0.0025 in) across.

subglacial—Formed or accumulated in or by the bottom parts of a glacier or ice sheet.

supraglacial—Carried upon, deposited from, or pertaining to the top surface of a glacier or ice sheet.

Map Unit (symbol)	Description and occurrence in the Park	Features and Processes and Potential Resource Management Issues
Filled and modified/ disturbed land (**Qlmm**)	Areas of **Qlmm** are associated with quarries, landfills, and heavily disturbed areas such as the Port of Indiana. **Qlmm** is a mix of natural and anthropogenic materials (e.g., fill). Only small portions of **Qlmm** occur within park boundaries along the Lake Michigan shoreline near West Beach and Dunes Learning Center.	**Shoreline erosion** **Qlmm** is commonly emplaced to armor shorelines. However, areas of **Qlmm** may disturb the natural sediment movement causing some areas to artificially gain or lose sediment. **Disturbed lands** **Qlmm** records the location and extent of local disturbed lands. It does not delineate urban/suburban developments or infrastructure such as roads or housing developments. Coastal/lacustrine features and processes Where **Qlmm** intersects the shoreline, coastal features and processes are impacted. Eolian features and processes In places were **Qlmm** alters the prevailing winds or impedes natural sand movement, eolian features and processes are impacted. **Fluvial features and processes** **Qlmm** may be emplaced in areas where river channels are encroaching on infrastructure.
Channel and floodplain over older valley fill (**Qlma2**)	Stretches of **Qlma2** occur as sinuous bands underlying and flanking modern stream channels. It is composed of layered silt, sand, organic sediment, and some clay. **Qlma2** records the migration of modern streams over older estuarine, lagoonal, and alluvial sediment. **Qlma2** occurs along the Little Calumet River through the Heron Rookery unit and near the Dunes Learning Center, as well as along the Deep River at the Hobart Prairie Grove unit.	**Geologic hazards** Fluvial processes may create undercut streambanks that may be prone to failure. **Fluvial features and processes** **Qlma2** lines modern stream and river channels and contains fluvial features such as point bars, floodplains, and channels.

Table 2, continued. Geologic features, processes, and associated resource management issues in Indiana Dunes National Park.

Map Unit (symbol)	Description and occurrence in the Park	Features and Processes and Potential Resource Management Issues
Strandplain (**Qlmts**)	**Qlmts** is composed of very fine sand and silt and gravel overlain by fine- to medium-grained sand that occurs in beach ridges, spits, and swales of the modern Tolleston beach. **Qlmts** has been accumulating since the Nipissing phase of ancestral Lake Michigan. Separated from Lake Michigan by disturbed areas of **Qlmm**, **Qlmts** dominates the northwestern portion of the map area near Miller Woods eastward to Long Lake.	**Shoreline erosion** **Qlmts** is lost to erosion along much of the park's exposed shoreline. **Disturbed lands** Outcrops of **Qlmts** are interrupted by areas of **Qlmm**. **Geologic hazards** In the event of an earthquake, units such as **Qlmts** would be prone to liquefaction. **Coastal/lacustrine features and processes** **Qlmts** fronts the modern shoreline of Lake Michigan in the absence of dunes (**Qlmtd**) composing beaches and low beach ridges.
Dunes (**Qlmtd**)	Unit **Qlmtd** includes fine- to medium-grained sand making up the large (5 to 50 m [16 to 164 ft]) parabolic dunes associated with the modern Tolleston beach. **Qlmtd** has been accumulating since the Nipissing phase of ancestral Lake Michigan. **Qlmtd** occurs in long, linear swaths fronting Lake Michigan inside park boundaries.	**Shoreline erosion** **Qlmtd** is the most shoreward unit along the southern Lake Michigan shoreline. Lack of renewable sand supply due to adjacent shoreline engineering structures is causing widespread erosion of the beaches and dunes. **Disturbed lands** Dune sand was mined for use in glass factories and urban development. Social trails that cross **Qlmtd** contribute to loss of stabilizing vegetation and increased erosion. **Geologic hazards** Dunes of **Qlmtd** may bury forests and cause sand tunnels to develop around decayed trees. Mount Baldy was recently closed due to an accident involving a child being buried in such a tunnel. When unconsolidated units are exposed along slopes or scarps, potential exists for slope movements. **Coastal/lacustrine features and processes** Landforms composed of **Qlmtd** front the modern shoreline in the park. Coastal engineering adjacent to the park is disrupting sand supply for dunes along the lakeshore. **Eolian features and processes** **Qlmtd** is ***the*** unit recording the modern eolian landscape at the park. Unit is primarily found as dunes, foredunes, and dune ridges.
Lagoon (**Qlmtl**)	**Qlmtl** contains lacustrine (lake), palustrine (pond), and minor eolian (wind-blown) sediments, including layered peat, marl, calcareous clay, silt, and sand that accumulated landward of **Qlmtd** during the Nipissing phase of ancestral Lake Michigan in washover fans, marl and clay ponds, and wetlands. Some accumulation of **Qlmtl** occurs today in wetlands. In the park, **Qlmtl** is mapped in long linear bands just landward of the **Qlmtd** units fronting Lake Michigan.	**Disturbed lands** **Qlmtl** and **Qlmcn** underlie portions of the disturbed Great Marsh, including Cowles Bog. **Coastal/lacustrine features and processes** **Qlmtl** underlies some of the inland ponds, lakes, and wetlands in the park. **Geologic hazards** In the event of an earthquake units such as **Qlmtl** would be prone to liquefaction. **Eolian features and processes** Some lagoon areas form by eolian excavation of intradunal swales creating low spots. **Paleontological resource inventory, monitoring, and protection** Sediments accumulating in Cowles Bog contain Pleistocene and Holocene fossil remains.

Table 2, continued. Geologic features, processes, and associated resource management issues in Indiana Dunes National Park.

Map Unit (symbol)	Description and occurrence in the Park	Features and Processes and Potential Resource Management Issues
Nearshore (**Qlmcn**)	Composing a flat platform lakeward of **Qlmcd**, very fine-grained sand to sandy gravel of **Qlmcn** accumulated in nearshore settings during the Calumet phase of ancestral Lake Michigan. These two units are landward of the active shoreline, recording a former, higher lake level. **Qlmcn** occurs along Salt Creek and the Calumet bike trail areas of the park.	**Disturbed lands** **Qlmtl** and **Qlmcn** underlie portions of the disturbed Great Marsh, including Cowles Bog. **Geologic hazards** In the event of an earthquake units such as **Qlmcn** would be prone to liquefaction. **Coastal/lacustrine features and processes** **Qlmcn** records shoreline conditions during a previous level of Lake Michigan. **Paleontological resource inventory, monitoring, and protection** Sediments accumulating in Cowles Bog contain Pleistocene and Holocene fossil remains.
Dunes (**Qlmcd**)	**Qlmcd** contains well-sorted, fine- to medium-grained sand in dunes that were part of the Calumet beach of ancestral Lake Michigan. **Qlmcd** is landward of **Qlmcn**. **Qlmcd** arcs across the map extent but is only in the park along the Calumet bike trail from near the Dunes Learning Center eastward to Tremont.	**Disturbed lands** Dune sand was mined for use in glass factories and urban development. Social trails that cross **Qlmcd** contribute to loss of stabilizing vegetation and increased erosion. **Eolian features and processes** **Qlmcd** records nearshore, dune evolution during a previous highstand of Lake Michigan. Unit is primarily found as stable, vegetated dunes and dune ridges.
Lagoon (**Qlmcl**)	**Qlmcl** contains lacustrine (lake), palustrine (pond), and minor eolian (wind-blown) sediments, including layered peat, marl, calcareous clay, silt, and sand that accumulated landward of **Qlmcd** during the Calumet phase of ancestral Lake Michigan. Some accumulation of **Qlmcl** occurs today in wetlands. In the park, **Qlmcl** is mapped near Dunewood.	**Geologic hazards** In the event of an earthquake units such as **Qlmcl** would be prone to liquefaction. **Coastal/lacustrine features and processes** **Qlmcl** underlies some of the inland ponds, lakes, and wetlands in the park. **Eolian features and processes** Some lagoon areas form by eolian excavation of intradunal swales creating low spots. **Paleontological resource inventory, monitoring, and protection** Sediments accumulating in lagoons may contain Pleistocene and Holocene fossil remains.
Nearshore, dunes (**Qlmgd**)	Unit **Qlmgd** contains well- to poorly sorted fine-grained sand to sandy gravel that was deposited in nearshore and dune areas during the Glenwood phase of ancestral Lake Michigan. At that time, the lake was lapping against scarps of the Lake Border moraine (**Qlbm1**). Inside park boundaries, **Qlmgd** occurs near Ly-Ko-Ki-We horse and hiking trail.	**Eolian features and processes** **Qlmgd** records the nearshore, dune evolution during a previous highstand of Lake Michigan. Unit is primarily found as stable, vegetated dunes and dune ridges. **Glacial features and processes** **Qlmgd** accumulated between the Lake Border terminal moraine and the receding glacier as Lake Michigan was forming.

Table 2, continued. Geologic features, processes, and associated resource management issues in Indiana Dunes National Park.

Map Unit (symbol)	Description and occurrence in the Park	Features and Processes and Potential Resource Management Issues
Spit (**Qlmgs**)	The fine- to medium-grained sand, coarse-grained sand, and sandy gravel of **Qlmgs** accumulated as a spit of nearshore and onshore deposits during the Glenwood phase of ancestral Lake Michigan. This spit formed westward of **Qlbm1**. **Qlmgs** is prevalent in the Hoosier Prairie unit of the park and crops out in a small sliver near Salt Creek.	**Disturbed lands** **Qlmgs** may provide a source of sorted sand and gravel. **Eolian features and processes** **Qlmgs** may have provided a sediment source for ancient sand dunes **Glacial features and processes** **Qlmgs** records conditions of an ancient Lake Michigan forming between retreating glacial ice and the terminal moraine.
Spit platform (**Qlmgp**)	The moderately sorted, fine- to medium-grained sand of **Qlmgp** was deposited in nearshore settings during the Glenwood phase. **Qlmgp** forms the level platform on which **Qlmgs** accumulated. Within the park, **Qlmgp** occurs only in the Hoosier Prairie unit.	**Disturbed lands** **Qlmgp** may provide a source of sorted sand. **Glacial features and processes** **Qlmgp** records conditions of an ancient Lake Michigan forming between retreating glacial ice and the terminal moraine.
Glenwood embayment fill (**Qlbl1**)	The layered deposits of **Qlbl1** coarsen upwards from clay to silt to sand. These accumulated in proglacial to back-barrier lacustrine (lake) settings during the glacial advance to and development of the Lake Border moraine. Some areas of **Qlbl1** also formed in lagoons landward of **Qlmgs**. **Qlbl1** is a prevalent mapped unit in the park area. Inside park boundaries, **Qlbl1** occurs in the Hoosier Prairie, Hobart Prairie Grove, and Heron Rookery units, as well as the Sand Creek area.	**Coastal/lacustrine features and processes** Clay-rich **Qlbl1** may act as an aquitard to surface water and support wetland development. The layered nature of the deposits records seasonal changes in deposition cycles: coarser during high energy periods and finer during cycles of still water. **Glacial features and processes** **Qlbl1** was deposited in proglacial-lake settings during the advance responsible for the Lake Border terminal moraine. **Paleontological resource inventory, monitoring, and protection** Lagoon depositional settings may have accumulated wind-blown fossil pollen in **Qlbl1**.
Beach, colluvial slope, and fan delta complex (**Qlbl2**)	Unit **Qlbl2** consists of clay, silt, and fine sand and fan-shaped sand and gravel that were deposited in wave-washed edges of prominent moraines (e.g., Tinley and Valparaiso moraines), as well as deltas associated with discharge from the ancestral Deep River, Salt Creek, and Trail Creek. **Qlbl2** forms a boundary between the Glenwood embayment fill (**Qlbl1**) and landward moraines. Within the park, **Qlbl2** crops out in the Heron Rookery unit.	**Coastal/lacustrine features and processes** Clay-rich **Qlbl2** may act as an aquitard to surface water and support wetland development. **Fluvial features and processes** **Qlbl2** contains fluvial deposits from precursors to the modern streams and rivers in the park as they flowed into ancient Lake Michigan. **Glacial features and processes** **Qlbl2** formed as waves from an ancient precursor of Lake Michigan washed up against the terminal moraines left by glacial advances.
Lake border ridges (**Qlbm1**)	A heterogenous mixture of clay loam, silty clay loam, silty clay diamicton, clay, silt, sand, and gravel deposits compose **Qlbm1**. These collected as proglacial lacustrine (lake), debris flows, and subglacial deposits in elongated, hummocky (irregular surface) ridges known as the Lake Border moraine. **Qlmb1** records a single glacial advance and retreat. **Qlbm1** occurs in the Hobart Prairie Grove and Heron Rookery units, as well as north of Sand Creek within park boundaries.	**Geologic hazards** When unconsolidated, heterogenous units are exposed along slopes or scarps, potential exists for slope movements. **Glacial features and processes** **Qlbm1** formed at the terminus of the glacial advance as part of the Valparaiso moraine collecting at the very edge of the glacial ice.

Table 2, continued. Geologic features, processes, and associated resource management issues in Indiana Dunes National Park.

Map Unit (symbol)	Description and occurrence in the Park	Features and Processes and Potential Resource Management Issues
Hummocky inner ramp (**Qvr2**)	Unit **Qvr2** contains fine-grained diamicton that collected as subglacial sediment that terminates abruptly at the Valparaiso moraine. **Qvr2** only occurs in a tiny sliver within park boundaries at the Pinhook Bog unit.	**Coastal/lacustrine features and processes** The clay-rich nature of the unit may act as an aquitard to surface water and support wetland development. **Glacial features and processes** **Qvr2** formed at the terminus of the glacial advance as fine-grained till beneath the glacial ice. The clay-rich nature of the unit may act as an aquitard to surface water and support wetland development.
Collapsed head-of-fan (**Qvm1**)	Unit **Qvm1** is diamicton with some interbedded sand over a thick sequence of clay and sandy, shale-rich gravel. These sediments collected in supraglacial debris flows and proximal fans. Today, this is a moderate- to high-relief hummocky surface in the eastern part of the map area. **Qvm1** is mapped over most of the Pinhook Bog unit within park boundaries.	**Geologic hazards** When unconsolidated, heterogenous units are exposed along slopes or scarps, potential exists for slope movements. **Glacial features and processes** A steep, north-facing hill in **Qvm1** marks the southern position of the glacier edge or ice-contact position. **Qvm1** is associated with kettles, such as the Pinhook Bog. **Paleontological resource inventory, monitoring, and protection** **Qvm1** of Pinhook Bog contains Pleistocene and Holocene fossil remains.
Core upland (**Qvm2b**)	**Qvm2b** consists of silty clay-loam diamicton that accumulated as ice-marginal and supraglacial debris flow sediments. Today, this forms a narrow, upland of the Valparaiso moraine. **Qvm2b** occurs only within the Pinhook Bog unit of the park but is a prominent unit, oriented northeast to southwest across the map extent.	**Geologic hazards** When unconsolidated, heterogenous units are exposed along slopes or scarps, potential exists for slope movements. **Glacial features and processes** **Qvm2b** formed at the terminus of the glacial advance as part of the Valparaiso moraine collecting at the very edge of the glacial ice.

Shoreline Erosion Management

Human development and use of the southern Lake Michigan shoreline have resulted in disruption of the natural movement and deposition of sand at Indiana Dunes National Park. According to the US Army Corps of Engineers, much of the local coastal infrastructure, which was built between 1884 and 1948, is deteriorating and in need of maintenance; lower lake levels contribute to the rapid decay of wooden breakwaters (US Army Corps of Engineers 2012) and higher lake levels erode into the shorelines and undermine infrastructure. Water levels in Lake Michigan surged from a historical low in 2013 to a record high in 2020, exacerbating many issues such as property loss and infrastructure damage (Argyilan et al. 2020).

Park managers want to restore natural shoreline processes. In places where restoration is impossible, park managers strive to replicate natural processes to protect park resources (KellerLynn 2010). Two options for the mitigation of shoreline erosion at the park include dredging/beach nourishment and establishing a sand bypass. Both options have limitations to solve this long-term problem. The US Army Corps of Engineers has used costly dredging and beach nourishment to mitigate erosion at Mount Baldy (fig. 7) and Portage

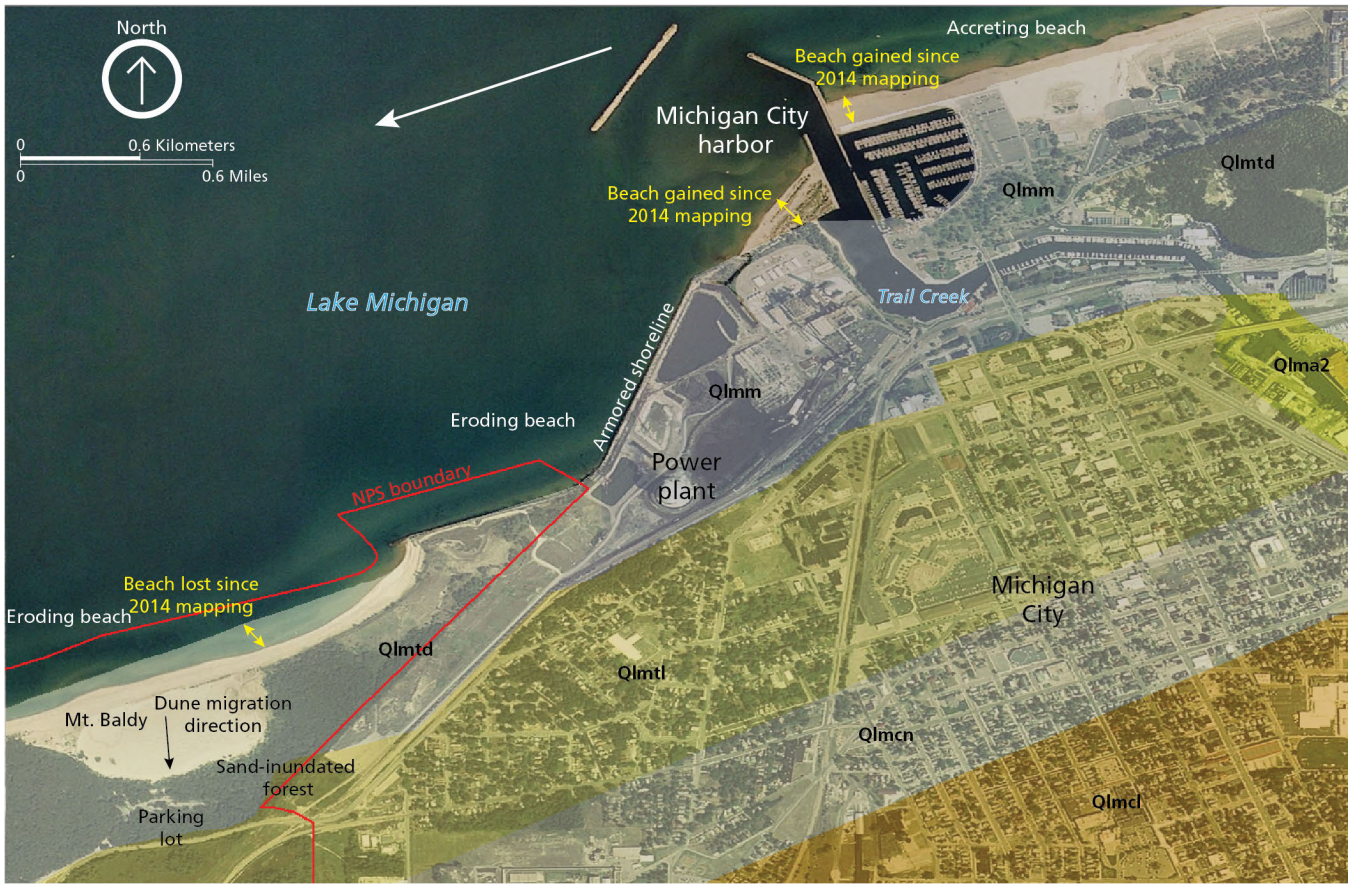

Figure 6. Aerial image of Mount Baldy and Michigan City Harbor.
Coastal engineering at Michigan City Harbor has caused erosion downdrift that is causing Mount Baldy to migrate landward without replenishment. Nearby forests are being buried with sand and the dune will eventually reach the park parking lot. White arrow indicates the general northeast to southwest direction of the drift. Geologic map units superimposed over aerial image. Shoreline change since mapping in 2014 is noted. Graphic by Trista Thornberry-Ehrlich (Colorado State University) using GRI GIS data with a base map by ESRI World Imagery (accessed 14 March 2018).

Lakefront using sand from inland sources and material dredged from Michigan City Harbor (Baird & Associates 2005). According to the park's shoreline environmental impact statement (EIS), high risk areas of the coastline are the eastern ends of the three littoral drift cells putting Mount Baldy and Portage Lakefront Park in jeopardy (Erin Argyilan, Indiana University Northwest, geologist, written communication, 19 May 2020). Rapid erosion continues at Mount Baldy (Watkins et al. 2010; KellerLynn 2010). The Crescent Dune/Mount Baldy area has an annual sand deficit of 3,865 m^3 (136,500 yd^3) and the Portage Lakefront's deficit is 2,095 m^3 (74,000 yd^3) (National Park Service 2016). Some local beaches are actually accreting sand and might be sources for a bypass (e.g., Washington Park); however, local authorities are not likely to agree to any activity that degrades popular beach areas. Offshore bars bypassed as pumped slurry may be an option available to the park (Brenda Waters, Indiana Dunes National Park, assistant chief of natural resources, written communication, 5 October 2010, *in* KellerLynn 2010, p. 10).

Baird & Associates (2005) noted cases where stabilizing the foredune and slope with native dune grasses helped with dune erosion (e.g., Hoffmaster State Park, Michigan). The present closure of Mount Baldy may help with such efforts.

Another issue arises with identifying and matching sand lithology and grain-size characteristics (KellerLynn 2010). If native sand is not closely matched, the natural behavior of the beach or dune will change (see Schupp 2013).

Argyilan et al. (2020) presented the following recommendations for geologists and resource managers at the park: (1) convey the concept of sediment cells and that each cell behaves differently, (2) map sediment

Figure 7. Photographs of issues associated with Mount Baldy.
Coastal engineering structures interrupted the sand supply to Mount Baldy. This caused coastal erosion, which is under constant management to renourish the supply. Mount Baldy is now migrating inland, burying forests and threatening park infrastructure. National Park Service photographs taken in 2010.

distribution out to the limit of cell closure, (3) conduct 3-D geological coastal mapping, e.g., topography and LiDAR (collected over many years to calculate differences in volume and shape of coastal sediments), (4) develop an understanding of conditions that remove sediment from the nearshore and place it in the shoreface, (5) conduct depositional process work in coastal wetlands, (6) promote recognition by the public and engineers that geologic data related to lake-level change is real, (7) manage shoreline in the context of long-term patterns of shoreline behavior so that people do not try to make the shoreline do something that it does not "want" to do, (8) foster a better understanding of isostatic rebound to be joined with very short-term GPS and tide gauge records, and (9) map the Nipissing shore lakeward throughout the Great Lakes basin, including 3-D geological coastal mapping with topography and LiDAR.

The following resources may provide further guidance for shoreline erosion management:

- Coastal engineering inventory: Coburn et al. (2010)
- Coastal adaptation strategies handbook: Beavers et al. (2016)
- Indiana Dunes National Lakeshore shoreline restoration and management plan / final environmental impact statement: National Park Service (2014).
- US Army Corps of Engineers office for harbors in Indiana, https://www.lrc.usace.army.mil/Missions/Civil-Works-Projects/Indiana-Harbor/.
- Sediment core samples to act as standards for determining native sand characteristics: contact Todd Thompson of the Indiana Geological and Water Survey.
- Vibracore techniques and analyses: Thompson et al. (1991)
- Dredging and coastal structure alternatives near Michigan City to impact the Mount Baldy area: Baird & Associates (2005)
- Shoreline restoration and management plan: National Park Service (2014) wherein the park's shoreline is divided into four management reaches based on sediment erosion and accretion. Reaches 1 and 2 extend from Crescent Dune to Willow Lane and will be managed with a submerged cobble berm and beach nourishment with annual frequency. Reaches 3 and 4 extend from Willow Lane to the Gary-US Steel East breakwater and will be managed with beach nourishment via dredged sources with annual frequency.
- LiDAR data (2010–2016) and aerial photograph coverage (dating back to 1935): According to the park's foundation document (National Park Service 2016), these data are available. Analysis of these data would help park managers understand shoreline and landform change through time. A Geoscientists-in-the-Parks (GIP) participant may be able to conduct this analysis (see "Sources for Geologic Resource Management Guidance").
- Coastal geomorphology and littoral cell divisions: Chrzastowski et al. (1994)
- Coastal change assessment to lake-level changes: Pendleton et al. (2005) wherein 21% of the mapped shoreline was classified as having very high potential for lake-level change, 23% is classified as having high potential, 29% as having moderate potential, and

26% as having low potential. The most influential variables in the assessment are local geomorphology, coastal slope, and shoreline erosion/accretion rates.

- Impacts of beach nourishment at Mount Baldy: Przybyla-Kelly and Whitman (2007)

Climate Change Impacts

Climate change is predicted to exacerbate shoreline erosion and overall sand loss at Indiana Dunes National Park. The park's foundation document (National Park Service 2016) identified planning for adaption to climate change as a resource management need. The foundation document identified needing modeling and scenarios to determine future shoreline/beach conditions as a high priority.

Predicted climate change trends will impact the shoreline and ecosystem (flora and fauna) at Indiana Dunes National Park. Climate models indicate that both temperature and precipitation are projected to increase by 1.9°C–3.1°C (3.5°F–5.6°F) and 6%–8%, respectively, by 2050 and storms will increase in frequency and severity (National Park Service 2016). The National Oceanic and Atmospheric Administration (NOAA) has been tracking climate fluctuations since the 1950s. The Great Lakes region has experienced above average temperature increases during that period of time. The park's foundation document (National Park Service 2016) identified climate change impacts and responses for scenario planning as a medium-priority planning and data need.

Resources related to climate change at the park include

- Weather and climate inventory: Davey et al. (2007)
- Climate change trends and vulnerabilities for planning: Gonzalez (2014)
- Climate change exposures: Monahan and Fisichelli (2014)
- Future warming and visitation: Fisichelli and Ziesler (2015).

Disturbed Lands

Indiana Dunes National Park has a long history of human use. Within or adjacent to the park's designated boundary—an outline of 166 km (103 mi) and an area covering 61 km^2 (24 mi^2)—are three residential communities, two fossil fuel power plants, three major steel mills, three major railroads, numerous transmission lines, pipelines, two US highways (12 and 20), the Indiana Toll Road (I-80 and I-90), interstate highway I-94, and miles of roads and streets (National Park Service 2016).

Human use has resulted in disturbed lands, some of which are deemed in need of restoration. Disturbed lands are those park lands where the natural conditions and processes have been directly impacted by development, including facilities, military bases, roads, dams, and abandoned campgrounds; agricultural activities such as farming, grazing, timber harvest, and abandoned irrigation ditches; overuse; or inappropriate use. The GRI GIS data contain map unit **Qlmm**, which defines disturbed areas large enough to appear at the specific map scale within the park and surrounding areas (see "Geologic Map Data"). Some of these features may be of historical significance, but most are not in keeping with the mandates of the National Park Service. KellerLynn (2010) detailed the disturbed areas within the park, including Great Marsh, sand mines, social trails and blowouts, fly ash (coal combustion residue collected by air pollution control systems) disposal sites, and homesites within the park boundaries (fig. 8).

Great Marsh was subdivided and drained by ditches such as Kintzele, Derby, Burns, and Brown for agriculture (Cook and Jackson 1978; KellerLynn 2010). Construction of roads, levees, factories, and housing developments encroached on the marsh. Overall, the marsh is drier than it would be without these disturbances. Moreover, the ditches contribute unnatural levels of sediment-laden water to Lake Michigan (National Park Service 2006a; National Park Service 2008a; KellerLynn 2010). Long Lake was similarly impacted by the construction of railroads, roads, and ditches along the southern side of US Route 12 and along County Line Road; today it is much smaller in size and shallower than its previous extent (Garza et al. 2002). The US Geological Survey is addressing this issue (Erin Argyilan, Indiana University Northwest, geologist, written communication, 14 May 2020). Ditches also facilitate rapid transport of land-based pollutants (e.g., E. coli) and changed natural streamflow patterns (see "Fluvial Features and Processes"; KellerLynn 2010; National Park Service 2016).

As discussed in "Human History Connections," disturbed lands include sand mines that removed entire dunes (**Qlmtd**, **Qlmcd**) from the park area. Disturbances also arise from social trails and other unauthorized uses that remove stabilizing vegetation from slopes and dunes within the park. When slopes are destabilized, large volumes of sand are lost at blowouts and depressions. Areas of concern for foot traffic issues include Mount Baldy, West Beach, and Portage Lakefront Park (KellerLynn 2010).

When disposed in large piles, fly ash—composed of fine-grained, silica (silicon dioxide, SiO_2) glass beads—can exhibit strong capillary action (wicking effect),

Figure 8. Photographs of disturbed areas and adjacent development near the Miller Woods area of the park.
Improper use of park lands leads to reductions in stabilization vegetation, which can increase erosion of the sand forms. Views from the park include those of the Port of Indiana and the US Steel Corporation Gary Works. Photographs by Katie KellerLynn (Colorado State University) taken in summer 2010. Annotation by Trista L. Thornberry-Ehrlich (Colorado State University).

causing local rises in water tables. For this reason, the beads also tend to adsorb metals and metalloids of concern (e.g., molybdenum, arsenic, and boron). Two areas adjacent to Indiana Dunes National Park have been used as fly ash disposal sites: Yard 520 landfill near Town of Pines, upgradient from the Great Marsh; and the settling ponds and landfill near the NIPSCO Bailly Generating Station, southwest of Cowles Bog (KellerLynn 2010).

When the park was established in 1966, the new park boundary contained about 1,000 commercial buildings and homes (National Park Service 2007). Some of these structures were renovated and incorporated into park use. However, most buildings and associated landscaping were removed to restore a natural appearance. Such restoration includes removing septic tanks, underground storage tanks, driveways, exotic vegetation, roads, and reestablishing native prairies (National Park Service 2008b; KellerLynn 2010).

Disturbed Lands Impacts and Restoration

Abandoned mineral land (AML) features pose a variety of resource management issues such as visitor and staff safety and environmental quality of air, water, and soil. AML features can also provide habitat for bats and other animals, some of which may be protected under the Endangered Species Act or state species listings. Resource management of AML features requires an accurate inventory and reporting. All AML features should be recorded in the Servicewide AML database. An accurate inventory identifies human safety hazards and contamination issues, and facilitates closure, reclamation, and restoration of AML features. When appropriate for resource management and visitor safety, AML features can also present opportunities for interpretation as cultural resources (Burghardt et al. 2014). The NPS AML website, http://go.nps.gov/aml provides further information. According to the NPS AML database and Burghardt et al. (2014), Indiana Dunes National Park contains six AML features at two sites. All sites are in Porter County and were part of sand-surface-mine operations. Problems associated with these sites include erosion and struggling vegetation. Both areas are largely recovering naturally, so conducting restoration activities to pre-disturbance conditions is of little interest (Burghardt et al. 2014).

Restoration of the Great Marsh has been a major park goal in an ongoing effort to remove invasive plants, restore native plants, and restore a more natural hydrologic regime by filling ditches, plugging culverts, and constructing spillways and levees to allow surface water to flow without restriction (National Park Service 2009; KellerLynn 2010). Such restoration will rely on cooperation with neighboring landowners because changing the existing hydrology may lead to water control issues adjacent to the Great Marsh. The National Park Service and US Geological Survey prepared a project to study groundwater and surface-water levels relative to wetland restoration in and north of the Great Marsh by identifying water-table elevations, as well as groundwater divides, and recharge areas (commonly under dune ridges and focused in intradunal depressions) (KellerLynn 2010; Buszka et al. 2011; Lampe 2016).

Foot traffic and unauthorized use are causing increases in erosion and sand blowouts, in some cases encroaching on adjacent forests. A need exists to understand the difference between natural versus anthropogenic blowouts. According to the GRI scoping summary (KellerLynn 2010), geologists with the Indiana Geological and Water Survey suggested that blowouts could be dated using optically stimulated luminescence to provide timing of various blowouts throughout the park (contact: Todd Thompson). Geologists with the US Geological Survey have mapped official and unofficial trails across the dunes at West Beach (contact: Noel Pavlovic); similar mapping in other areas of the park would yield a useful data set to resource managers seeking to limit access or restore those areas. Blowout dating and mapping are potential GIP projects.

The topographically elevated landfill at Yard 520 (fly-ash disposal site) threatens the Great Marsh with migrating boron-rich groundwater. The other major fly-ash disposal area near the Bailly and Michigan City generating stations caused contaminated water (pumped as slurry into landfills or settling ponds) to flow into the Cowles Bog wetland complex and into Blag Slough to the north (Pavlovic et al. 2009; KellerLynn 2010). This groundwater plume is migrating toward Lake Michigan, impacting park resources in its wake.

The following resources may provide further guidance for disturbed lands restoration and management:

- Vegetation changes in fly-ash disposal sites: Pavlovic et al. (2009)
- Brown ditch watershed groundwater flow simulations: Lampe (2016)
- Relating hydrologic responses to water levels and flow directions in beach dune complexes: Buszka et al. (2011)
- Contaminants in water and sediment near restored areas of Great Marsh: Egler et al. (2013)

Geologic Hazards: Slope Movements, Sand Collapses, and Earthquakes

A geologic hazard ("geohazard") is a natural or human-caused geologic condition or process that may impact park resources, infrastructure, or visitor safety. Risk is the probability of a hazard to occur combined with the expected degree of damage or loss that may result from exposure to a hazard, or the likelihood of a hazard causing losses (see Holmes et al. 2013). Potential geohazards in the park include slope movements, sand collapses, and earthquakes.

Slope movements, also called "mass movements" or referred to generally as "landslides," have occurred and will continue to occur in the park. Slope movements are the downslope transfer of material (e.g., soil, regolith, and/or rock) (fig. 9). Slope movements can occur rapidly (e.g., soil fall or sand flow) or slowly over long periods of time (e.g., slope creep or slumps). The magnitude of slope failures depends on slope, aspect, soil type, and geology. Within the park, the steep dunes, composed of unconsolidated sand are susceptible to rapid failure if disturbed, undercut by waves, or if the vegetation is changed by anthropogenic activities or climate change (see "Climate Change Impacts").

In July 2013, a six-year old child fell into a hole midway up the lakeward slope of Mount Baldy. Though unprecedented, this accident prompted the closure of Mount Baldy to the more than 150,000 annual visitors for safety concerns (Bremer 2013). Geologists with the Indiana Geological and Water Survey and Indiana University Northwest mapped the dune in 3-D detail and determined that the sand collapse features (also called dune decomposition chimneys) occur in places where dune migration has buried trees that then decayed in situ. The buried trees are rooted into a paleosol (buried soil) that overlies the relic dunes (dunes that are stabilized, fixed, and/or degraded and not migrating) and are buried by sands mobilized by historical erosion along the shoreline that results from sediment starvation caused by the harbor structure at Michigan City (Argyilan et al. 2018). Wood-decay fungi promote the internal decomposition of the trunk and limbs while the formation of a weak carbonate-rich cement works with organic material to make sands around the buried and decaying trees slightly more cohesive. Oak trees dominate the landscape of relic dunes in the area, and within oaks the pattern of decay largely progresses upward from the base of the trunk and outward from the center of limbs. This decay pattern allows the buried trees to maintain their overall structure until decomposition progresses to the point of internal collapse, producing voids that are temporarily stable before infilling that may, or may not, be visible at the dune surface (Argyilan et al. 2015, 2018; Monaghan et al. 2016). The hazardous collapse features occur between the paleosol that is visible on the lakeward slope of the dune and the surface. Noting that the paleosol and trees exist on a surface that has variable topography is important. The thickness of sand between the paleosol and the dune surface determines risk, not an absolute location on the dune or depth. Maximum risk occurs where the sand thickness is less than 12 m (40 ft) (Argyilan et al. 2018). Because of the dune's rapid migration, a slightly different risk is emerging on the stoss slope (see "Eolian Features and Processes") of Mount Baldy. Trees buried recently or over the past several decades are largely still alive and only beginning the long process of internal decomposition. Buried limbs occur as hard obstacles near the surface and pose a related, but different, type of geologic hazard for visitors that attempt to run up and slide down the dune's steep slip face (see "Eolian Features and Processes"). Efforts are ongoing to restrict access to the slip face from both the parking lot and crest of the dune.

Earthquakes are ground vibrations—shaking—that occur when rocks suddenly move along a fault, releasing accumulated energy (Braile 2009). Earthquake intensity ranges from imperceptible by humans to total destruction of developed areas and alteration of the landscape. The "Richter magnitude" is a measure of the energy released by an earthquake. Earthquakes can directly damage park infrastructure or trigger other hazards such as slope movements that may impact park resources, infrastructure, or visitor safety. The likelihood of a magnitude-5 earthquake over the next 100 years for Indiana Dunes National Park is small (fig. 10). The park is not located near a known active seismic zone; however, earthquakes with magnitudes between 2 and 3 are not uncommon. The 2011 Virginia earthquake caused major damage in an area that was likewise considered to be relatively inactive (Perkins 2012). Unconsolidated surficial units, such as those occurring at Indiana Dunes National Park, may be prone to liquefaction during seismic shaking. Liquefaction causes loss of cohesion of sediments and great instability.

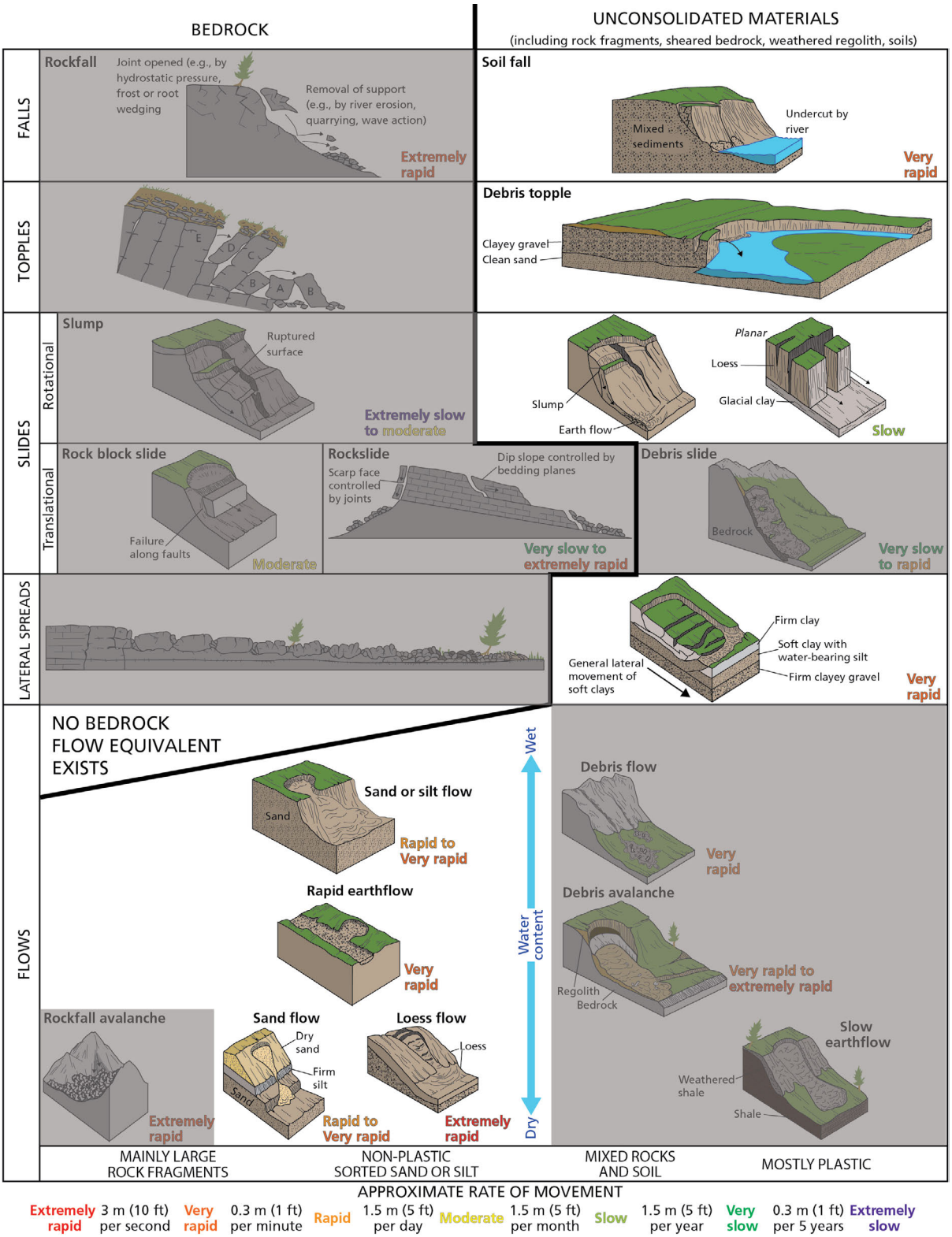

Figure 9. Illustrations of slope movements.
Different categories of slope movement are defined by material type, nature of the movement, rate of movement, and moisture content. Grayed areas depict conditions unlikely to exist at Indiana Dunes National Park. The abundant vegetation in the park stabilizes some slopes, but slope issues could be exacerbated by factors such as natural or anthropogenic removal of vegetation and climate change. Graphic by Trista Thornberry-Ehrlich (Colorado State University) redrafted after a graphic and information in Varnes (1978) and Cruden and Varnes (1996).

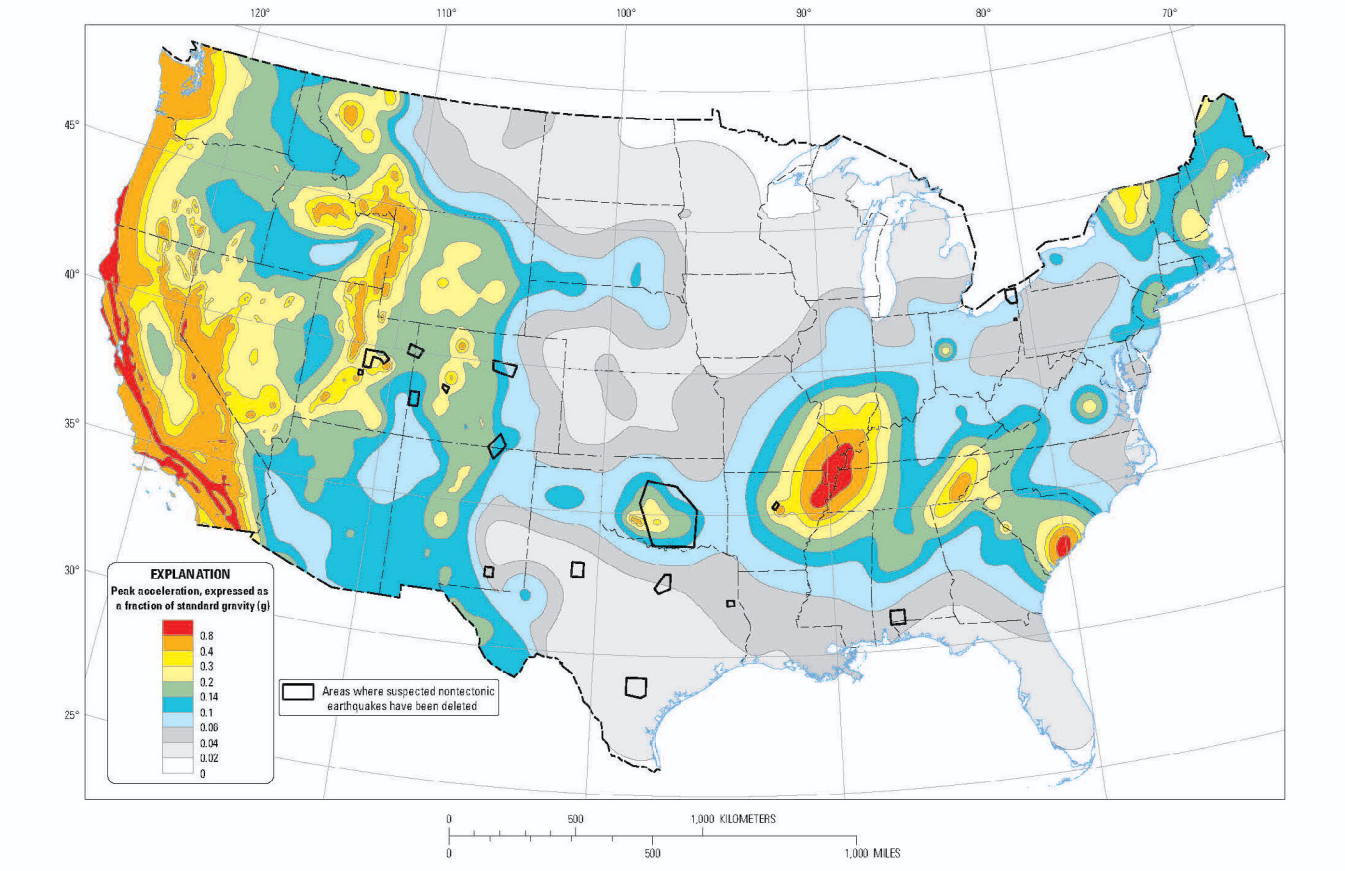

Figure 10. Seismic hazards map of the lower 48 states.
Legend depicts the probability of a strong (~magnitude [M] 5) earthquake within the next hundred years. Red colors in some areas (e.g., the San Andreas fault zone in California, the New Madrid area in Missouri) show strong probability of an earthquake, whereas blue colors show moderate probability, and gray colors show low probability. Northern Indiana is considered at low risk for an earthquake. US Geological Survey graphic available at https://earthquake.usgs.gov/static/lfs/nshm/conterminous/2014/2014pga2pct.pdf (accessed 24 June 2020

Monitoring Geologic Hazards

Primary resource management issues in the park are geologic hazards from slope movements, sand collapses, erosion, and earthquakes. The following references provide additional background information, suggested vital signs, and resources for assessing and documenting geologic hazards:

- Geological Monitoring chapter about slope movements: Wieczorek and Snyder 2009), which described five vital signs for understanding and monitoring slope movements: (1) types of landslide, (2) landslide causes and triggers, (3) geologic materials in landslides, (4) measurement of landslide movement, and (5) assessment of landslide hazards and risks
- The Landslide Handbook—A Guide to Understanding Landslides (Highland and Bobrowsky 2008) produced by the US Geological Survey
- US Geological Survey landslides website: http://landslides.usgs.gov/
- NPS Geologic Resources Division Geohazards website: http://go.nps.gov/geohazards
- NPS Geologic Resources Division Slope Movement Monitoring website: http://go.nps.gov/monitor_slopes
- Natural hazards science strategy: Holmes et al. (2013)
- Sand-collapse hazard mapping for Mount Baldy: Monaghan et al. (2016)
- Origin of collapse features (dune decomposition chimneys): Argyilan et al. (2015), which recommended ongoing work to address the relative contributions of individual environmental factors on the formation of dune decomposition chimneys, including the biomineralization of cement, sand

mineralogy, rate of dune movement, tree species, climate, and the composition of fungal communities

- Landslide hazards and climate change: Coe (2016)
- The NPS Geologic Resources Division Seismic Monitoring website (http://go.nps.gov/seismic_monitoring), and the US Geological Survey Earthquakes Hazards website (http://earthquake.usgs.gov/) provide more information about seismic hazards.
- In the Geological Monitoring chapter about earthquakes and seismic activity, Braile (2009) described the following methods and vital signs for understanding earthquakes and monitoring seismic activity: (1) monitoring earthquakes, (2) analysis and statistics of earthquake activity, (3) analysis of historical and prehistoric earthquake activity, (4) earthquake risk estimation, (5) geodetic monitoring and ground deformation, and (6) geomorphic and geologic indications of active tectonics.

Coastal/Lacustrine Features and Processes

Indiana Dunes National Park boundary extends 90 m (300 ft) into Lake Michigan—the second largest of the Great Lakes by volume at 4,900 km^3 (1,400 mi^3) after Lake Superior. Coming from the Ojibwe word *michi-gami*, meaning "great water," the word "Michigan" originally referred to the lake itself (Superior Watershed Partnership 2007). Nevertheless, as a re-source, Lake Michigan has both lacustrine (referring to lakes and deposits that accumulate in standing or quiet water) and coastal (referring to the border between land and water) features. Furthermore, the coastline of Lake Michigan is the premier resource at the park.

The internal construction of a coastline is a product of long-term responses to variations in water level, sediment supply, hydrographic regime, and preexisting topography and composition (Thompson 1987). Lake Michigan's shoreline has devel-oped over thousands of years to its current configuration (figs. 11 and 12). Indiana was part of a sediment sink for the southern half of Lake Michigan during the late Pleistocene Epoch up to today, and under relatively constant wave energy, produced a punctuated record of beach-ridge development (Thompson 1987; Thompson and Baedke 1995; Todd Thomp-son, Indiana and Water Geological Survey, director, written communication, 9 May 2019). Today's shoreline is a continua-tion of the Tolleston beach from 6,500 years ago including the development of more than 100 beach ridges in the western part of the south shoreline; these beach ridges arc across northwestern Indiana and fan out into northeastern Illinois. In addition, shoreline development included the accumulation of high dunes in the eastern part of the south shoreline (Thompson 1992; KellerLynn 2010; Todd Thompson, Indiana and Water Geological Survey, director, written communica-tion, 9 May 2019). Fluctuation in lake levels, with periodicities of about 160 and 30 years, results in the formation of beach ridges. The 30-year fluctuation produced individual beach ridges around Gary, Indiana, whereas the 160-year fluctuation produced groups of ridges (four to six beach ridges) in the Miller Woods area (Thompson and Baedke 1995; Baedke and Thompson 2000; KellerLynn 2010).

Modern Lake Michigan levels fluctuate naturally over seasons, years, and decades, varying by as much as 1.5 m (5 ft) within the last 15 years (National Park Service 2006b). Strong winter winds create high-energy waves that result in a narrow, steep beach along Lake Michigan's shoreline. Summer's stable lake levels, gentler winds, and smaller waves result in wider, gently sloping beaches (National Park Service 2006b; KellerLynn 2010).

Modern lake level fluctuations reflect a balance between precipitation and evaporation. Lake Michigan experienced below average lake levels from 2000 to 2014, with a record monthly low in 2013. This prolonged low has been followed by a rapid rise of over 1 m (3 ft) to new record high water levels in 2020. High lake levels, diminished ice cover, and strong winter storms have led to extreme coastal erosion (Erin Argyilan, Indiana University Northwest, geologist, written communication, 14 May 2020).

In addition to Lake Michigan and its shorelines, inland lakes, ponds, and wetlands are part of the park's landscape (fig. 13). Several natural lakes, such as Long Lake and those in the Miller Woods area, formed via eolian processes whereby wind transported sand out of an expansive, intradunal swale creating an eroded blowout depression that can fill with water depending on the position of the local water table. Blowouts form unique wetland habitats called pannes. Interdunal wetland areas include Great Marsh, Cowles Bog wetland complex, and more than 62 wetlands in the Miller Woods area (Lafrancois and Glase 2005). Other ponds are artificial, including three Grand Calumet lagoons, ponds at US Steel, four settling ponds at the Portage lakefront, and a pond near the NIPSCO property (KellerLynn 2010). Pinhook Bog is a glacial kettle lake (officially a bog), whose origin is entirely different from the intradunal wetlands (see "Glacial Features and Processes"; Erin Argyilan, Indiana University Northwest, geologist, written communication, 14 May 2020).

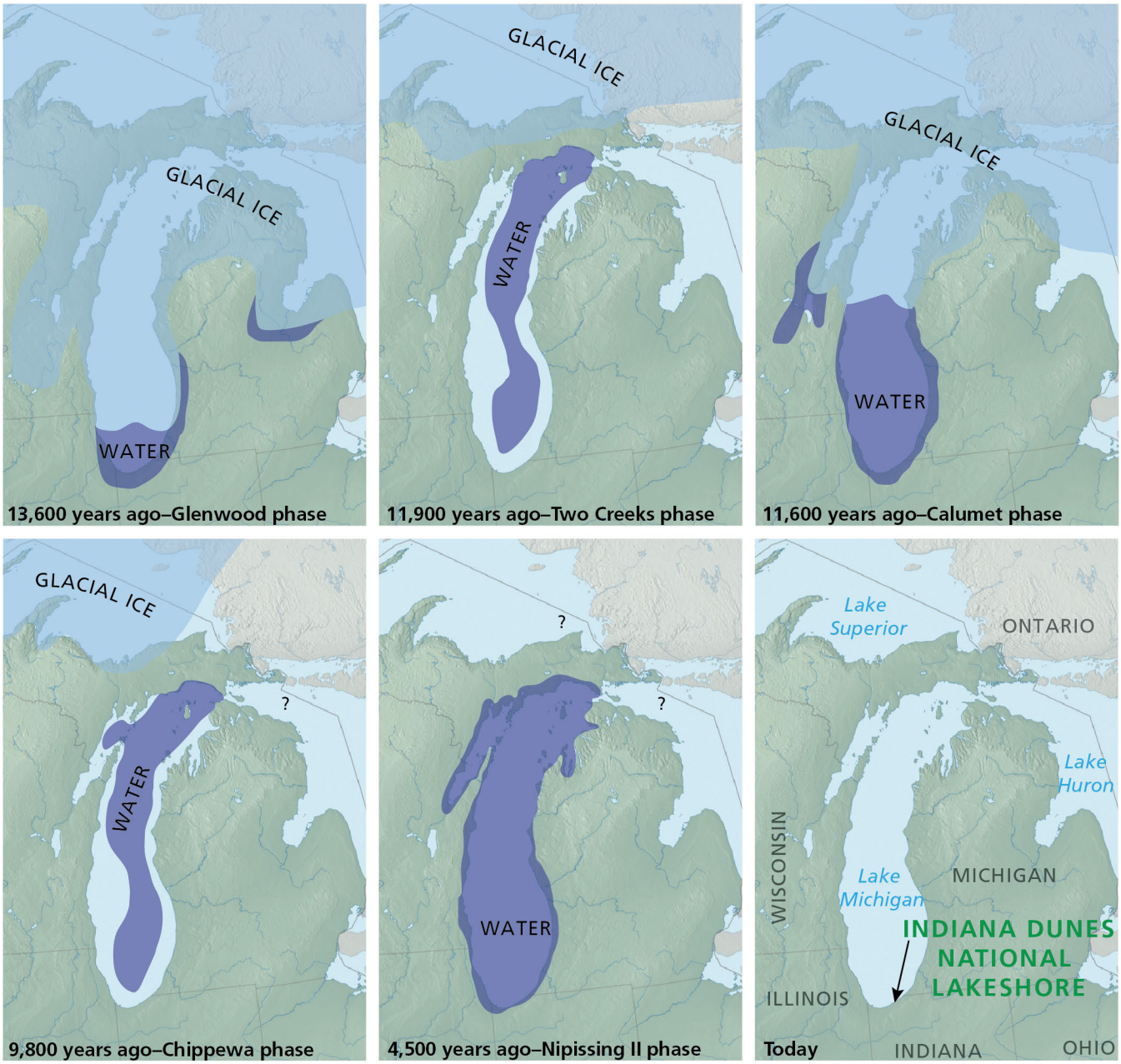

Figure 11. Maps showing phases of Lake Michigan through time.
Glacial ice repeatedly inundated the Lake Michigan basin, commonly impounding a meltwater, proglacial lake. Higher lake levels left beach deposits and dunes at progressively higher and landward elevations in northern Indiana. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) adapted from Hansel et al. (1985) with information from Todd Thompson (Indiana Geological and Water Survey) as presented at the GRI scoping meeting. Shaded relief base map courtesy of Tom Patterson (National Park Service).

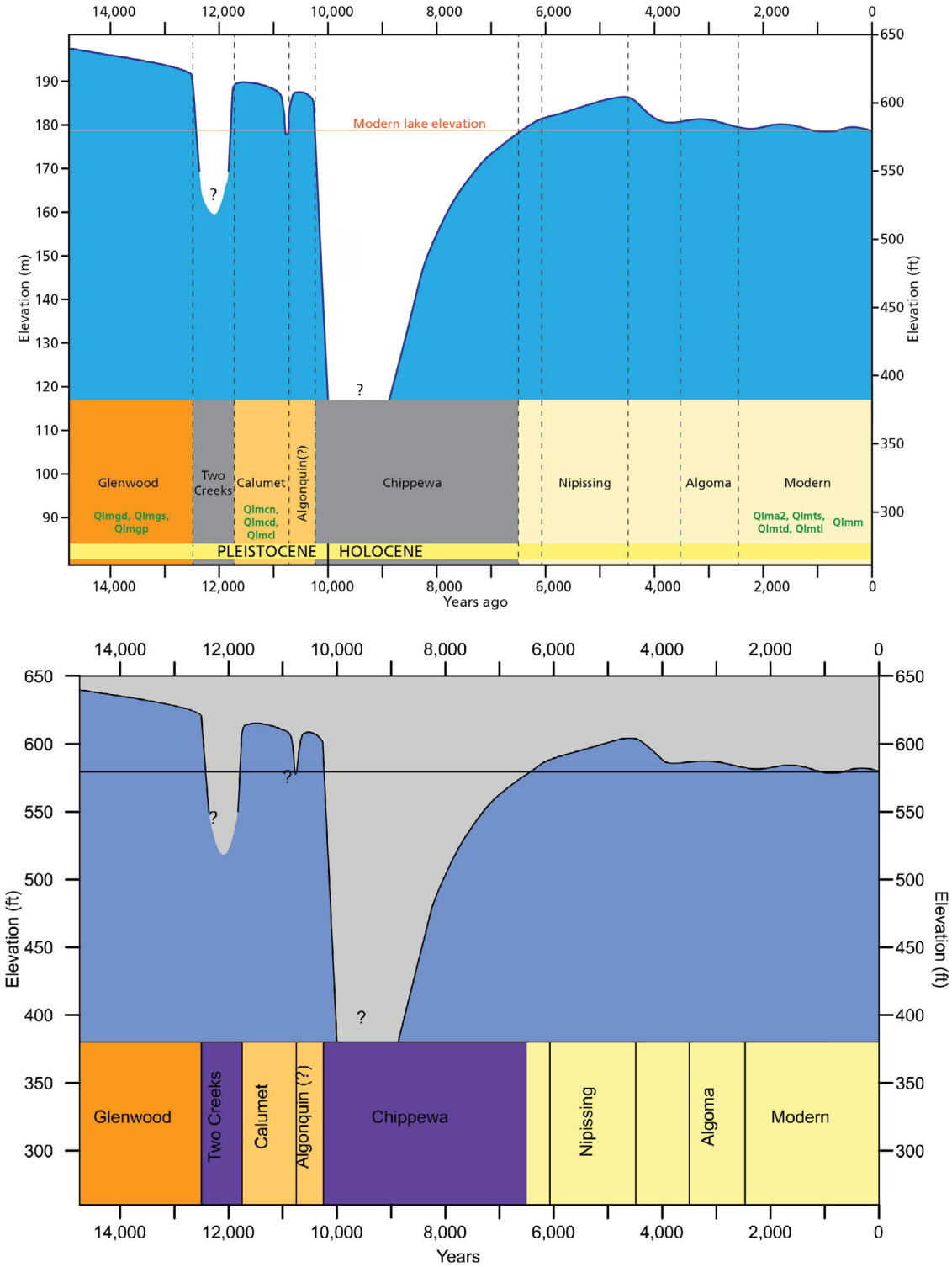

Figure 12. Graph of Lake Michigan lake levels.
The three major shorelines of Lake Michigan (Glenwood, Calumet, and Tolleson) record changing lake levels over the past 14,800 years, including the Glenwood shoreline, which encapsulates the Glenwood lake-level phase. The Calumet shoreline formed during the Calumet and Algonquin phases. The Tolleston shoreline records the Nipissing I and II, the Algoma, and present day (orange line) levels. GRI GIS data units are included for each corresponding phase (green text). Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) adapted from a figure presented at GRI scoping meeting by Todd Thompson (Indiana Geological and Water Survey) with information from Thompson and Johnson (2014) and Todd Thompson (Indiana and Water Geological Survey, director, written communication, 9 May 2019).

Figure 13. Photographs of inland wetlands at Indiana Dunes National Park.
Locally, inland wetlands form from kettles (glacial features) or where eolian processes have excavated intradunal areas to create low points below the water table. Top left photograph was taken at West Beach. Remaining three photographs were taken at Inland Marsh. Photographs by Katie KellerLynn (Colorado State University) taken in summer 2010.

Eolian Features and Processes

Eolian processes refer to windblown erosion, transportation, and deposition of sediments (Lancaster 2009). Features created by eolian processes include dunes, loess, sand sheets, desert pavement, yardangs, and alcoves. As of February 2018, at least 48 designated units of the National Park System contain sand dunes. The NPS Geologic Resources Division Eolian (Aeolian) Resource Monitoring website, https://www.nps.gov/articles/aeolian.htm, provides additional information.

Indiana Dunes National Park encompasses three major dune complexes formed as predominant winds whip sediments into characteristic dune ridges (fig. 14), blowouts, and intradunal swales or valleys. The three complexes correspond to the three most recent, major shorelines in Lake Michigan's local history, listed in order of increasing age: Tolleston, Calumet, and Glenwood (fig. 15). The large dunes that are characteristic of the "Indiana Dunes" occur as part of the Tolleston beach complex. Much of the development of the dunes took place during and after the peak Nipissing phase (ca. 4,500 years ago) as lake level stabilized and then fell more than 4 m (13 ft), providing an abundant sediment source for dune building (Thompson et al. 2011). The largest dunes are located just landward of the modern beach in areas of the park that include West Beach eastward to Michigan City. West of West Beach into Miller Woods, the dunes fan out into hundreds of dune-capped beach ridges. Older sets of dunes can be seen within the park. The largest Tolleston dunes were among the first to form after the fall from Nipissing high lake levels. These dunes stabilized around 3,500 years ago (Argyilan et al. 2010). Glenwood dunes represent the oldest dune complex and formed lakeward of the Lake Border moraine that was deposited as glacial ice departed from the area and a coastal/lacustrine system formed (KellerLynn 2010).

The coastal dunes at Indiana Dunes National Park have specific morphologies that suggest formation processes as well as wind speeds and directions; some features are successional, evolving into other morphologies. The most abundant local types are parabolic dunes (fig. 16), rarer are transverse ridge and coastal foredunes (Kilibarda et al. 2014; Monaghan et al. 2016). In the 1930s, Mount Baldy was a dune with a steep shoreward side but changed to a shorter parabolic dune with a blowout on its north side after coastal engineering structures changed the sediment supply in Lake Michigan (fig. 17; Kilibarda et al. 2009b; Monaghan et al. 2016). Regardless of their specific environment, sand dunes can form only when three factors coincide: a supply of sand to move, wind to move the sand, and ability to replenish the sand supply (Monaghan et al. 2016).

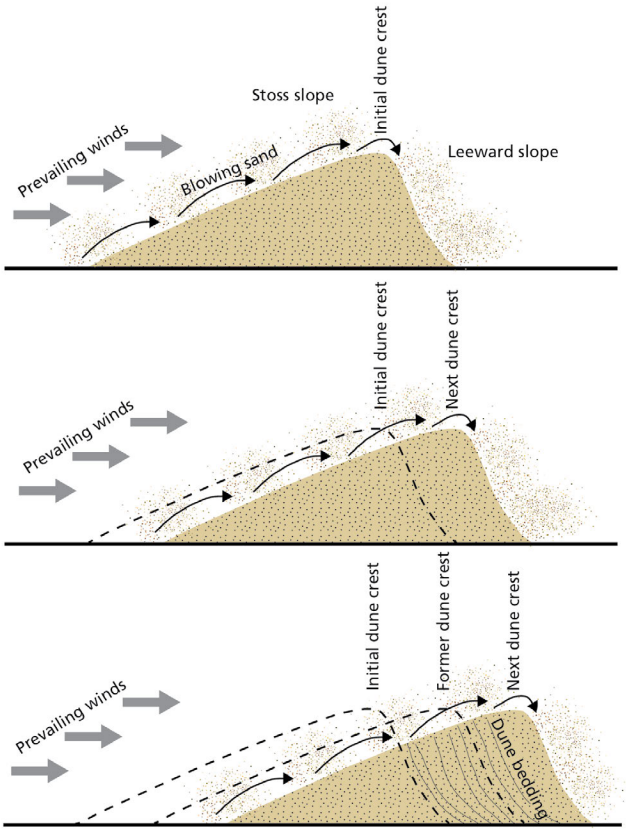

Figure 14. Diagram of eolian sand transportation and dune movement.
Prevailing winds transport sand grains up the windward side or stoss slope of dunes toward the crest, and gravity deposits them in cascades down the steep leeward side. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

The eolian features at the park are either actively migrating or vegetated and more-or-less stable. Among the more active landforms is Mount Baldy, a large parabolic sand dune that rises 37 m (123 ft) above the southern shore of Lake Michigan. Mount Baldy is migrating landward at varying rates, but recently measured at 1.0 m (3.3 ft) per year southward (Pranger 2006; KellerLynn 2010). Recent 3-D mapping revealed a complex palimpsest (area of extensive evidence of layering) of lacustrine, shoreline, and dune deposits composing the modern dune. The current dune form consists of two generations of dunes with different histories separated by a paleosol and rooted trees. The modern Mount Baldy likely developed as a blowout originating in the late 19th century. The shoreline changed from a series of en echelon (overlapping or staggered elements, collectively forming a zone) parabolic dunes to one of sequential blowouts in association with human modification of the Lake

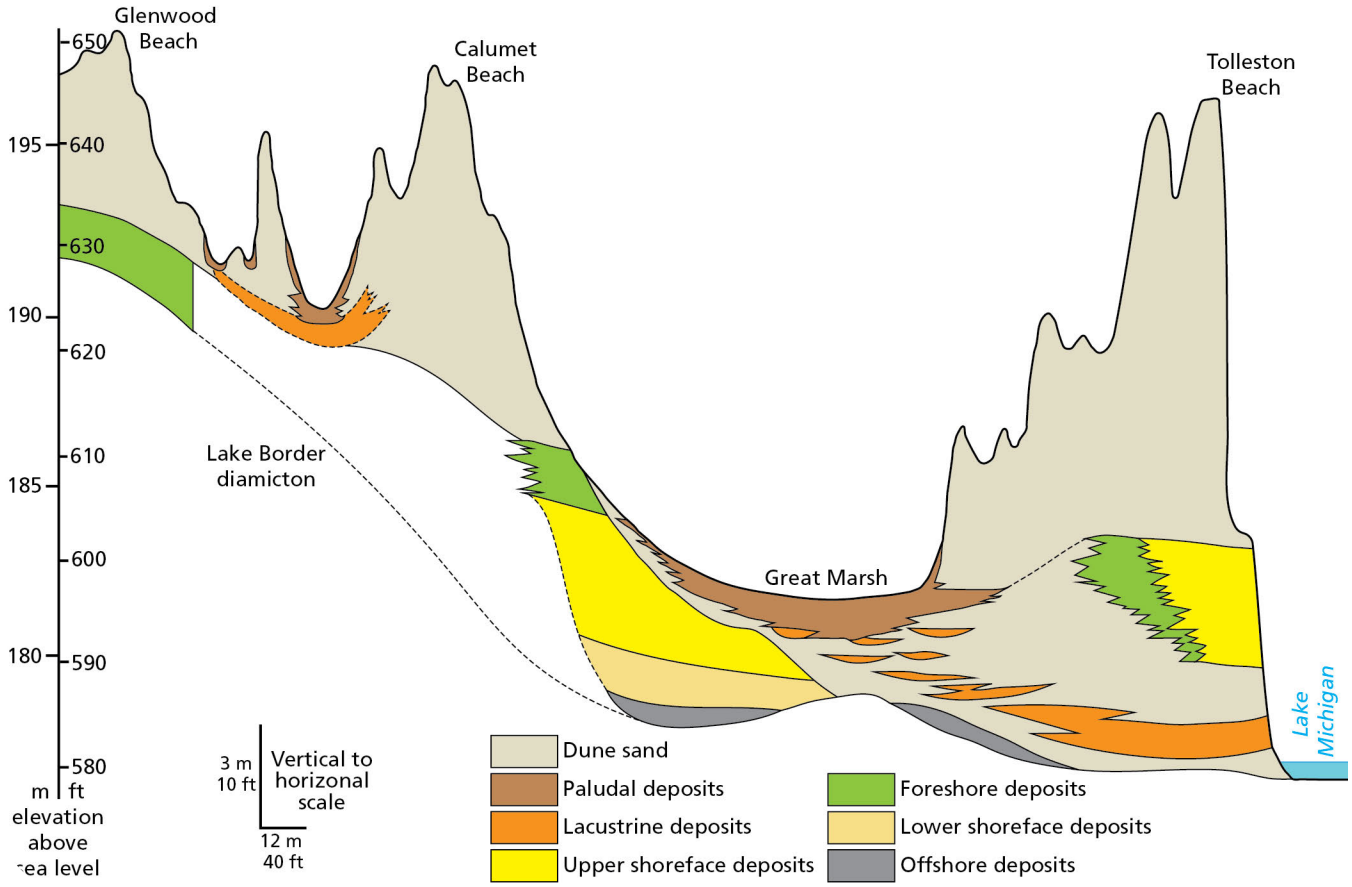

Figure 15. Cross section through the major dune systems at Kemil Road.
From Lake Michigan's shoreline landward, the progressively older Tolleston, Calumet, and Glenwood dunes dominate the park's landforms. Beneath the dunes (dune sand) and wetlands (paludal deposits) is a complex geologic record of shifting shorelines (represented by lacustrine, upper shoreface, foreshore, and lower shoreface deposits) and, ultimately, glacial deposits (e.g., Lake Border diamicton) atop solid bedrock. Graphic by Trista Trista L. Thornberry-Ehrlich (Colorado State University) adapted from a figure presented at GRI scoping meeting by Todd Thompson (Indiana Geological and Water Survey) and Thompson (1987, 1990).

Michigan shoreline at Michigan City Harbor which starved the system of longshore sand (see "Disturbed Lands"; Monaghan et al. 2016).

Older, vegetated, stable dunes and other eolian features contain a vital record of past conditions at the park. Because parabolic dunes migrate parallel to predominant (storm) winds, mapping parabolic dunes and noting their orientation shows wind-direction changes through time (Thompson 1992; Thompson and Baedke 1997; Thompson et al. 2004; KellerLynn 2010). For example, measuring dunes that formed about 6,500 to 3,500 years ago (during the Nipissing phase; see fig. 11) leads to the conclusion that the southern short of Lake Michigan experienced predominant westerly winds that shifted to the northwest and north. These winds resulted in littoral drifts from west to east, opposite of those found today on the southern tip of Lake Michigan (Thompson et al. 2004; KellerLynn 2010).

At Indiana Dunes National Park, the rate of these processes appears to be seasonal with autumn and spring having higher rates of sand accretion and dune movement than summer and winter. Precipitation and freezing temperatures (i.e., climate) also greatly affect sand movement (Kilibarda et al. 2009a; KellerLynn 2010).

Management of Eolian Features and Processes

Eolian features at Indiana Dunes National Park are commonly migrating with prevailing winds thus management is ongoing. Increased storms predicted by climate change models could increase dune erosion events, potentially requiring additional management

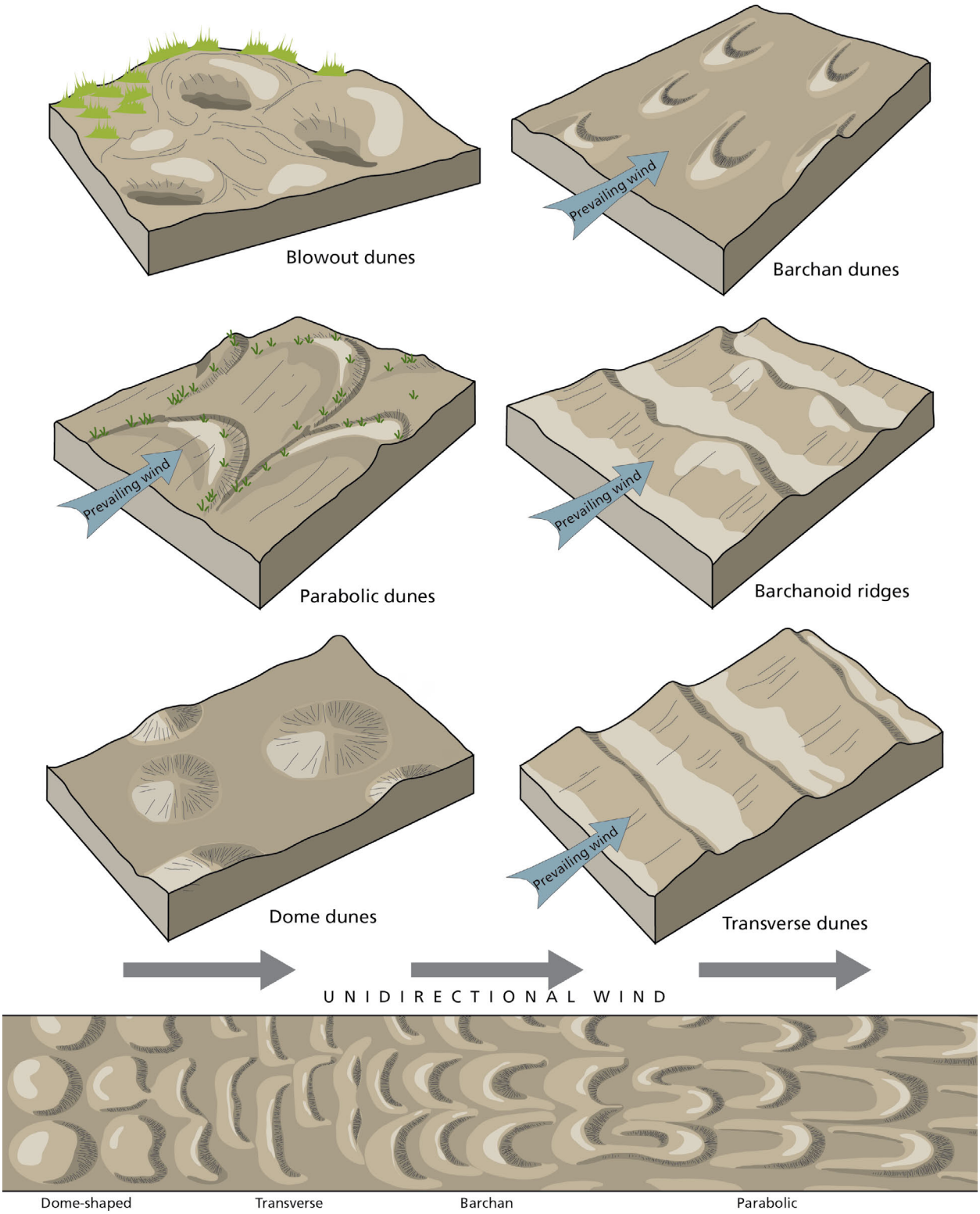

Figure 16. Diagram of dune types and formation.
The primary types of dunes at Indiana Dunes National Park are parabolic dunes, with some transverse and blowout dunes. Blowout dunes are comparable to parabolic dunes, but without the parabolic extensions. Sand supply, wind direction, and interactions among lake levels, groundwater availability, topographic elevation, and vegetation growth affect dune morphology. The lower graphic illustrates barchanoid dune morphologies. Graphics by Trista L. Thornberry-Ehrlich (Colorado State University) after Fryberger et al. (1990) and McKee (1983).

Figure 17. Annotated photographs of Mount Baldy. Coastal armoring and engineering structures have caused a shortage of sand supply to the Mount Baldy dune. The north side of the dune is a blowout, and the dune is migrating quickly inland burying forests and threatening park infrastructure. Photographs by Todd Thompson (Indiana Geological and Water Survey) taken in summer 2010. Restoration efforts since these photos were taken have resulted in remarkable revegetation of the dune. Annotations by Trista L. Thornberry-Ehrlich (Colorado State University).

actions (see "Geologic Significance and Connections"; National Park Service 2016). At current rates of migration (see "Eolian Features and Processes"), the parking lot at Mount Baldy will be buried in 7 to 20 years; the restroom will be covered in 18 to 50 years (Pranger 2006; KellerLynn 2010). Sand migration impacts the preservation of archeological sites (National Park Service 2016). Also, any sediment coming over the dune from the beach represents a permanent sink or loss from the coastal sediment budget, exacerbating shoreline erosion (see "Shoreline Erosion"; Hicks 2006; KellerLynn 2010).

The dunes are fragmented by residential communities and other local development (National Park Service 2016). At the park, anthropogenic uses such as shoreline development at Michigan City (causing lack of available sand), lack of vegetation, and foot traffic (i.e., social trails causing stabilizing vegetation loss) are contributing to migration of large features such as the upper part of Mount Baldy (Erin Argyilan, Indiana University Northwest, geologist, written communication, 19 May 2020). Mount Baldy is intermittently closed due to dangerous conditions (see "Geologic Hazards"; National Park Service 2016). On the "upside," this allows scientific study and revegetation to help stabilize the dune. The park's foundation document (National Park Service 2016) identified a dune protection plan and a survey of social trails as high priorities; a management plan for Crescent dunes is a medium priority.

The following resources may provide further guidance for the management of eolian features and processes:

- LiDAR data (2010–2016) and aerial photograph coverage (dating back to 1935). These types of data help understand landform change through time. Analysis of these data would be an ideal GIP project.
- Geological Monitoring chapter about eolian features and processes by Lancaster (2009), which highlighted 10 vital signs: (1) frequency and magnitude of dust storms, (2) rate of dust deposition, (3) rate of sand transport, (4) wind erosion rate, (5) changes in total area occupied by sand dunes, (6) area of stabilized and active dunes, (7) dune morphology and morphometry, (8) dune field sediment state, (9) rates of dune migration, and (10) erosion and deposition patterns of dunes. The discussion about each vital sign provided estimated costs of the monitoring methods, a complexity rating for each method, an explanation of specific methodologies, and recommended timing of monitoring activity.
- Monaghan et al. (2016) used ground-penetrating radar (GPR), solid earth cores, imagery, topographic maps, digital elevation data, and natural exposures to analyze sedimentary deposits within Mount Baldy and conduct 3-D mapping of the dune's composition. Such techniques could be employed elsewhere to predict dune behavior and understand the history of landform evolution at the park.
- Resource managers could consider obtaining quantitative information to assess the frequency and magnitude of dune migration (and other landform changes) in high-visitation areas. A photo-monitoring program is one possibility as demonstrated in the thesis work by Brown and Arbogast (1999) and the NPS Photogrammetry website (http://go.nps.gov/grd_photogrammetry). The GIP program is an option to support this effort.

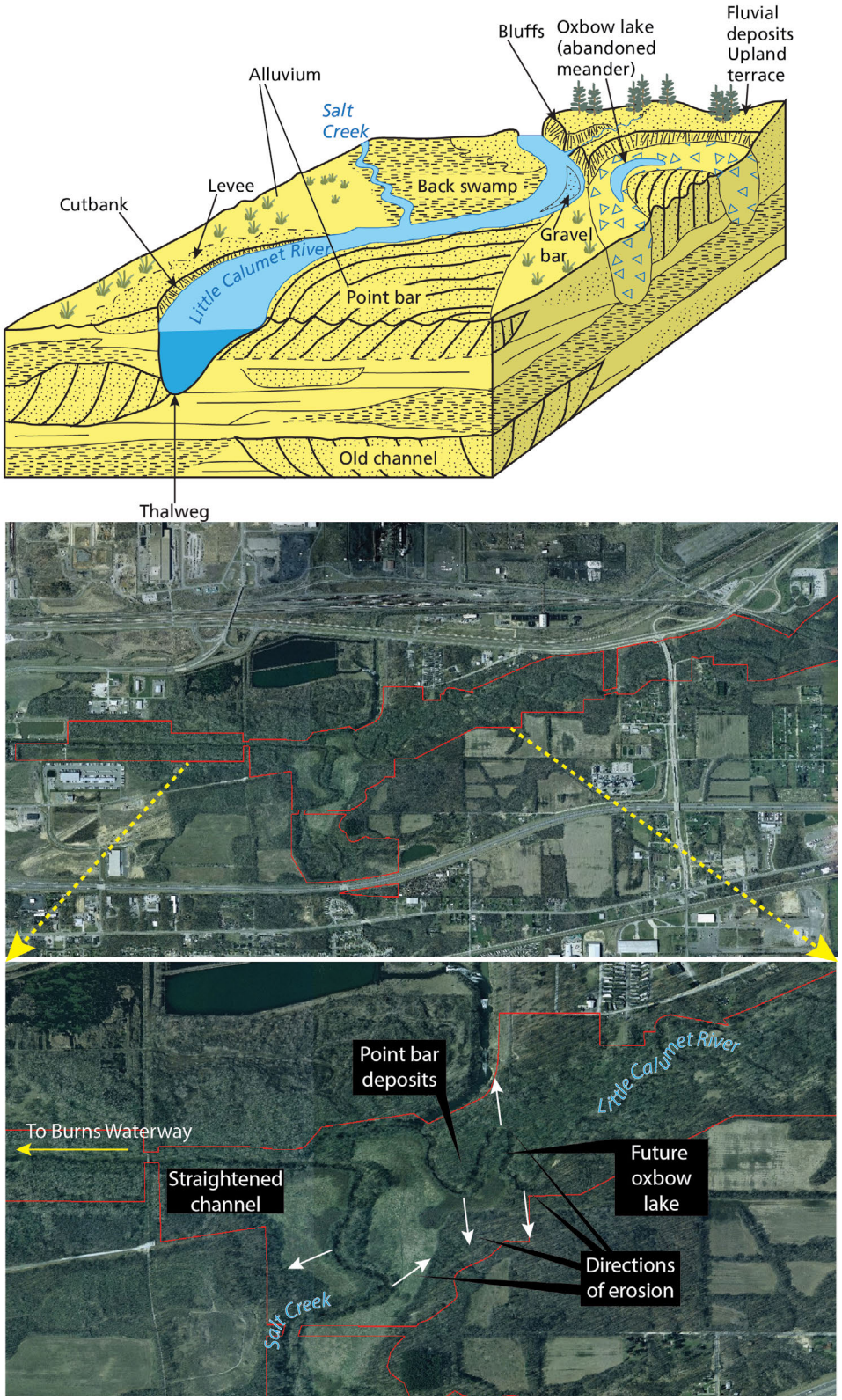

Figure 18. Illustration of fluvial features with park examples.
Many of the features presented in the figure occur along the lengths of the park's waterways. Some stretches of stream are artificially straightened and ditches are armored. Ditches profoundly impact how water flows through the park area. Graphic by Trista Thornberry-Ehrlich (Colorado State University) using GRI GIS data with a base map by ESRI World Imagery (accessed 18 January 2018).

Fluvial Features and Processes

Fluvial features are those which are formed by flowing water. Fluvial processes both construct and erode landforms. They take place on many scales, ranging from large river valleys to the smallest streams. Examples of the park's fluvial features include meandering river channels, point bars, floodplains, and terraces (fig. 18). River channels are the perennial course of the flowing water. As a river flows around curves, the flow velocity (and thus erosive energy) is greatest on the outside of the bend. The river erodes into its bank on the outside of a curve and leaves point bar deposits on the inside of the bend. Point bars are crescent-shaped ridges of sand, silt, and clay deposited on the inside of meander loops where the water's velocity is slowest. As the process continues, the outside bend retreats farther, while the inside bend migrates laterally, thus creating migrating meanders. Meandering reaches its extreme when the narrow neck of land between two bends is breached. Oxbow lakes form where meanders are cut off; they preserve a former river course and provide snapshots of the previous channel substrate as well as preserve pollen records. Many streams drain into the southern end of Lake Michigan. In the park, Grand Calumet River, Little Calumet River, and Dunes Creek are the largest. Some of these are diverted or altered by artificial ditches (see "Disturbed Lands").

Rivers may have bedrock-confined channels or floodplain dominated channels. Floodplain dominated channels experience more lateral meandering than a channel hemmed in by bedrock. All the park's rivers are floodplain dominated. The modern fluvial system developed as the last glacial ice retreated. The Pleistocene glaciations "reset" the river system creating in rapid fashion a new baseline.

Levels of Lake Michigan strongly influence fluvial processes in the park. For instance, when lake levels are high, the lower reach of the west fork of the Little Calumet River reverses flow direction from east to west. Coincident with lake-level rises are rises to the local water table. This contributes water to fluvial features and wetlands. High lake levels also erode the shoreline, moving sediment offshore. If spits (an emergent, narrow deposition bar or beach landform off coasts or lake shores) or offshore bars form, they can change the location of stream channels by forcing the flows around them (KellerLynn 2010).

Fluvial Issues

Many of the fluvial features in the park have been channelized, diverted, or otherwise impacted by human activities. Artificial ditches feed into Dunes Creek including Markowitz ditch, constructed in the 1950s to improve septic-tank operation (Cook and Jackson 1978; KellerLynn 2010). Portions of Dunes Creek are under restoration (KellerLynn 2010). Recreational use of the park's rivers also creates impacts where shorelines are degraded in order to reduce the number of portages and facilitate canoeing on the river. People remove trees from the streambanks and within the stream, which changes streamflow, sedimentation patterns, and the formation of riparian habitat. Notable locations for tree removal are stretches of the Little Calumet River downstream from Chesterton (KellerLynn 2010).

Glacial Features and Processes

Pleistocene glaciers scoured and reshaped the landscape of the northeastern United States, including Indiana Dunes National Park. The most recent ice age (called the "Wisconsinan") completely covered northern Indiana with ice. The two major categories of glacial features are (1) those directly created by glacial ice and (2) those indirectly created by glacial ice, including by rivers flowing beneath or out of glaciers, referred to as "glaciofluvial," or by lakes near glaciers, referred to as "glaciolacustrine." Glacial ice carried vast amounts of sediment that were dumped as the ice melted; glacial deposits fall into four main categories: till (heterogenous mixture of rock of varying sizes and shapes), lacustrine deposits, outwash (glacial sediment transported and deposited by meltwater streams), and ice-contact sand and gravel (fig. 19). Following deposition, glacial sediments are reworked by streams and re-deposited in lakes, which formed as the ice melted. The sediment-rich system left sorted channel, floodplain, and delta deposits across the area among mantles of glacial till.

A series of end moraines exist in northwest Indiana that mark former positions of the terminus of the Lake Michigan lobe of the ice sheet. The moraines appear as long, curved, higher elevation areas that generally trend east to west. Just south of Indiana Dunes National Park, the Valparaiso moraine is a prominent geologic feature in the landscape from Wisconsin, through Illinois and Indiana, into southwestern Michigan.

After the Valparaiso moraine was deposited, the glacier retreated some distance north and then advanced again to construct the (west) Tinley (geologic map units **Qlbr1**, **Qlbr2**, **Qlbm2**, and **Qlbm3**) and (east) Lake Border (**Qlbm1**) moraines on the lakeward flank of the Valparaiso moraine. The Valparaiso moraine intersects Indiana Dunes National Park at Pinhook Bog. It corresponds to several map units included in the GRI GIS data: **Qvr2**, **Qvm1**, and **Qvm2b** (KellerLynn 2010; Thompson and Johnson 2014). Park headquarters are

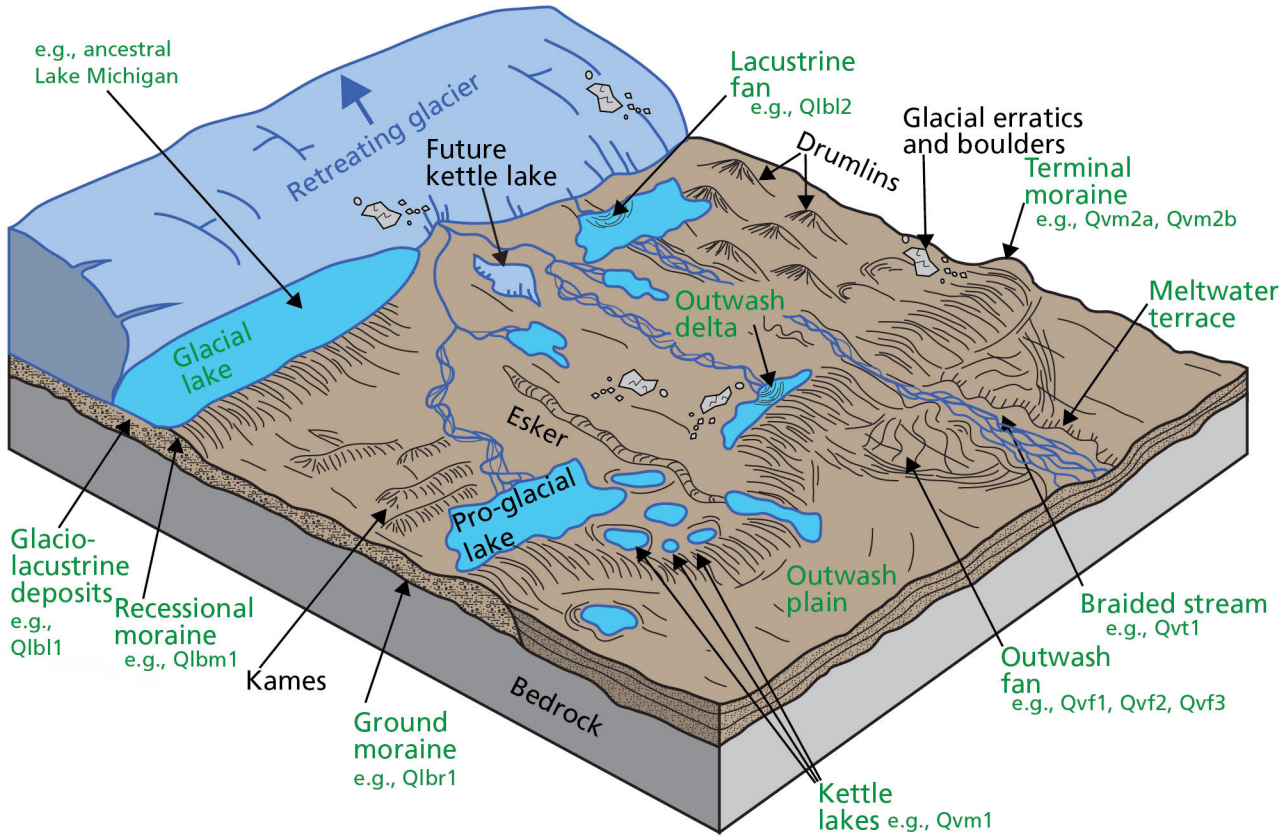

Figure 19. Block illustration of glacial features and deposits.
Glacial features that occur within the map area for Indiana Dunes National Park are labeled in green with local examples indicated. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

located on the Lake Border moraine and the Glenwood- and Calumet-phase beach/dune complexes rest on glaciolacustrine sediments (KellerLynn 2010).

About 14,800 years ago, retreating glaciers left vast deposits in what would become Lake Michigan basin and produced floods of meltwater. The Lake Border moraine trapped much of the retreating glacier's meltwater from draining (Schoon 2003; KellerLynn 2010), and a series of proglacial lakes or ancestral Lake Michigans formed in the basin. The Lake Border moraine was deposited before the Glenwood phase of ancestral Lake Michigan (during which the Glenwood Beach onlapped the moraines) and was responsible for the deposition of map units **Qlbl1**, **Qlbl2**, and **Qlbm1** within park bounda-ries (KellerLynn 2010; Thompson and Johnson 2014; Argyilan et al. 2018).

More than 100 m (350 ft) of glacial sediment covers the park area. The material composing the local moraines is till. The till of the Lake Border moraine is more clay rich than the sandy Valparaiso moraine material (Schoon 2003; Todd Thompson, Indiana Geological and Water Survey, senior scientist, written communication, 20 October 2010; KellerLynn 2010). Meltwa-ter from the glaciers also transported and reworked sediments across the landscape as outwash, for example, the Kanka-kee outwash plain extends south of the Valparaiso moraine. Pinhook Bog in Indiana Dunes National Park formed as a kettle (depression) in ice-deposited sediments (KellerLynn 2010; Erin Argyilan, Indiana University Northwest, geologist, written communication, 15 May 2020).

Another process associated with continental glaciation is isostatic rebound (the rise of land masses that were once depressed by the huge weight of glacial ice sheets). Although investigators agree that after the ice sheet receded, the land surface began to rebound, the amount and rate of local rebound is still a subject of scientific debate but may be on the order of 1 cm (0.4 in) per century. In the Great Lakes, isostatic rebound was linked to rises in paleo-lake level (Thompson 1998; KellerLynn 2010; Erin Argyilan, Indiana University Northwest, geologist, written communication, 15 May 2020). Today, glacio-isostatic adjustments are locally quite small compared to seasonal fluctuations in lake level. Although isostatic rebound may still be affecting the lakeshore today, scientists do not really consider it [as a significant part of] the historical record (Erin Argyilan, Indiana University Northwest, geologist, written communication, 15 May 2020).

Paleontological Resources

Paleontological resources (fossils) are any evidence of life preserved in a geologic context (Santucci et al. 2009). All fossils are nonrenewable. Body fossils are any remains of the actual organism such as bones, teeth, shells, or leaves. Trace fossils are evidence of biological activity; examples include burrows, tracks, or coprolites (fossil dung). Fossils in NPS areas occur in rocks or unconsolidated deposits, museum collections, and cultural contexts such as building stones or archeological resources. As of April 2019, 271 parks had documented paleontological resources in at least one of these contexts.

Ancient, fossiliferous bedrock is not exposed along the Indiana shoreline of Lake Michigan, including Indiana Dunes National Park. However, the Illinois shoreline, which was exposed during Pleistocene highstands yield fossils that occasionally wash up onto the shoreline at the park. The park's collection of crinoids (a marine invertebrate [echinoderm] that uses a stalk to attach itself to a substrate; "arms" are used to capture food) is likely from Illinois limestone exposures (KellerLynn 2010). Several crinoids, a crinoidal concretion, and a fragmented shell-bearing rock collected during cultural investigations in Indiana Dunes National Park are in Midwest Archeological Center (MWAC) collections (Justin Tweet, National Park Service, paleontologist, written communication, 10 May 2019).

According to Hunt et al. (2008) and Western Great Lakes Global Change Research Program (1998), the park has a well-documented fossil record from the Pleistocene and Holocene Epochs that contains information regarding post-glacial changes in climate, flora, and fauna. Post-glacial fossil material includes spruce pollen and wood. Paleoecological studies at Pinhook Bog discovered 8,000-year-old sphagnum moss (floating mat), sedges, heath shrubs, white pine, and larch (Futyma 1988; Davis et al. 1998; KellerLynn 2010). Studies at Cowles Bog found 7,000-year-old floating, leaved aquatics; algae; and abundant grass pollen, as well as 2,000-year-old grass-dominated marsh, containing sphagnum moss, larch, and white pine. Succeeding the grass-dominated marsh was a conifer swamp hosting tamarack, eastern white pine, winterberry, and/or mountain holly, speckled alder, polypodiaceous ferns, royal fern, and sphagnum moss (Futyma 1988; Western Great Lakes Global Change Research Program 1998; KellerLynn 2010). In addition, vibracores drilled in Cowles Bog contained 6,000-year-old mollusks (Miller and Thompson 1990; Thompson 1990; Thompson et al. 1991; Miller et al. 1996; KellerLynn 2010). At the northeastern end of Indiana Dunes National Park, near Michigan City, Holocene fossils are present in the Mount Baldy area. An assemblage dating to between 6,350 ± 200 yr BP (radiocarbon years) and 5,475 ± 250 yr BP (radiocarbon years) includes charophyte algae, grass/moss fragments, wood, ostracodes, fragmentary clams and snails, several bony fish (gar, pike, catfish, perch-like species, bass, and sauger), turtle shell pieces, a loon skull, and pocket gopher remains (Winkler 1962; Bland and Bardack 1973; Teller and Bardack 1975; Gutschick and Gonsiewski 1976). An interval with bivalve and snail fossils predating at least 4,500 yr BP (radiocarbon years) occurs in the Beverly Shores area (Argyilan et al. 2014).

Paleontological Resource Inventory, Monitoring, and Protection

Indiana Dunes National Park has surficial geologic units known to contain fossil remains and the potential for fossils to wash up on beaches. All paleontological resources are nonrenewable and subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act.

Hunt et al. (2008) prepared a paleontological resource summary for the parks of the Great Lakes Network, including Indiana Dunes National Park. The summary was compiled through extensive literature reviews and interviews with park staff and professional geologists and paleontologists, but no field-based investigations. An on-the-ground paleontological survey would be an ideal GIP project. Resource-management recommendations from Hunt et al. (2008) for the park included

- Encourage park staff to observe exposed areas for fossil material while conducting their usual duties. Staff should document any observations with photographs using a common item (e.g., pocketknife) for scale. Fossils and their associated geologic context (rock matrix) should be documented but left in place unless they are subject to imminent degradation by artificially accelerated natural processes or direct human impacts.
- Promote field-based paleontological resource surveys that may yield additional fossils washing up along the shoreline. Further research or field surveys may demonstrate the practicality of a paleontological resource monitoring plan based on the frequency with which fossils wash up along the beaches.
- Contact the NPS Geologic Resources Division for paleontological resource management assistance.

Other resources for guidance on paleontological issues include

- The NPS Fossils and Paleontology website: http://go.nps.gov/paleo
- A summary of National Park Service fossils in a cultural resource context: Kenworthy and Santucci (2006)
- Paleontological resource monitoring strategies: Santucci et al. (2009)

Sources for Geologic Resource Management Guidance

The park's foundation document (National Park Service 2016) and general management plan (National Park Service 1997) are primary sources of information for resource management within the park. Cultural landscape restoration and management are also addressed in a number of publications such as the park's list of classified structures and Interior Collections Management System (ICMS), Cockrell (1988), Shive-Hattery, Inc. (2000), and Evans (2000); however, the park needs a cultural landscape report as noted in the foundation document. Another source of information is the National Park Service historical archives website (http://www.npshistory.com/park_histories.htm#indu), which has more than 13 entries for the park.

The Geologic Resources Division provides technical and policy support for geologic resource management issues in three emphasis areas:

- geologic heritage,
- active processes and hazards, and
- energy and minerals management.

Contact the division (http://go.nps.gov/grd) for assistance with resource inventories, assessments and monitoring; impact mitigation, restoration, and adaptation; hazards risk management; law, policy, and guidance; resource management planning; data and information management; and outreach and youth programs (Geoscientists-in-the-Parks and Mosaics in Science). Park staff can formally request assistance via https://irma.nps.gov/Star/.

Resource managers may find *Geological Monitoring* (Young and Norby 2009) useful for addressing geologic resource management issues. The manual provides guidance for monitoring vital signs—measurable parameters of the overall condition of natural resources. Each chapter covers a different geologic resource and includes detailed recommendations for resource managers, suggested methods of monitoring, and case studies.

The Geoscientists-in-the-Parks (GIP) and Mosaics in Science (MIS) programs are internship programs to place scientists (typically undergraduate students) in parks to complete geoscience-related projects that may address resource management issues. As of February 2018, GIP projects at the park include interpretation and education in 2001 and a pollination study in 2017. Products created by the program participants may be available on that website or by contacting the Geologic Resources Division. Refer to the programs' websites for more information (https://go.nps.gov/gip; https://go.nps.gov/mosaics).

More research projects are undertaken at Indiana Dunes National Park than any other park in the Midwest Region. Requests for scientific studies go through the Great Lakes Research and Education Center (https://www.nps.gov/rlc/greatlakes/index.htm). The park participates in the iSWOOP (Interpreters and Scientists Working on our Parks) program funded by the National Science Foundation (http://www.iswoopparks.com/parkslocations/indiana-dunes-national-lakeshore/).

Thompson (1987) provided a comprehensive look at the surficial geology and geologic history at the park. Argyilan et al. (2018) provided a geologic field trip of the park with marked stops and detailed explanations of the lakeshore history. The Indiana Geological and Water Survey website (https://igws.indiana.edu/) provides information about Indiana geology, encompassing general geology (including surficial and site-specific areas), energy and mineral resources, water and environment, and geologic hazards (earthquakes, mine subsidence, flooding, landslides, coastal erosion, and mine-related accidents). The website also serves as a data store for well records, geologic names information, water balance information, geophysical logs from boreholes, rock unit compendium, coal miner information, limestone photographs, and 3-D elevation data.

Geologic Map Data

A geologic map in GIS format is the principal deliverable of the GRI program. GRI GIS data produced for the park follows the source maps listed here and includes components described in this chapter. A poster displays the data over imagery of the park and surrounding area. Complete GIS data are available at the GRI publications website: http://go.nps.gov/gripubs.

Geologic Maps

A geologic map is the fundamental tool for depicting the geology of an area. Geologic maps are two-dimensional representations of the three-dimensional geometry of rock and sediment at or beneath the land surface (Evans 2016). Colors and symbols on geologic maps correspond to geologic map units. The unit symbols consist of an uppercase letter indicating the age (see table 2) and lowercase letters indicating the formation's name. Other symbols depict structures such as faults or folds, locations of past geologic hazards that may be susceptible to future activity, and other geologic features of significance to a particular mapping project. Anthropogenic features such as mines or quarries, as well as observation or collection locations, may be indicated on geologic maps. The American Geosciences Institute website, http://www.americangeosciences.org/environment/publications/mapping, provides more information about geologic maps and their uses.

Geologic maps are typically one of two types: surficial or bedrock. Surficial geologic maps typically encompass deposits that are unconsolidated and formed during the past 2.6 million years (the Quaternary Period). Surficial map units are differentiated by geologic process or depositional environment. Bedrock geologic maps encompass older, typically more consolidated sedimentary, metamorphic, and/or igneous rocks. Bedrock map units are differentiated based on age and/or rock type. The source map that the GRI team used to compile the GRI GIS data for the park is a surficial map.

Source Maps

The GRI team does not conduct original geologic mapping. The team digitizes paper maps and compiles and converts digital data to conform to the GRI GIS data model. The GRI GIS data set includes essential elements of the source maps such as map unit descriptions, a correlation chart of units, a map legend, map notes, cross sections, figures, and references. These items are included in the indu_geology.pdf.

This report is supported by a map of the surficial geology of Indiana Dunes National Park and its surrounding region on the southern shore of Lake Michigan. The maps were compiled by the Indiana Geological and Water Survey to provide digital coverage of the Quaternary geology of Lake, Porter, and LaPorte Counties in northern Indiana. The GRI team used the following source to produce the GRI GIS data set for Indiana Dunes National Park. This source also provided information for this report.

- Surficial map: Thompson and Johnson, compilers (2014)

GRI GIS Data

The GRI team standardizes map deliverables by using a data model. The GRI GIS data for Indiana Dunes National Park was compiled using data model version 2.1, which is available is available at http://go.nps.gov/gridatamodel. This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software.

GRI GIS data are available on the GRI publications website, http://go.nps.gov/gripubs, and through the NPS Integrated Resource Management Applications (IRMA) portal, https://irma.nps.gov/App/Portal/Home. Enter "GRI" as the search text and select a park from the unit list.

The following components are part of the data set:

- A GIS readme file (indu_gis_readme.pdf) that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information;
- Data in ESRI geodatabase GIS format;
- Layer files with feature symbology (table 3);
- Federal Geographic Data Committee (FGDC)–compliant metadata;
- An ancillary map information document (indu_geology.pdf) that contains information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross sections, and figures;
- An ESRI map document (indu_geology.mxd) that displays the GRI GIS data; and
- A version of the data viewable in Google Earth (indu_geology.kmz; table 3).

Table 3. GRI GIS data layers for Indiana Dunes National Park.

Data Layer	On Poster?	Google Earth Layer?
Surficial Contacts	Yes	Yes
Surficial Units	Yes	Yes

GRI Map Poster

A poster of the GRI GIS draped over aerial imagery of the park and surrounding area is included with hard copies of this report and available for download through the IRMA portal, https://irma.nps.gov/App/Portal/Home (enter "GRI" as the search text and select a park from the unit list). The GIS feature classes that are included on the poster are indicated in table 3. Geographic information and selected park features have been added to the poster. Digital elevation data and added geographic information are not included in the GRI GIS data but are available online from a variety of sources. Contact the GRI team for assistance in locating these data.

Use Constraints

Graphic and written information provided in this report is not a substitute for site-specific investigations. Ground-disturbing activities should neither be permitted nor denied based upon the information provided here. Please contact the GRI team with any questions.

Minor inaccuracies may exist regarding the locations of geologic features relative to other geologic or geographic features in the data or on the poster. Based on the source map scale (1:48,000) and US National Map Accuracy Standards, geologic features are expected to be horizontally within 24 m (80 ft) of their true locations.

Further Geologic Data Needs

The GRI GIS data is restricted to surficial coverage. Bedrock coverage exists elsewhere (e.g., Schneider and Keller 1970); however, these types of data would be of limited use for resource management because no bedrock crops out within the park. Detailed geomorphic mapping and sandscape mapping would provide useful baselines of current conditions to be applied to future monitoring efforts of shoreline and landform change. Given the dynamic nature of the landforms within the park, these data would be relevant.

At the GRI scoping meeting, participants identified the following digital data needs:

- Digitizing older shoreline information to help with shoreline management plans. Park managers are trying to determine where the shoreline was prior to construction of the Michigan City Harbor around 1830 and the Port of Indiana in 1962. These data may be available from older US Geological Survey topographic maps.
- Obtaining historical information on former sand mines. The park's foundation document (National Park Service 2016) identified this an a low priority. The locations of sand mines are probably available on US Geological Survey topographic maps.
- Sand movement surveys were identified as a data need in the park's foundation document (National Park Service 2016).
- Developing aquifer sensitivity maps to show areas sensitive to contamination
- Compiling aquifer level maps to show a "snapshot" of water level.
- Legal survey of all park lands and boundaries. The park's foundation document (National Park Service 2016) identified this as a need. Notably, the most recent National Park Service boundary GIS layer is available through IRMA at https://irma.nps.gov/DataStore/Reference/Profile/2225713. Indiana Dunes National Park tract and boundary data are available through IRMA at https://irma.nps.gov/DataStore/Reference/Profile/2225696.

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Additional References

These references, resources, and websites may be of use to resource managers. Refer to Appendix B for laws, regulations, and policies that apply to NPS geologic resources.

Geology of National Park Service Areas

- NPS Geologic Resources Division (Lakewood, Colorado) Energy and Minerals; Active Processes and Hazards; Geologic Heritage: http://go.nps.gov/grd
- NPS Geoscience Concepts: http://go.nps.gov/geoeducation
- NPS Geodiversity Atlas: http://go.nps.gov/geodiversity_atlas
- NPS Geologic Resources Inventory: http://go.nps.gov/gri
- NPS Geoscientist-In-the-Parks (GIP) internship and guest scientist program: http://go.nps.gov/gip
- NPS Mosaics in Science internship program: http://go.nps.gov/mosaics

NPS Resource Management Guidance and Documents

- Management Policies 2006 (Chapter 4: Natural resource management): http://www.nps.gov/policy/mp/policies.html
- 1998 National parks omnibus management act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf
- NPS-75: Natural resource inventory and monitoring guideline: https://irma.nps.gov/DataStore/Reference/Profile/622933
- NPS Natural resource management reference manual #77: https://irma.nps.gov/DataStore/Reference/Profile/572379
- Geologic monitoring manual (Young, R., and L. Norby, editors. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado): http://go.nps.gov/geomonitoring
- NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents): https://www.nps.gov/dsc/technicalinfocenter.htm

Climate Change Resources

- NPS Climate Change Response Program Resources: http://www.nps.gov/subjects/climatechange/resources.htm
- US Global Change Research Program: http://www.globalchange.gov/home
- Intergovernmental Panel on Climate Change: http://www.ipcc.ch/

Geological Surveys and Societies

- Indiana Geological and Water Survey (Indiana University): https://igws.indiana.edu/
- US Geological Survey: http://www.usgs.gov/
- Geological Society of America: http://www.geosociety.org/
- American Geophysical Union: http://sites.agu.org/
- American Geosciences Institute: http://www.americangeosciences.org/
- Association of American State Geologists: http://www.stategeologists.org/

US Geological Survey Reference Tools

- National geologic map database (NGMDB): http://ngmdb.usgs.gov/ngmdb/ngmdb_home.html
- Geologic names lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/search
- Geographic names information system (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/
- GeoPDFs (download PDFs of any topographic map in the United States): http://store.usgs.gov (click on "Map Locator")
- Publications warehouse (many publications available online): http://pubs.er.usgs.gov
- Tapestry of time and terrain (descriptions of physiographic provinces): http://pubs.usgs.gov/imap/i2720/

Appendix A: Scoping Participants

The following people attended the GRI scoping meeting, held on 28-29 June 2010, or the follow-up report writing conference call, held on 25 April 2018. Discussions during these meetings supplied a foundation for this GRI report. The scoping summary document is available on the GRI publications website: http://go.nps.gov/gripubs.

2010 Scoping Meeting Participants

*Pre- and post-scoping contributor

Name	Affiliation	Position
Bob Daum	Indiana Dunes National Lakeshore	Chief of resource management
Constantine Dillon	Indiana Dunes National Lakeshore	Superintendent
Georgia Hybels	NPS Geologic Resources Division	GIS specialist
Katie KellerLynn	Colorado State University	Geologist, report writer
John Kwilosz	Indiana Dunes National Lakeshore	Natural resources program manager
Dan Mason	Indiana Dunes National Lakeshore	Botanist
Charles Morris	Indiana Dunes National Lakeshore	Environmental protection specialist
Lisa Norby	NPS Geologic Resources Division	Geologist
Noel Pavlovic	US Geological Survey	Ecologist
Pete Penoyer*	NPS Water Resources Division	Hydrologist
Todd Thompson	Indiana Geological and Water Survey	Senior scientist
Brenda Waters	Indiana Dunes National Lakeshore	Assistant chief of natural resources

2018 Conference Call Participants

Name	Affiliation	Position
Ted Gostomski	NPS Great Lakes Network	GIS specialist
Jason Kenworthy	NPS Geologic Resources Division	Geologist, GRI reports coordinator
Henry Loope	Indiana Geological and Water Survey	Mapper, glacial geologist
Chris Pergiel	Indiana Dunes National Park	Deputy superintendent
Dan Plath	Indiana Dunes National Park	Chief of resource management
Todd Thompson	Indiana Geological and Water Survey	Director
Trista L. Thornberry-Ehrlich	Colorado State University	Geologist, report writer, graphic designer
Gia Wagner	Indiana Dunes National Park	Natural resource branch chief

Appendix B: Geologic Resource Laws, Regulations, and Policies

The NPS Geologic Resources Division developed this table to summarize laws, regulations, and policies that specifically apply to NPS minerals and geologic resources. The table does not include laws of general application (e.g., Endangered Species Act, Clean Water Act, Wilderness Act, National Environmental Policy Act, or National Historic Preservation Act). The table does include the NPS Organic Act when it serves as the main authority for protection of a particular resource or when other, more specific laws are not available. Information is current as of December 2019. Contact the NPS Geologic Resources Division for detailed guidance.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Caves and Karst Systems	**Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301 – 4309** requires Interior/Agriculture to identify "significant caves" on Federal lands, regulate/restrict use of those caves as appropriate, and include significant caves in land management planning efforts. Imposes civil and criminal penalties for harming a cave or cave resources. Authorizes Secretaries to withhold information about specific location of a significant cave from a Freedom of Information Act (FOIA) requester. **National Parks Omnibus Management Act of 1998, 54 USC § 100701** protects the confidentiality of the nature and specific location of cave and karst resources. **Lechuguilla Cave Protection Act of 1993, Public Law 103-169** created a cave protection zone (CPZ) around Lechuguilla Cave in Carlsbad Caverns National Park. Within the CPZ, access and the removal of cave resources may be limited or prohibited; existing leases may be cancelled with appropriate compensation; and lands are withdrawn from mineral entry.	**36 CFR § 2.1** prohibits possessing/destroying/disturbing…cave resources…in park units. **43 CFR Part 37** states that all NPS caves are "significant" and sets forth procedures for determining/releasing confidential information about specific cave locations to a FOIA requester.	**Section 4.8.1.2** requires NPS to maintain karst integrity, minimize impacts. **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.2** requires NPS to protect caves, allow new development in or on caves if it will not impact cave environment, and to remove existing developments if they impair caves. **Section 6.3.11.2** explains how to manage caves in/adjacent to wilderness.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Paleontology	**National Parks Omnibus Management Act of 1998, 54 USC § 100701** protects the confidentiality of the nature and specific location of paleontological resources and objects. **Paleontological Resources Preservation Act of 2009, 16 USC § 470aaa et seq.** provides for the management and protection of paleontological resources on federal lands. **Archaeological Resources Protection Act of 1979, 16 USC §§ 470aa – mm Section 3 (1)** Archaeological Resource—nonfossilized and fossilized paleontological specimens, or any portion or piece thereof, shall not be considered archaeological resources, under the regulations of this paragraph, unless found in an archaeological context. Therefore, fossils in an archaeological context are covered under this law. **Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301 – 4309 Section 3 (5)** Cave Resource—the term "cave resource" includes any material or substance occurring naturally in caves on Federal lands, such as animal life, plant life, paleontological deposits, sediments, minerals, speleogens, and speleothems. Therefore, every reference to cave resource in the law applies to paleontological resources.	**36 CFR § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof. **Prohibition in 36 CFR § 13.35** applies even in Alaska parks, where the surface collection of other geologic resources is permitted. **43 CFR Part 49** (in development) will contain the DOI regulations implementing the Paleontological Resources Preservation Act.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.1** emphasizes Inventory and Monitoring, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria.
Recreational Collection of Rocks Minerals	**NPS Organic Act, 54 USC. § 100101 et seq.** directs the NPS to conserve all resources in parks (which includes rock and mineral resources) unless otherwise authorized by law. **Exception: 16 USC. § 445c (c)** Pipestone National Monument enabling statute. Authorizes American Indian collection of catlinite (red pipestone).	**36 C.F.R. § 2.1** prohibits possessing, destroying, disturbing mineral resources…in park units. **Exception: 36 C.F.R. § 7.91** allows limited gold panning in Whiskeytown. **Exception: 36 C.F.R. § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, and Katmai) by non-disturbing methods (e.g., no pickaxes), which can be stopped by superintendent if collection causes significant adverse effects on park resources and visitor enjoyment.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Geothermal	**Geothermal Steam Act of 1970, 30 USC. § 1001 et seq. as amended in 1988**, states ● No geothermal leasing is allowed in parks. ● "Significant" thermal features exist in 16 park units (the features listed by the NPS at **52 Fed. Reg. 28793-28800** (August 3, 1987), plus the thermal features in Crater Lake, Big Bend, and Lake Mead). ● NPS is required to monitor those features. ● Based on scientific evidence, Secretary of Interior must protect significant NPS thermal features from leasing effects. **Geothermal Steam Act Amendments of 1988, Public Law 100--443** prohibits geothermal leasing in the Island Park known geothermal resource area near Yellowstone and outside 16 designated NPS units if subsequent geothermal development would significantly adversely affect identified thermal features.	None applicable.	**Section 4.8.2.3** requires NPS to ● Preserve/maintain integrity of all thermal resources in parks. ● Work closely with outside agencies. ● Monitor significant thermal features.
Mining Claims (Locatable Minerals)	**Mining in the Parks Act of 1976, 54 USC § 100731 et seq.** authorizes NPS to regulate all activities resulting from exercise of mineral rights, on patented and unpatented mining claims in all areas of the System, in order to preserve and manage those areas. **General Mining Law of 1872, 30 USC § 21 et seq.** allows US citizens to locate mining claims on Federal lands. Imposes administrative and economic validity requirements for "unpatented" claims (the right to extract Federally-owned locatable minerals). Imposes additional requirements for the processing of "patenting" claims (claimant owns surface and subsurface). Use of patented mining claims may be limited in Wild and Scenic Rivers and OLYM, GLBA, CORO, ORPI, and DEVA. **Surface Uses Resources Act of 1955, 30 USC § 612** restricts surface use of unpatented mining claims to mineral activities.	**36 CFR § 5.14** prohibits prospecting, mining, and the location of mining claims under the general mining laws in park areas except as authorized by law. **36 CFR Part 6** regulates solid waste disposal sites in park units. **36 CFR Part 9, Subpart A** requires the owners/operators of mining claims to demonstrate bona fide title to mining claim; submit a plan of operations to NPS describing where, when, and how; prepare/ submit a reclamation plan; and submit a bond to cover reclamation and potential liability. **43 CFR Part 36** governs access to mining claims located in, or adjacent to, National Park System units in Alaska.	**Section 6.4.9** requires NPS to seek to remove or extinguish valid mining claims in wilderness through authorized processes, including purchasing valid rights. Where rights are left outstanding, NPS policy is to manage mineral-related activities in NPS wilderness in accordance with the regulations at **36 CFR Parts 6 and 9A**. **Section 8.7.1** prohibits location of new mining claims in parks; requires validity examination prior to operations on unpatented claims; and confines operations to claim boundaries.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Nonfederal Oil and Gas	**NPS Organic Act, 54 USC § 100751 et seq.** authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights). Individual Park Enabling Statutes: • **16 USC § 230a** (Jean Lafitte NHP & Pres.) • **16 USC § 450kk** (Fort Union NM), • **16 USC § 459d-3** (Padre Island NS), • **16 USC § 459h-3** (Gulf Islands NS), • **16 USC § 460ee** (Big South Fork NRRA), • **16 USC § 460cc-2(i)** (Gateway NRA), • **16 USC § 460m** (Ozark NSR), • **16 USC § 698c** (Big Thicket N Pres.), • **16 USC § 698f** (Big Cypress N Pres.)	**36 CFR Part 6** regulates solid waste disposal sites in park units. **36 CFR Part 9, Subpart B** requires the owners/operators of nonfederally owned oil and gas rights outside of Alaska to • demonstrate bona fide title to mineral rights; • submit an Operations Permit Application to NPS describing where, when, how they intend to conduct operations; • prepare/submit a reclamation plan; and • submit a bond to cover reclamation and potential liability. **43 CFR Part 36** governs access to nonfederal oil and gas rights located in, or adjacent to, National Park System units in Alaska.	**Section 8.7.3** requires operators to comply with 9B regulations.
Soils	**Soil and Water Resources Conservation Act, 16 USC §§ 2011–2009** provides for the collection and analysis of soil and related resource data and the appraisal of the status, condition, and trends for these resources. **Farmland Protection Policy Act, 7 USC § 4201 et. seq.** requires NPS to identify and take into account the adverse effects of Federal programs on the preservation of farmland; consider alternative actions, and assure that such Federal programs are compatible with State, unit of local government, and private programs and policies to protect farmland. NPS actions are subject to the FPPA if they may irreversibly convert farmland (directly or indirectly) to nonagricultural use and are completed by a Federal agency or with assistance from a Federal agency. Applicable projects require coordination with the Department of Agriculture's Natural Resources Conservation Service (NRCS).	**7 CFR Parts 610 and 611** are the US Department of Agriculture regulations for the Natural Resources Conservation Service. **Part 610** governs the NRCS technical assistance program, soil erosion predictions, and the conservation of private grazing land. **Part 611** governs soil surveys and cartographic operations. The NRCS works with the NPS through cooperative arrangements.	**Section 4.8.2.4** requires NPS to • prevent unnatural erosion, removal, and contamination; • conduct soil surveys; • minimize unavoidable excavation; and • develop/follow written prescriptions (instructions).

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Federal Mineral Leasing (Oil, Gas, and Solid Minerals)	**The Mineral Leasing Act, 30 USC § 181 et seq., and the Mineral Leasing Act for Acquired Lands, 30 USC § 351 et seq.** do not authorize the BLM to lease federally owned minerals in NPS units. **Combined Hydrocarbon Leasing Act, 30 USC §181**, allowed owners of oil and gas leases or placer oil claims in Special Tar Sand Areas (STSA) to convert those leases or claims to combined hydrocarbon leases, and allowed for competitive tar sands leasing. This act did not modify the general prohibition on leasing in park units but did allow for lease conversion in GLCA, which is the only park unit that contains a STSA. **Exceptions: Glen Canyon NRA (16 USC § 460dd et seq.), Lake Mead NRA (16 USC § 460n et seq.), and Whiskeytown-Shasta-Trinity NRA (16 USC § 460q et seq.)** authorizes the BLM to issue federal mineral leases in these units provided that the BLM obtains NPS consent. Such consent must be predicated on an NPS finding of no significant adverse effect on park resources and/or administration. American Indian Lands Within NPS Boundaries Under the **Indian Allottee Leasing Act of 1909, 25 USC §396, and the Indian Leasing Act of 1938, 25 USC §396a, §398 and §399, and Indian Mineral Development Act of 1982, 25 USCS §§2101-2108**, all minerals on American Indian trust lands within NPS units are subject to leasing. **Federal Coal Leasing Amendments Act of 1975, 30 USC § 201** prohibits coal leasing in National Park System units.	**36 CFR § 5.14** states prospecting, mining, and…leasing under the mineral leasing laws [is] prohibited in park areas except as authorized by law. **BLM regulations at 43 CFR Parts 3100, 3400, and 3500** govern Federal mineral leasing. **43 CFR Part 3160** governs onshore oil and gas operations, which are overseen by the BLM. Regulations re: Native American Lands within NPS Units: • **25 CFR Part 211** governs leasing of tribal lands for mineral development. • **25 CFR Part 212** governs leasing of allotted lands for mineral development. • **25 CFR Part 216** governs surface exploration, mining, and reclamation of lands during mineral development. • **25 CFR Part 224** governs tribal energy resource agreements. • **25 CFR Part 225** governs mineral agreements for the development of Indian-owned minerals entered into pursuant to the **Indian Mineral Development Act of 1982, Pub. L. No. 97-382, 96 Stat. 1938** (codified at **25 USC §§ 2101-2108**). • **30 CFR §§ 1202.100-1202.101** governs royalties on oil produced from Indian leases. • **30 CFR §§ 1202.550-1202.558** governs royalties on gas production from Indian leases. • **30 CFR §§ 1206.50-1206.62 and §§ 1206.170-1206.176** governs product valuation for mineral resources produced from Indian oil and gas leases. • **30 CFR § 1206.450** governs the valuation coal from Indian Tribal and Allotted leases. • **43 CFR Part 3160** governs onshore oil and gas operations, which are overseen by the BLM.	**Section 8.7.2** states that all NPS units are closed to new federal mineral leasing except Glen Canyon, Lake Mead and Whiskeytown-Shasta-Trinity NRAs.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Nonfederal minerals other than oil and gas	**NPS Organic Act, 54 USC §§ 100101 and 100751**	NPS regulations at **36 CFR Parts 1, 5, and 6** require the owners/operators of other types of mineral rights to obtain a special use permit from the NPS as a **§ 5.3** business operation, and **§ 5.7 – Construction of buildings or other facilities**, and to comply with the solid waste regulations at **Part 6**.	**Section 8.7.3** states that operators exercising rights in a park unit must comply with **36 CFR Parts 1 and 5**.
Coal	**Surface Mining Control and Reclamation Act of 1977, 30 USC § 1201 et. seq.** prohibits surface coal mining operations on any lands within the boundaries of a NPS unit, subject to valid existing rights.	**SMCRA Regulations at 30 CFR Chapter VII** govern surface mining operations on Federal lands and Indian lands by requiring permits, bonding, insurance, reclamation, and employee protection. **Part 7** of the regulations states that National Park System lands are unsuitable for surface mining.	None applicable.
Uranium	**Atomic Energy Act of 1954** Allows Secretary of Energy to issue leases or permits for uranium on BLM lands; may issue leases or permits in NPS areas only if president declares a national emergency.	None applicable.	None applicable.
Common Variety Mineral Materials (Sand, Gravel, Pumice, etc.)	**Materials Act of 1947, 30 USC § 601** does not authorize the NPS to dispose of mineral materials outside of park units. **Reclamation Act of 1939, 43 USC §387**, authorizes removal of common variety mineral materials from federal lands in federal reclamation projects. This act is cited in the enabling statutes for Glen Canyon and Whiskeytown National Recreation Areas, which provide that the Secretary of the Interior may permit the removal of federally owned nonleasable minerals such as sand, gravel, and building materials from the NRAs under appropriate regulations. Because regulations have not yet been promulgated, the National Park Service may not permit removal of these materials from these National Recreation Areas. **16 USC §90c-1(b)** authorizes sand, rock and gravel to be available for sale to the residents of Stehekin from the non-wilderness portion of Lake Chelan National Recreation Area, for local use as long as the sale and disposal does not have significant adverse effects on the administration of the national recreation area.	None applicable.	**Section 9.1.3.3** clarifies that only the NPS or its agent can extract park-owned common variety minerals (e.g., sand and gravel), and: ● only for park administrative uses; ● after compliance with NEPA and other federal, state, and local laws, and a finding of non-impairment; ● after finding the use is park's most reasonable alternative based on environment and economics; ● parks should use existing pits and create new pits only in accordance with park-wide borrow management plan; ● spoil areas must comply with Part 6 standards; and ● NPS must evaluate use of external quarries. Any deviation from this policy requires a written waiver from the Secretary, Assistant Secretary, or Director.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Coastal Features and Processes	**NPS Organic Act, 54 USC § 100751 et. seq.** authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights). **Coastal Zone Management Act, 16 USC § 1451 et. seq**. requires Federal agencies to prepare a consistency determination for every Federal agency activity in or outside of the coastal zone that affects land or water use of the coastal zone. **Clean Water Act, 33 USC § 1342/ Rivers and Harbors Act, 33 USC 403** require that dredge and fill actions comply with a Corps of Engineers Section 404 permit. **Executive Order 13089** (coral reefs) (1998) calls for reduction of impacts to coral reefs. **Executive Order 13158** (marine protected areas) (2000) requires every federal agency, to the extent permitted by law and the maximum extent practicable, to avoid harming marine protected areas. *See also "Climate Change"*	**36 CFR § 1.2(a)(3)** applies NPS regulations to activities occurring within waters subject to the jurisdiction of the US located within the boundaries of a unit, including navigable water and areas within their ordinary reach, below the mean high water mark (or OHW line) without regard to ownership of submerged lands, tidelands, or lowlands. **36 CFR § 5.7** requires NPS authorization prior to constructing a building or other structure (including boat docks) upon, across, over, through, or under any park area. *See also "Climate Change"*	**Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks unless directed otherwise by Congress. **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety. **Section 4.8.1** requires NPS to allow natural geologic processes to proceed unimpeded. NPS can intervene in these processes only when required by Congress, when necessary for saving human lives, or when there is no other feasible way to protect other natural resources/ park facilities/ historic properties. **Section 4.8.1.1** requires NPS to: ● Allow natural processes to continue without interference, ● Investigate alternatives for mitigating the effects of human alterations of natural processes and restoring natural conditions, ● Study impacts of cultural resource protection proposals on natural resources, ● Use the most effective and natural-looking erosion control methods available, and avoid new developments in areas subject to natural shoreline processes unless certain factors are present. *See also "Climate Change"*

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Climate Change	**Secretarial Order 3289** (Addressing the Impacts of Climate Change on America's Water, Land, and Other Natural and Cultural Resources) (2009) requires DOI bureaus and offices to incorporate climate change impacts into long-range planning; and establishes DOI regional climate change response centers and Landscape Conservation Cooperatives to better integrate science and management to address climate change and other landscape scale issues. **Executive Order 13693** (Planning for Federal Sustainability in the Next Decade) (2015) established to maintain Federal leadership in sustainability and greenhouse gas emission reductions.	*No applicable regulations, although the following NPS guidance should be considered:* **Coastal Adaptation Strategies Handbook (Beavers et al. 2016)** provides strategies and decision-making frameworks to support adaptation of natural and cultural resources to climate change. **Climate Change Facility Adaptation Planning and Implementation Framework**: The NPS Sustainable Operations and Climate Change Branch is developing a plan to incorporate vulnerability to climate change (Beavers et al. 2016b). **NPS Climate Change Response Strategy** (2010) describes goals and objectives to guide NPS actions under four integrated components: science, adaptation, mitigation, and communication. **Policy Memo 12-02** (Applying National Park Service Management Policies in the Context of Climate Change) (2012) applies considerations of climate change to the impairment prohibition and to maintaining "natural conditions". **Policy Memo 14-02** (Climate Change and Stewardship of Cultural Resources) (2014) provides guidance and direction regarding the stewardship of cultural resources in relation to climate change. **Policy Memo 15-01** (Climate Change and Natural Hazards for Facilities) (2015) provides guidance on the design of facilities to incorporate impacts of climate change adaptation and natural hazards when making decisions in national parks. *Continued in 2006 Management Policies column*	**Section 4.1** requires NPS to investigate the possibility to restore natural ecosystem functioning that has been disrupted by past or ongoing human activities. This would include climate change, as put forth by Beavers et al. (2016). *NPS guidance, continued:* **DOI Manual Part 523, Chapter 1** establishes policy and provides guidance for addressing climate change impacts upon the Department's mission, programs, operations, and personnel. **Revisiting Leopold: Resource Stewardship in the National Parks** (2012) will guide US National Park natural and cultural resource management into a second century of continuous change, including climate change. **Climate Change Action Plan** (2012) articulates a set of high-priority no-regrets actions the NPS will undertake over the next few years **Green Parks Plan** (2013) is a long-term strategic plan for sustainable management of NPS operations.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Upland and Fluvial Processes	**Rivers and Harbors Appropriation Act of 1899, 33 USC § 403** prohibits the construction of any obstruction on the waters of the United States not authorized by congress or approved by the USACE. **Clean Water Act 33 USC § 1342** requires a permit from the USACE prior to any discharge of dredged or fill material into navigable waters (waters of the US [including streams]). **Executive Order 11988** requires federal agencies to avoid adverse impacts to floodplains. (see also **D.O. 77-2**) **Executive Order 11990** requires plans for potentially affected wetlands (including riparian wetlands). (see also **D.O. 77-1**)	None applicable. *2006 Management Policies, continued:* **Section 4.6.6** directs the NPS to manage watersheds as complete hydrologic systems and minimize human-caused disturbance to the natural upland processes that deliver water, sediment, and woody debris to streams. **Section 4.8.1** directs the NPS to allow natural geologic processes to proceed unimpeded. Geologic processes…include…erosion and sedimentation…processes. **Section 4.8.2** directs the NPS to protect geologic features from the unacceptable impacts of human activity while allowing natural processes to continue.	**Section 4.1** requires NPS to manage natural resources to preserve fundamental physical and biological processes, as well as individual species, features, and plant and animal communities; maintain all components and processes of naturally evolving park ecosystems. **Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks, unless directed otherwise by Congress. **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety. **Section 4.6.4** directs the NPS to (1) manage for the preservation of floodplain values; [and] (2) minimize potentially hazardous conditions associated with flooding. *continued in Regulations column*

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