CHAPTER 9

GEOLOGY

Geology is the study of the Earth and involves examining the physical, chemical and biological processes that have shaped, and continue to shape, its landscapes. The geologic history of the Earth is divided into time intervals that help chronologically date layers of rock (strata) with respect to time. Subdivisions of geologic time, in order from larger units of time to smaller units of time, include: eon, era, period, epoch and age.

The subtle processes that formed the underlying bedrock in Ohio occurred over the course of hundreds of millions of years. During the Ordovician (446 to 460 million years ago), Silurian (416 to 435 million years ago) and Devonian (359 to 407 million years ago) periods, Ohio was located south of the equator and submerged under a large, shallow saltwater sea. Over time, as the North American continent slowly moved north toward the equator, mud and sediment from the ancient seafloor compacted under the weight of new deposits, forming layers of limestone, dolomite, shale and sandstone bedrock. Massive amounts of rock salt (halite) were also deposited in eastern Ohio from the evaporating Silurian-age sea water. During the Carboniferous Period (302 to 359 million years ago)—which is often divided into two shorter intervals: the Mississippian (earlier) and Pennsylvanian (later) periods—Ohio was located at the equator and close to sea level. The climate was warm and humid and the landscape was swampy with lush vegetation. Ohio's extensive coal deposits can be attributed to the decayed and compressed plant material of the tropical, Carboniferous-era swamps. During the late Permian Period (251 to 299 million years ago), the entire Mesozoic Era (66 to 252 million years ago), and much of the Cenozoic Era (present-day to 66 million years ago), Ohio was north of the equator nearing its current latitude and situated well above sea level. Due to extensive water and wind erosion, surface rocks and fossils (including Mesozoic-age dinosaur bones) were not preserved, and subsequently, no corresponding bedrock layers exist in Ohio. The Quaternary Period (present-day to 2.6 million years ago) is the current and most recent period of the Cenozoic Era. It is divided into two epochs: (1) the Pleistocene Epoch (earlier) and (2) the Holocene Epoch (current). The present-day topography of nearly three-fourths of Ohio, including the entire Lake Erie Watershed, was deposited and shaped by multiple glaciations that occurred during the Pleistocene Epoch (also known as the Ice Age).

PHYSIOGRAPHIC REGIONS

Physiographic regions are large geographic areas that can be grouped and characterized by similar geology, topography and groups of vegetation and wildlife. There are eight distinct physiographic divisions in the United States. These broad areas are further divided into more detailed regions, called physiographic provinces. Ohio's physical landscape is very diverse and can be delineated into three main physiographic provinces: (1) the Central Lowland; (2) the Appalachian Plateaus, and; (3) the Interior Low Plateau, which covers a very small portion of southwest Ohio. The Central Lowland encompasses much of central, western and southwestern Ohio and extends east of Cleveland along a roughly ten-mile-wide ribbon that borders and parallels the Lake Erie shore. The Appalachian Plateaus are prevalent in eastern and southeastern Ohio. Both provinces are subdivided into smaller regional sections.


North Shore Alvar State Nature Preserve, Kelleys Island, Erie County

The Central Lowland is comprised of low-relief and glacially-influenced landscapes. It is underlain by limestone and dolomite bedrock, with some shale. Sediments that were deposited from Pleistocene-epoch glaciations (see page 212) cover the entire lowland, except where outcrops of bedrock exist. Prior to the glaciers, the landscape of the Central Lowland featured moderate relief and many tributaries. The movement of the glacial ice scoured and smoothed the bedrock and destroyed ancient river systems. The unconsolidated material left behind by the retreating ice consists of sand, clay, peat, gravel and boulders, and can be several hundred feet thick.

In Ohio, the Central Lowland province is subdivided in two physiographic sections: (1) the Till Plains and (2) the Huron-Erie Lake Plains. The Till Plains cover much of southwestern and western Ohio, including the southwestern portion of the Lake Erie Watershed. Glacial material that was mixed, crushed, compressed and transported by the movement of the ice sheet is called "**till**." Landscapes composed of glacial till are generally flat and feature gently rolling hills (ground moraines). Long narrow ridges containing thick layers of sand and gravel, called end moraines, and irregularly-placed hummocks are also common landforms in the Till Plains. End moraines, or terminal moraines, mark the temporary positions of the ice front during the glacial retreat. Hummocks are rounded landforms, such as small knolls or mounds, that typically occur in groups or fields.

The Huron-Erie Lake Plains cover much of northwestern Ohio as well as a narrow ten-mile-wide strip along the Lake Erie shore to the Pennsylvania border. This region is characterized by very flat terrain with very low and little relief. In northwestern Ohio, the Huron-Erie Lake Plains extend as far as 50 miles from the shore and encompasses the area formerly covered by the Great Black Swamp. As glacial ice retreated out of the Erie basin—about 14,000 years ago—Lake Maumee and other precursors of Lake Erie developed along the margin of the retreating ice and covered lowland areas (see "Formation of Lake Erie" section). Landscapes include beach ridges and wave-planed moraines. Deposits are relatively uniform-textured materials (fine-grained clay and silt-sized sediments) that originated in proglacial lake bottoms during the various stages of Lake Erie's formation. In northeast Ohio, lowland areas extend from the shore southward to a series of southwest-to-northeast trending ridge moraines that border the Appalachian Plateaus.

The Appalachian Plateaus province includes high-relief and high-elevation bedrock hills (greater than 1,000 feet above mean sea level). Geologic formations in this physiographic province consist primarily of Mississippian-, Pennsylvanian- and Permian-age (southeast Ohio) sandstone and shale. In Ohio, the Appalachian Plateaus is subdivided into two physiographic sections: (1) the Glaciated Allegheny Plateaus and (2) the Allegheny Plateaus.

Landforms and topography of the Glaciated Allegheny Plateaus section were influenced by Pleistocene-epoch glaciations. The Mississippian- and Pennsylvanian-age sandstone and shale in the bedrock highland areas of Medina, Summit, Portage, Geauga, Trumbull and Ashtabula counties were more resistant to glacial advancement and erosion, which greatly inhibited the southward progression of Ice Age glaciers. However, because of the glaciers, elevations and relief in the glaciated section of the Appalachian Plateaus are much lower than in the unglaciated section. The glaciers also broadened valleys for post-glacial drainage and uncovered vestiges of pre-glacial valleys.

The western boundary of the Appalachian Plateaus (and eastern boundary of the Central Lowland) is marked by the Berea Escarpment (not mapped). No portion of the Lake Erie Watershed extends into the unglaciated section of the Appalachian Plateaus province.


Glacial Grooves, Kelleys Island, Erie County

FORMATION OF LAKE ERIE

Lake Erie owes its existence to the extensive lowlands and valley formed by the east-flowing Erigan River, a pre-glacial river system that existed long before the start of the Pleistocene Ice Age. The advance and retreat of glacial ice during multiple glaciation events destroyed this drainage system. These events also greatly deepened and enlarged the Erigan basin. The initial phases of Lake Erie's formation began as soon as the Erie lobe of the Wisconsinan ice sheet commenced its northward retreat, exposing the vastly expanded lowlands where the ancient Erigan River once flowed.

Glacial material consisting of unsorted, clay-to-boulder-size debris was transported and deposited by the movement of the glaciers. End moraines, or terminal moraines, are long narrow ridges of till that was deposited at the terminus of the glacier. After the ice retreated, these landforms acted as basin divides to help contain vast glacial meltwater lakes.

The earliest proglacial lake to take shape in the Erie basin was **Lake Maumee**. It formed about 14,000 years ago. The timeline of Lake Maumee can be divided into three distinct substages: (1) an initial stage, known as Highest Maumee, or Maumee I; (2) an intermediate stage, known as Lower Maumee, or Maumee II, and; (3) a later stage, known as Middle Maumee, or Maumee III.

During the Highest Maumee stage, beaches formed at an elevation of about 800 feet above sea level (ASL). In Ohio, the highest remnant beaches—at 801 feet ASL and 798 feet ASL, respectively—are found in the villages of West Unity (Williams County) and Fayette (Fulton County). The highest beach along the south shore of Lake Maumee ranged between 775 feet ASL and 785 feet ASL, from Fort Wayne to Cleveland. As Maumee I waters continued to rise, an outlet through a low point in the Fort Wayne Moraine (near present-day Fort Wayne, Indiana) was eventually breached. This caused a catastrophic drainage event, called the "Maumee Torrent," in which a massive flow of water scoured a one- to two-mile-wide path between Lake Maumee and the Wabash River (part of the Mississippi River drainage basin).

As the ice continued to recede, Lake Maumee's surface area expanded, but water levels significantly dropped to an elevation of 760 feet ASL, initiating the Lowest Maumee (Maumee II) stage. The change in water levels was due to the exposure of a new drainage outlet in central Michigan. This outlet discharged water through the Grand River to Lake Chicago (an early phase of Lake Michigan) and then to the Mississippi River.

The Middle Maumee (Maumee III) stage—the final Lake Maumee phase—initiated as another glacial advance blocked the Grand River outlet. This obstruction caused water levels to rise to about 780 feet ASL. A westward-flowing, intermediate drainage outlet, called the Imlay Channel, was established near present-day Imlay City, Michigan. This new channel eventually connected with the Grand River.

Lake Arkona followed Lake Maumee as glacial ice resumed its northward retreat. Downcutting of the Grand River outlet lowered the water levels to successive elevations of 710, 700 and 695 feet ASL. Evidence suggests that dropping lake levels may have been influenced by changes in climate and precipitation. Each stage of Lake Arkona is marked by indistinct, poorly-developed beaches. This is likely due to the constant water level drop and from erosion by the later, and higher, Lake Whittlesey. The lowest stage of Lake Arkona has been dated at about 13,600 years ago.

Lake Whittlesey formed about 13,000 years ago as a major southward push of the Wisconsinan ice sheet, known as the "Port Huron readvance," closed part of the Grand River drainage outlet and raised water levels to an elevation of about 738 feet. The outlet for Lake Whittlesey was a westward-flowing channel, known as the Ubly Channel that connected with the Grand River in central Michigan. The beach ridges that mark the former south shore of Lake Whittlesey are some of the most prominent and well-preserved in Ohio, and are particularly well developed in Lorain, Cuyahoga, Lake and Ashtabula counties. During a significant glacial retreat, water levels of Lake Whittlesey dropped dramatically—even below the levels of modern Lake Erie. Drainage was redirected to the east through an outlet in the Niagara Gorge area.

The first of three **Lake Warren** phases, known as Highest Lake Warren, or Warren I, followed Lake Whittlesey. Lake Warren formed around 12,700 years ago as the readvance of glacial ice raised water levels to about 685 feet ASL. Poorly-developed and discontinuous beach ridges at an elevation of about 675 feet ASL define an intermediate phase of Lake Warren, called Middle Lake Warren (Warren II). Following Warren II and immediately preceding the lowest Lake Warren (Warren III) phase, was **Lake Wayne** (660 feet ASL). Lake levels of Lowest Lake Warren were about 670 feet ASL. The drainage outlet for the phases of Lake Warren was the Grand River in central Michigan, whereas Lake Wayne is thought to have drained to the east through the Mohawk River Valley in New York.

The last stage of Lake Erie's formation was **Lake Lundy**, which formed after the Wisconsinan ice sheet made its final retreat into Canada. The immense weight of the ice had applied great pressures on the landscape. The exposed land began to slowly rise through a process called "**isostatic rebound.**" This rebound process closed off drainage outlets and allowed the water levels to rise. When the outlet at the Niagara Gorge was breached, water levels in the Erie basin drastically lowered by 150 feet. This event completely drained the Western Basin; however, the moderately slow rise of the land near the Niagara outlet allowed water levels to rise again. By about 3,500 to 4,000 years ago, the lake level was around 30 feet below that of modern Lake Erie. A rapid ten- to 20-foot rise in water level occurred about 2,600 years ago when the upper Great Lakes began to drain through the St. Clair and Detroit rivers into the Erie basin. **Lake Erie** eventually took its present shape as water levels reached a mean level of 571.3 feet IGLD85. On Lake Erie's south shore, isostatic rebound continues at a rate of 0.2 to 0.3 feet every 100 years.

PHYSICAL FEATURES OF THE LAKE ERIE COAST

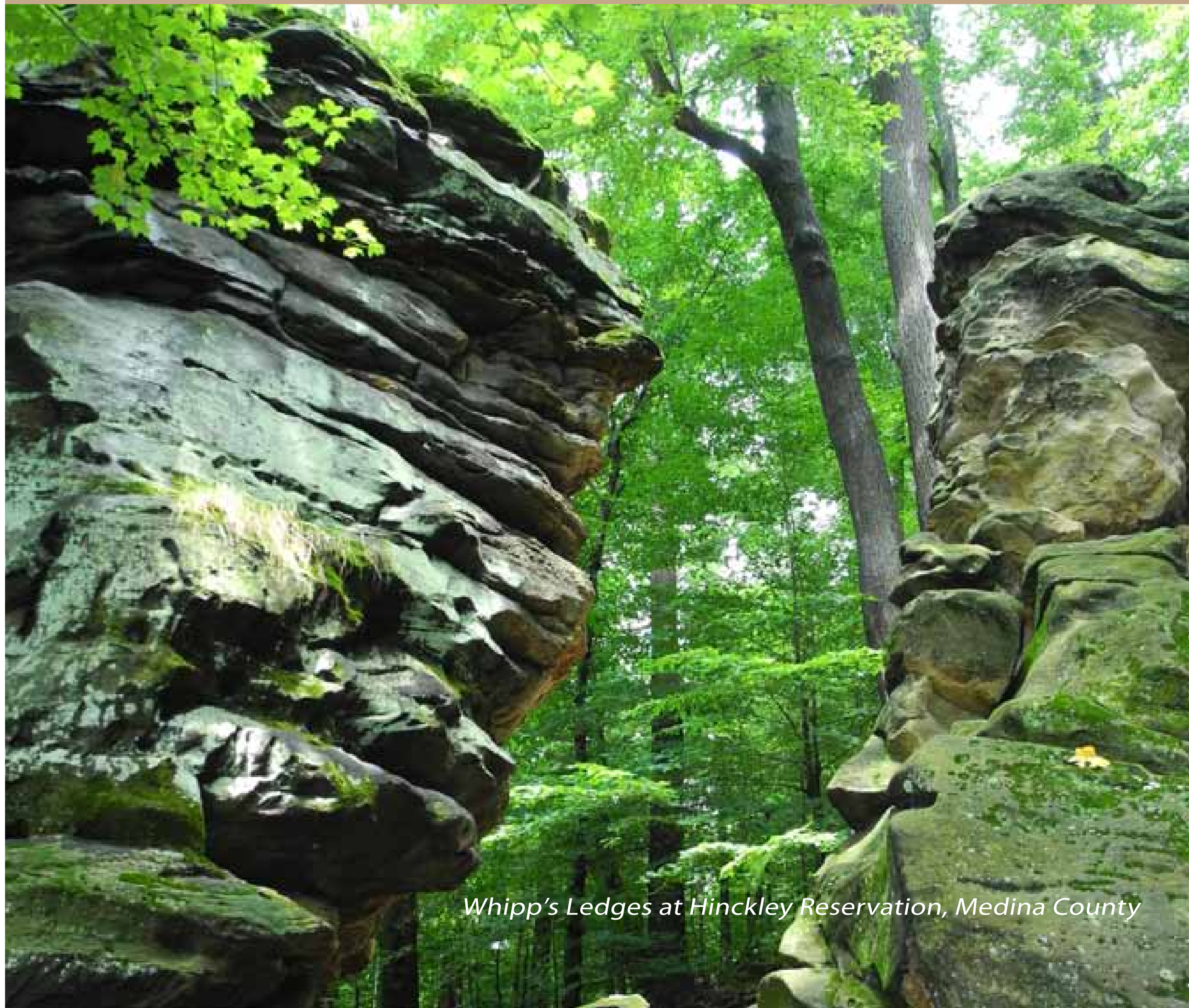
The physical characteristics of Ohio's Lake Erie coast vary significantly, ranging from lowlands in Lucas, Ottawa, Sandusky and western Erie counties, to impressive bluffs that generally increase in height from west to east between eastern Erie County and Ashtabula County. Along the shore west of Sandusky, bedrock units—exposed at the surface or buried beneath glacial deposits—are mostly Silurian- and Devonian-age limestone and dolomite. Silurian-age dolomite underlies Sandusky Bay and crops out at Catawba Island and in the Bass Islands. Devonian-age limestone is exposed on Kelleys Island. Formation of the Lake Erie Islands is attributed to the hardness and resistance of these bedrock units. Exposed glacial striations (scratches) and grooves are present on Kelleys, South Bass, Middle Bass and Gibraltar islands, and on Marblehead Peninsula. These features were slowly gouged into the underlying bedrock surfaces by the rocks and boulders that were imbedded in the moving ice sheet. North America's finest example of glacial grooves are found on the north side of Kelleys Island (430 feet long, 35 feet wide, 15 feet deep). East of Sandusky, Devonian-age shale trends along the shore into northeastern Ohio. This shale is well-exposed in the valley walls of the Vermilion, Black, Rocky, Chagrin and Grand rivers. The eastern portion of Ohio's coast is generally composed of glaciolacustrine deposits and glacial till.

Additional information about the geology of Lake Erie and the Lake Erie Watershed are presented throughout this chapter, including: (1) Bedrock Geology; (2) Glacial Geology; (3) Drift Thickness; (4) Karst Geology; (5) Petroleum Geology, and; (6) Mineral Industries.

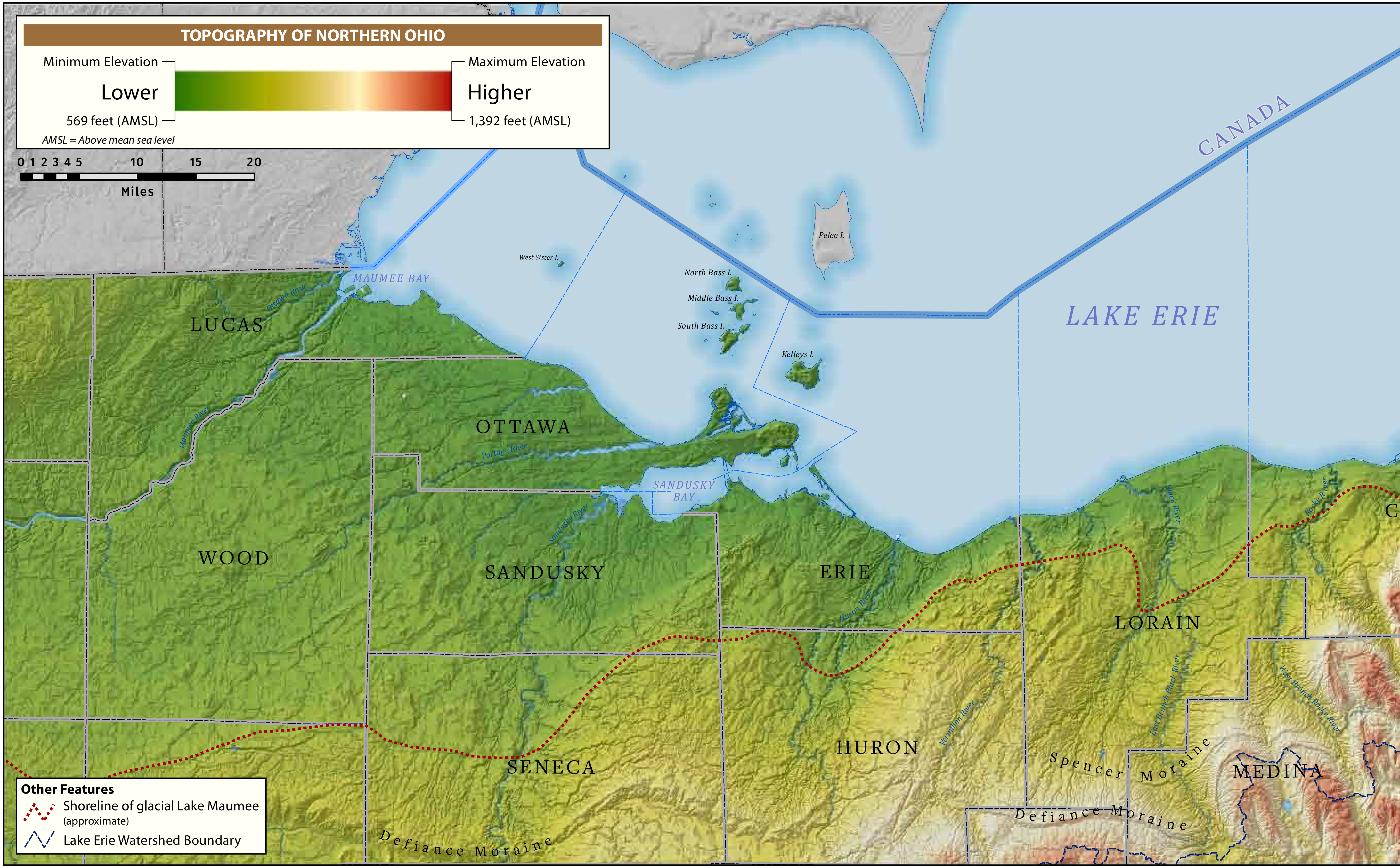
Learn more about the information presented in this chapter:
Ohio Department of Natural Resources (ODNR), Division of Geological Survey
geosurvey.ohiodnr.gov

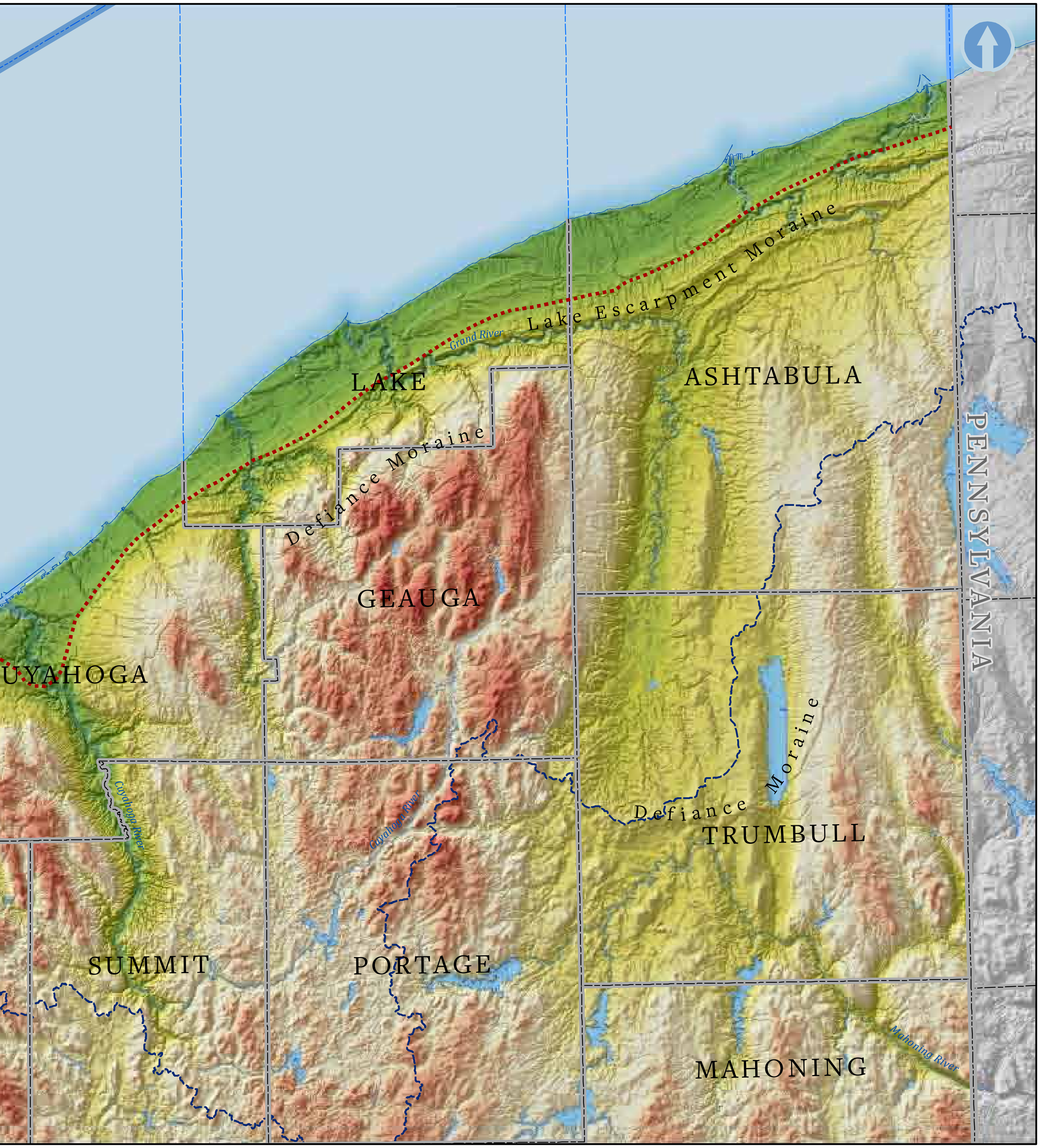
Hansen, M.C. "The History of Lake Erie." ODNR Division of Geological Survey

A complete list of chapter sources is found in the Appendix.


Whipp's Ledges at Hinckley Reservation, Medina County

TOPOGRAPHY AND LANDFORMS





Topography is the physical relief and configuration of natural and artificial features that make up surface terrain. In this map, elevation is represented using a green-to-red color ramp; where greens show lower topographies and oranges and reds represent higher areas. Digitally-applied shading (from the northwest) helps emphasize changes in elevation, or topographic relief, and provides a three-dimensional appearance on the map. This map is based on elevation data from the U.S. Geological Survey's National Elevation Dataset.

Terrain in northern Ohio can be divided into three main regions based on elevation and topographic relief: (1) the Lake Erie lowland (represented by shades of darker green); (2) bedrock highlands (represented by beige and reddish brown); and (3) the ridge and ground moraine area (represented by yellowish green).

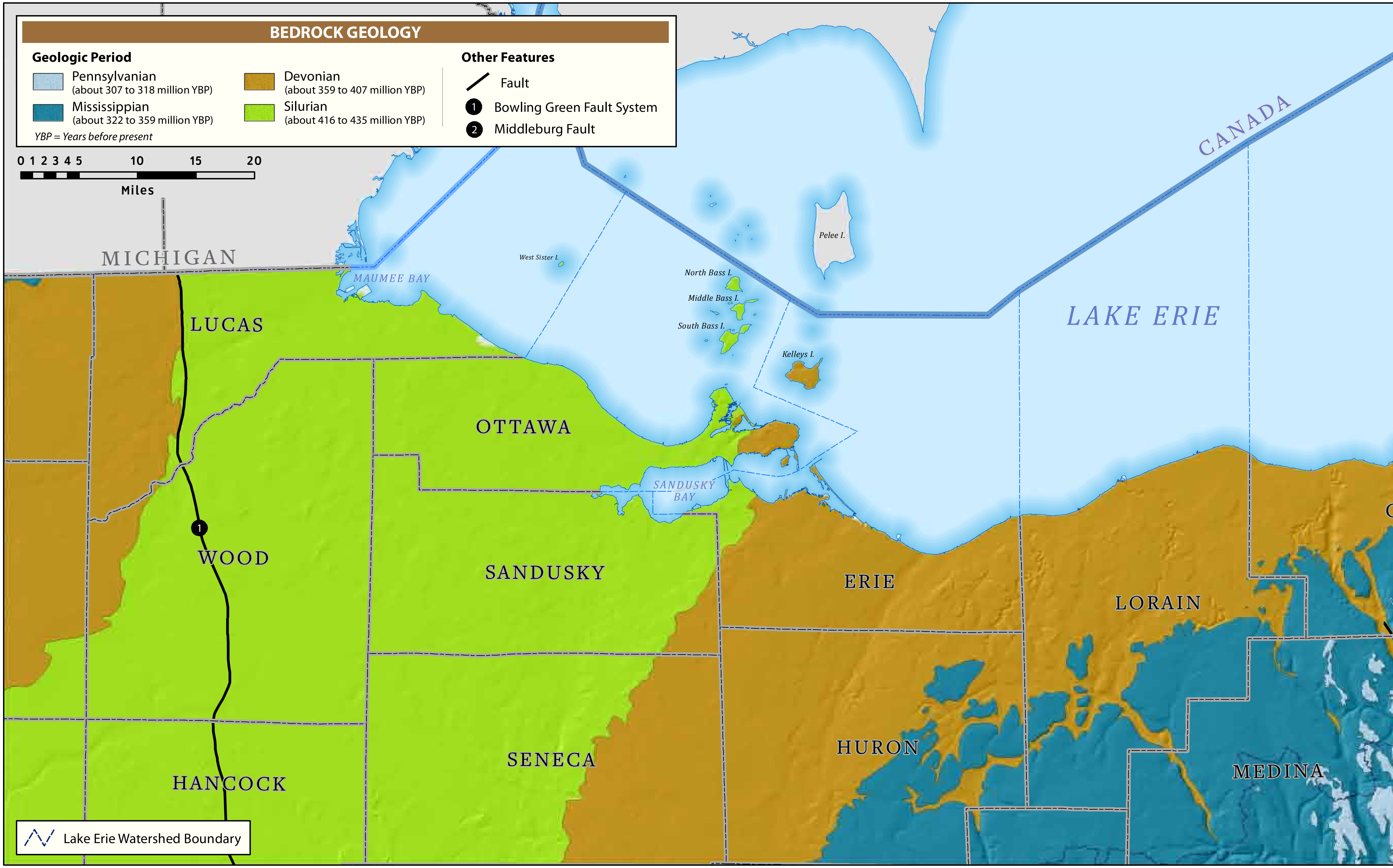
The Lake Erie lowland extends from the Lake Erie shore to areas 800 feet above mean sea level. Lowland areas are characterized by low-relief, wave-planed till overlain by silt and clay of lake origin. In northeast Ohio, the lowland area is generally ten miles wide and extends from the shore southward to a series of southwest-to-northeast-oriented ridge moraines that border Mississippian- and Pennsylvanian-age bedrock highlands. In northwestern Ohio, the lowland extends as far as 50 miles from the Lake Erie shore and encompasses the area formerly covered by the Great Black Swamp. As glacial ice retreated out of the Erie basin—about 14,000 years ago—Lake Maumee (see approximate shoreline extent on map) and other precursors of Lake Erie developed along the margin of the retreating ice and covered lowland areas.

Bedrock highlands include high-relief and high-elevation landscapes (greater than 1,000 feet above mean sea level). These areas are found in Geauga, Portage, Summit, Medina, southeastern Cuyahoga and southern Lake counties. Unlike the softer limestones, dolomites and shales in northwestern Ohio, geologic formations in the highlands consist primarily of Mississippian- and Pennsylvanian-age sandstone and shale, which were more resistant to glacial erosion and glacial advance. While the glaciers eventually overtopped highland areas, their southward progression was greatly reduced to approximately 70 miles (as opposed to about 200 miles in western Ohio).

The third terrain, between 800 and 1,000 feet above mean sea level, can be found between the Lake Erie lowland and higher-relief upland areas. This terrain is characterized by rolling hills and low-relief till plains. Ridge moraines and ground moraines dominate the surface features and deposits in the area.

In western Ohio, the Lake Erie Watershed boundary follows the crests of glacial moraines (not visible on map; see map on page 44), while in north-central and northeastern Ohio the boundary follows bedrock-controlled hills and glacial valleys containing thick glacial deposits. The watershed divide is visible across a portion of this map through Medina, Summit, Portage, Geauga, Trumbull and Ashtabula counties.

BEDROCK GEOLOGY



Bedrock is the hard, consolidated rock found beneath surficial materials and glacial deposits. In much of northern and western Ohio, loose and unconsolidated glacial materials of varying sizes were released from the receding ice sheets and dispersed overtop the bedrock. Irregular protrusions of bedrock through these materials are called "outcrops."

Bedrock is a major source of groundwater—in fractured layers (see maps on pages 232 and 234)—and helps define regional topography. Bedrock geology maps are important for land use planners, engineers, environmentalists and decision makers. They can be used for construction siting, water supply evaluation, sinkhole identification, and locating oil, gas and mineral resources, among other uses.

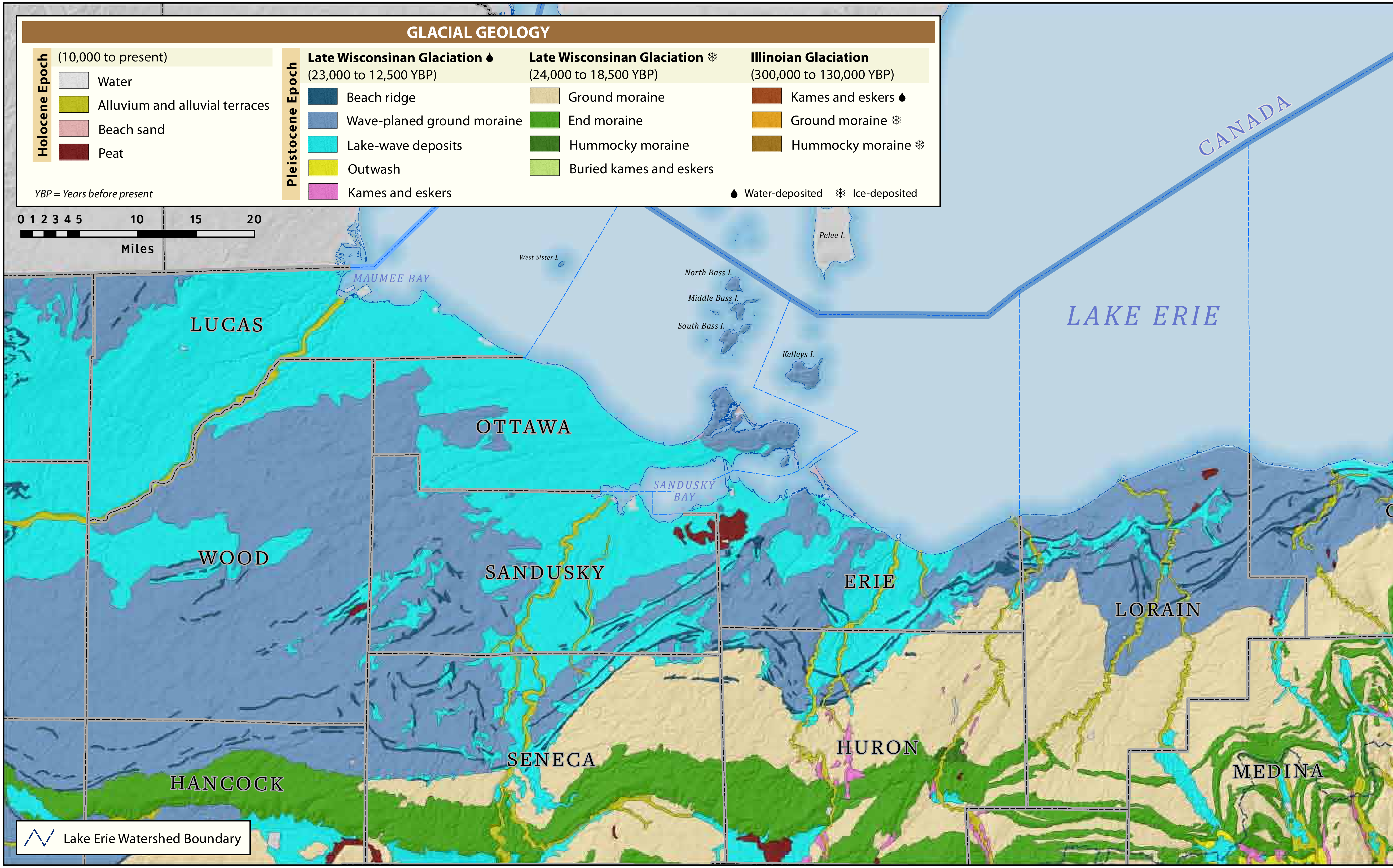
This map shows the age (geologic period) of bedrock layers, or "strata," at the land surface and directly underlying unconsolidated quaternary sediments. Bedrock types, including shale, siltstone, sandstone, conglomerate, limestone and dolomite, vary widely in northern Ohio, but can be generally characterized by age and geographic location. Bedrock units in the coastal region range in age from the Silurian Period (416 to 435 million years ago) in western Ohio to the Pennsylvanian Period (307 to 318 million years ago) in the bedrock highland areas.

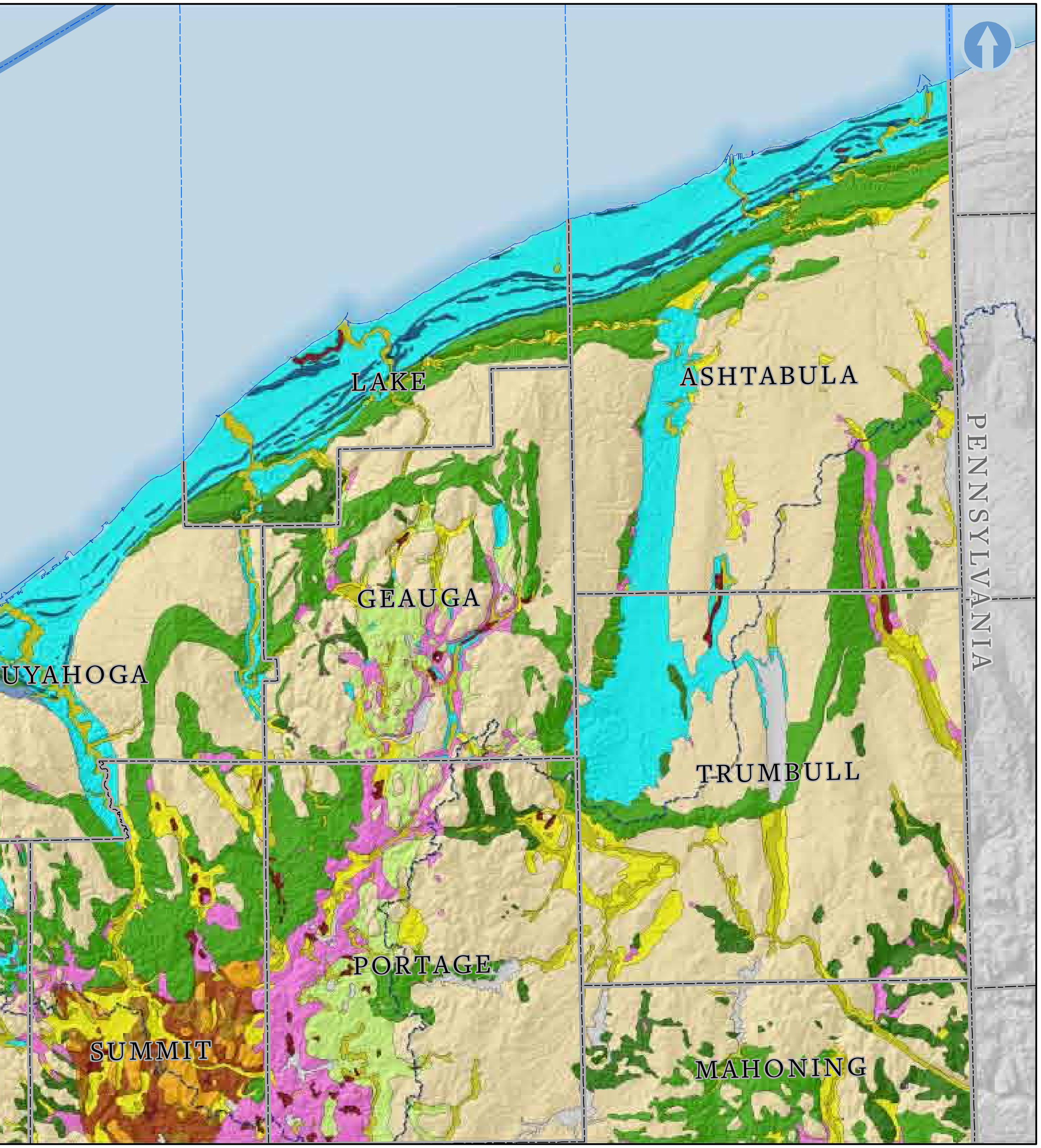
Along the Lake Erie shore west of Sandusky, bedrock units exposed at the surface or buried beneath glacial deposits are mostly Silurian- and Devonian-age limestone and dolomite. Silurian-age dolomite underlies Sandusky Bay and crops out at Catawba Island and in the Bass Islands. Devonian-age limestone is exposed on Kelleys Island. East of Sandusky, Devonian-age shale trends along the shore into northeastern Ohio. This shale is well-exposed in the valley walls of the Vermilion, Black and Rocky rivers.

The Carboniferous System is divided into two subsystems, the Mississippian and Pennsylvanian. Shale, siltstone and sandstone are dominant Mississippian-age rock types in Ohio. These formations crop out along a trend landward of Lake Erie in northeast Ohio. Pennsylvanian-age rocks consisting primarily of sandstone with some conglomerate, shale and siltstone with some coal are exposed in the bedrock highlands.

Three large-scale geologic structures (not labeled on map) affect the distribution of bedrock in Ohio's coastal region. They are the Appalachian Basin, Michigan Basin and Findlay Arch. These regional structures cause bedrock units to gently, and predictably, rise and fall in elevation. Near Lake Erie, the western edge of the downward-folding Appalachian Basin swings to the northeast and causes Devonian-age bedrock to crop out parallel the lakeshore and dip to the southeast (from Ashtabula County to the Sandusky Bay area). West of Sandusky Bay, the rise of the Findlay Arch—a convex-up anticline extending between southwest Ohio and the Western Basin—causes older formations to be exposed at the surface. West of Toledo, the Findlay Arch begins to dip into the southeastern portion of the Michigan Basin, causing surface bedrock to become progressively younger.

GLACIAL GEOLOGY





Within the last 1.6 million years, during the Pleistocene Epoch (also known as the Ice Age), almost three-fourths of Ohio, including the entire Lake Erie Watershed, has been covered by multiple massive ice sheets. Of the more than one dozen glaciations, parts of Ohio were covered by the most recent two: the Wisconsinan (24,000 to 12,500 years before present) and the Illinoian (300,000 to 130,000 years before present).

The unconsolidated material left behind by the advancing and retreating ice sheets consists of sand, clay, peat, gravel and boulders, and can be several hundred feet thick. This debris was deposited either directly by the moving ice or by glacial meltwater (see map legend). Most materials and topographic features shown on this map were deposited and shaped by the Wisconsinan glaciation.

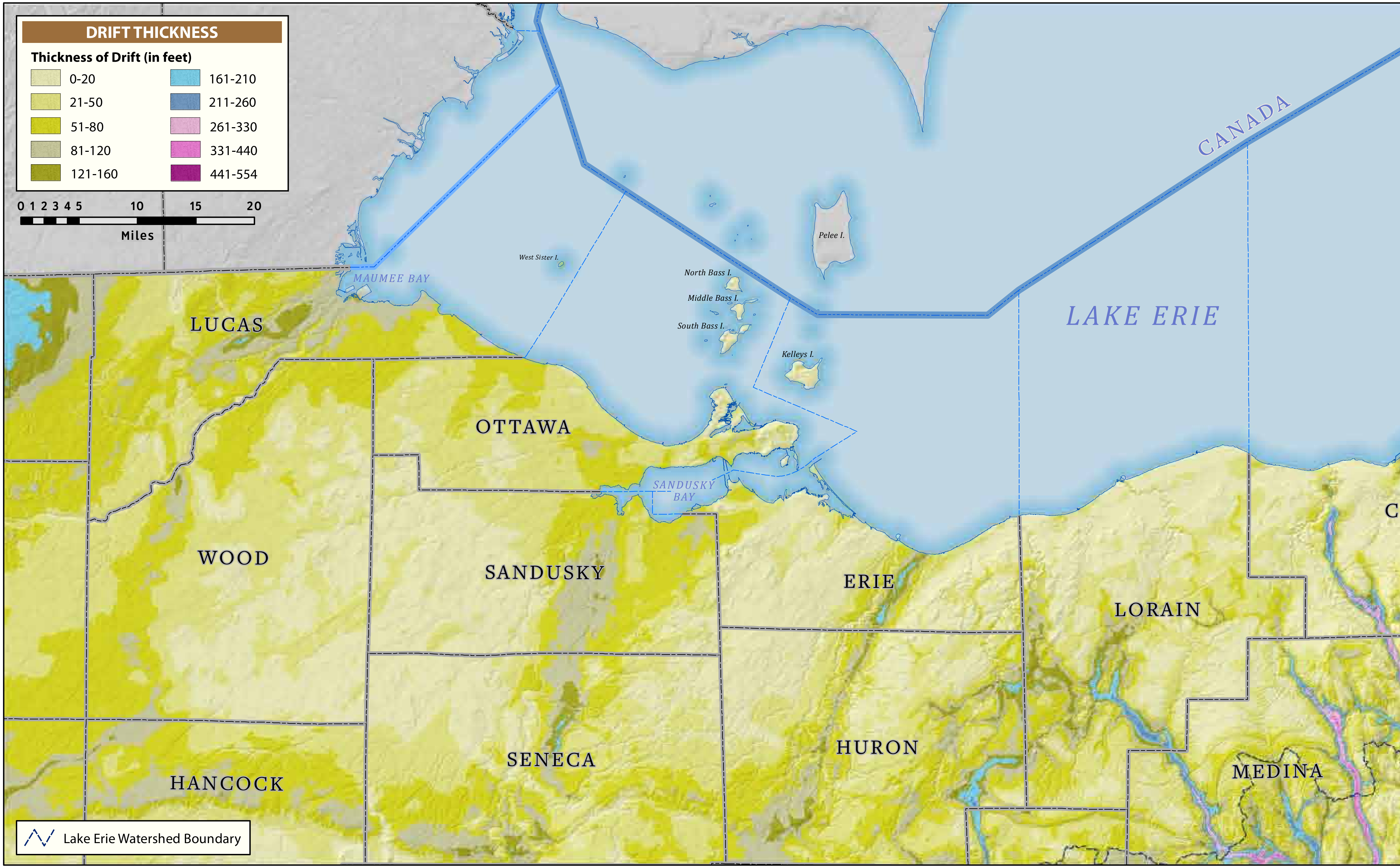
Material deposited by flowing meltwater on and under the surface of the glacier formed ice-contact features called "kames" and "eskers." Kames are conical mound-shaped features that consist of sand and gravel. Eskers are long, serpentine-shaped landforms consisting of sand and gravel that formed within tunnels under the ice. Smaller sediments reaching the front edge of the ice and carried away by streams of meltwater are called "outwash" deposits. Outwash contains relatively coarse and layered sand and gravel deposits.

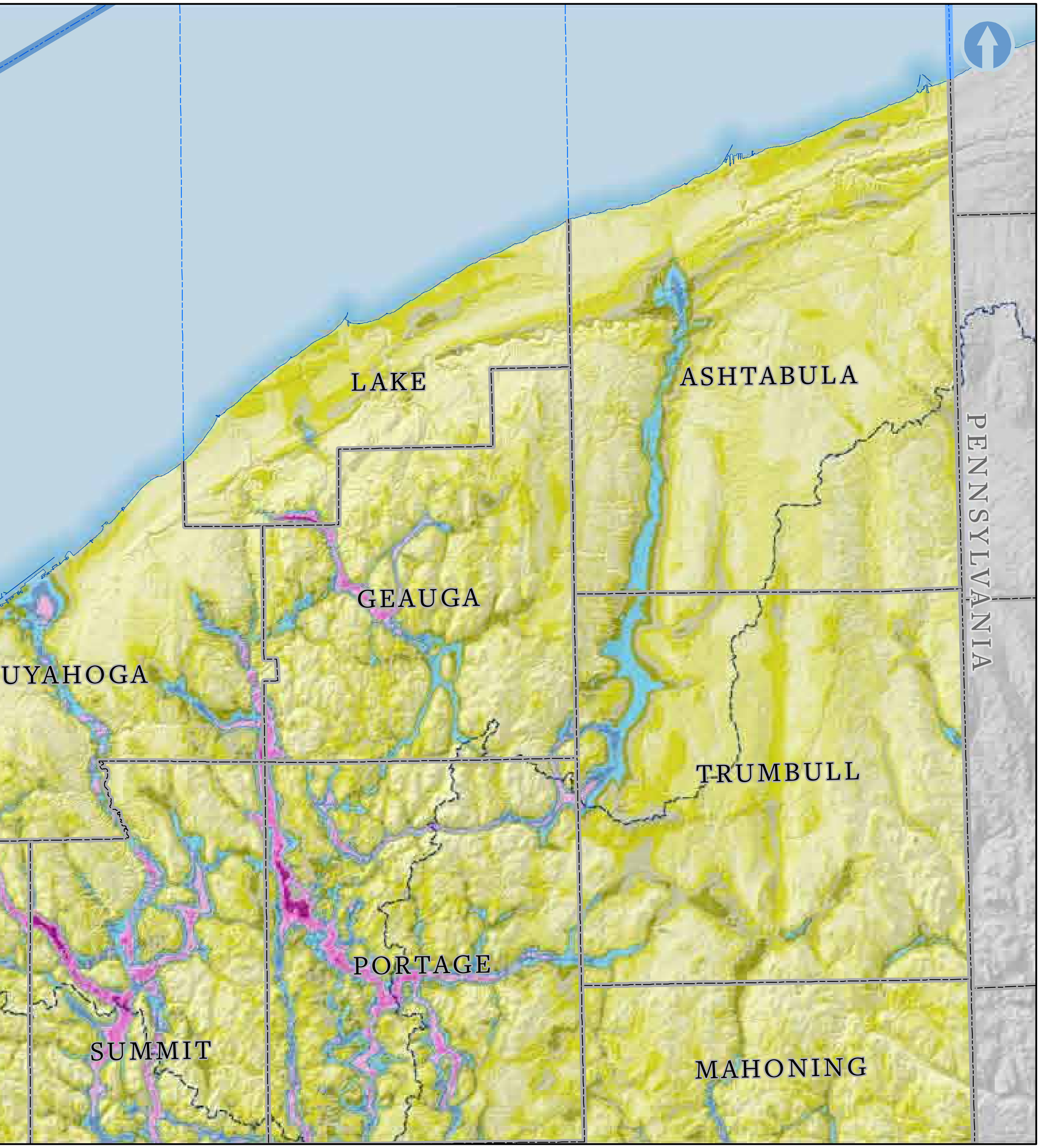
Water-deposited materials also include beach ridges, wave-planed ground moraines and lake-wave deposits. Beach ridges are linear sand features that formed along the margins of the proglacial lakes that predated Lake Erie. These features were once used as trails by Native Americans and early settlers (see the Native American Trails map on page 70), and are currently used for roadways. Lake deposits are relatively uniform-textured materials (fine-grained clay and silt-sized sediments) that originated in proglacial lake bottoms during the various stages of Lake Erie's formation. These occur in Ohio's flat western landscapes and in northeast Ohio's low-lying lake plain.

Material that was mixed, crushed, compressed and transported by the movement of glaciers, rather than by meltwater, is called **till**. Glacial till consists of unsorted, clay-to-boulder-size debris. "End moraines," or "terminal moraines," are long narrow ridges of till that was deposited at the terminus of the glacier. These landforms mark the temporary positions of the ice front during the glacial retreat. End moraines typically contain thick layers of sand and gravel and function as local drainage divides. "Ground moraines" are commonly flat, gently-rolling landforms composed of till that was contained within the glacier and deposited as the ice melted. Hummocky moraines are irregular and rounded landforms, such as small knolls or mounds, that typically occur in groups or fields.

Glacial deposits make up the entire Lake Erie bluff along over 50 percent of the shore and overlie many rocky areas of the shore. These deposits also occur in many nearshore areas. Bluff erosion and longshore currents add sand and gravel to beaches (see Chapter 7: "Coastal Processes").

DRIFT THICKNESS





This map shows the thickness and distribution of glacially-derived sediments ("drift") and post-glacial stream sediments that overlie the consolidated bedrock surface. The thickness of unconsolidated drift materials in northern Ohio ranges from a few feet to several hundred feet.

Due to numerous geologic processes acting alone or in combination, drift thickness in western and northern Ohio is highly variable. In some areas, drift has been deposited on a relatively flat bedrock surface. Variations in thickness are attributable to the amount of drift deposited on top of the bedrock. Relatively uniform thickness occurs where the elevation of the modern land surface parallels the top of the underlying bedrock. In other areas, drift thickness increases greatly where ancient river valleys (buried beneath the land surface) exist.

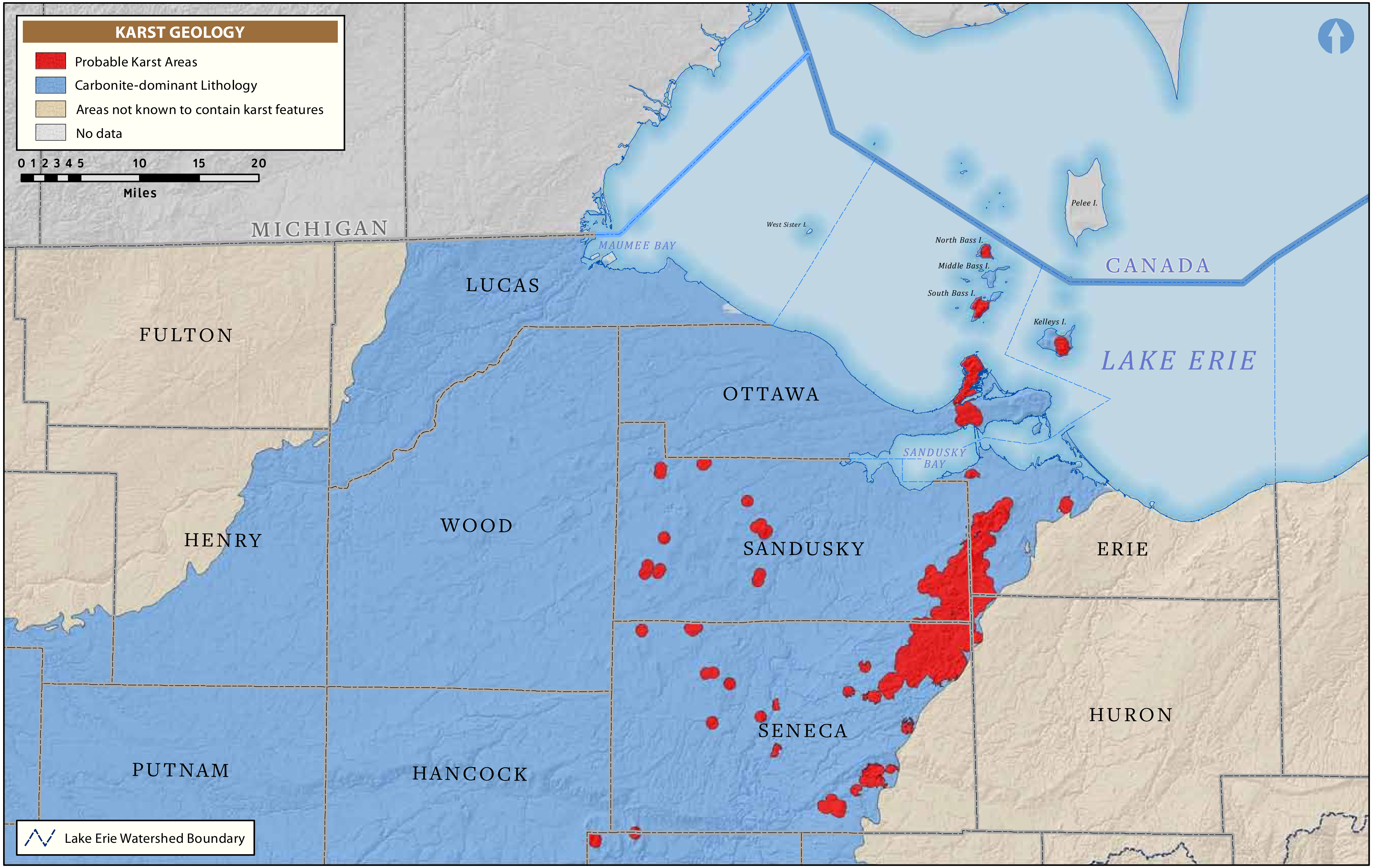
In northeastern Ohio, narrow, but thick drift areas south of Lake Erie delineate the courses of pre-glacial bedrock valleys, which have been partially or entirely filled by as much as 450 feet of glacial drift. Some of these buried valleys have been partially excavated by present-day, northward-flowing rivers such as the Cuyahoga and portions of the East Branch Rocky River. Glacial deposits exposed in the steep valley walls of the Cuyahoga River can be more than 250 feet thick. Variation in drift thickness is also illustrated in the bluffs along Lake Erie. In Ashtabula County, where bedrock occurs just below lake level, bluffs as high as 60 feet are composed entirely of glacial drift. In contrast, from Cleveland to Vermilion, bedrock rises above lake level and is capped by thin deposits of drift. The thickness and composition of drift affects the stability of the bluffs along the Lake Erie shore and in the valleys of its tributaries (see the Bluff Classification maps on pages 180 and 182).

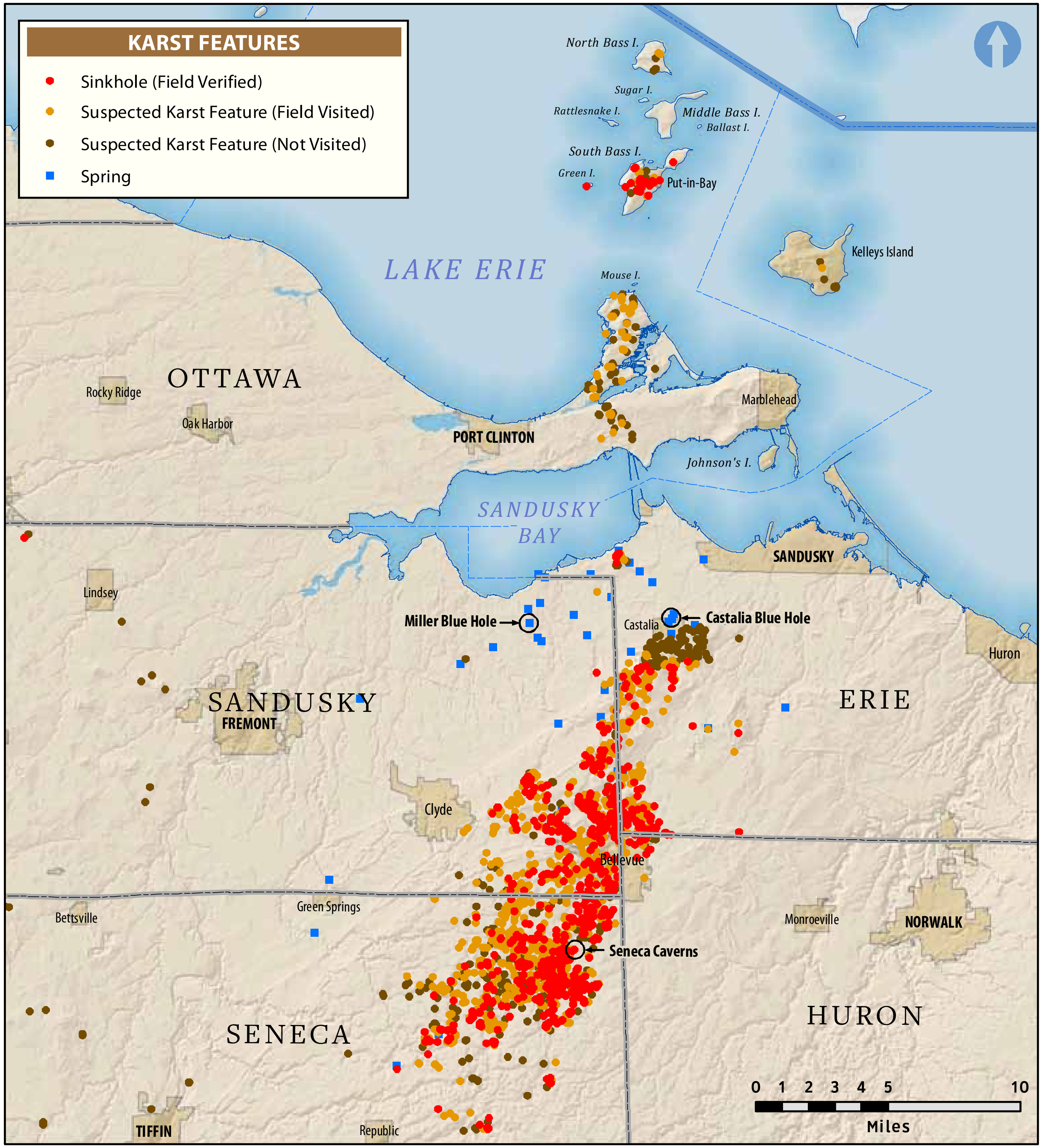
In northwestern Ohio, glacial ice flowing southwest from Lake Erie repeatedly scoured and smoothed the relatively soft bedrock surface, destroying most of the preexisting drainage systems and depositing additional sediments. Drift thickness is generally less than 50 feet and varies less than other parts of Ohio. The upper surface of the drift was flattened by wave action from the proglacial lakes that formed along the margin of the retreating glacier.

Linear features of thick drift called ridge moraines formed along the temporarily stationary ice front as glacial sediment was released from the ice. In western Ohio, because the ice moved more easily through the Lake Erie lowlands, these features have a draped appearance. The resistant bedrock highlands in northeastern Ohio caused ridge moraines to be especially curved and stacked close together, parallel to the Lake Erie shore.

Drift thickness is useful for land use planning, construction, engineering and resource management. Shallow depth to bedrock significantly impacts the location, development, maintenance and cost of public services, such as sewers, water supply systems and roads.

KARST GEOLOGY AND KARST FEATURES





Karst landscapes form due to groundwater dissolving soluble bedrock formations and minerals, such as limestone, dolomite and gypsum. The process begins as groundwater permeates the bedrock, either through fractures called "joints," or through horizontal layers called "bedding planes." As the bedrock along these zones of weakness dissolves, these areas become conduits through which more groundwater travels, widening the zones into voids. Eventually, overlying bedrock layers collapse into the voids. The resulting landscape is characterized by the presence of one or more of either sinkholes, caves, springs or blue holes.

Karst features in Ohio can be very scenic, attract tourists and host rare flora and fauna. They also pose significant hazards. Collapse of an underground cavern or opening of a sinkhole can cause surface subsidence and lead to severe damage to overlying buildings, bridges and/or highways. Improperly backfilled sinkholes are also prone to further subsidence.

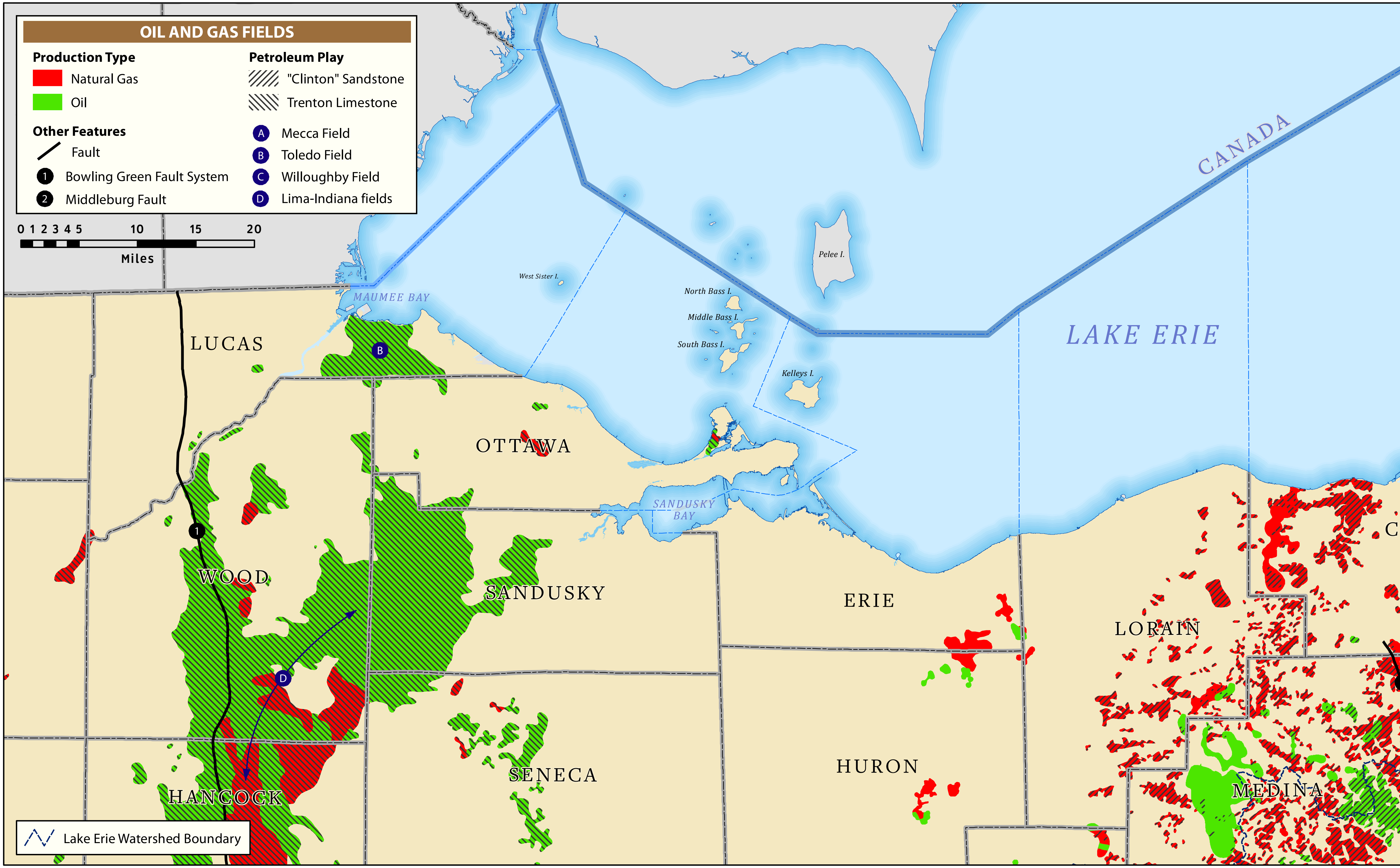
Areas underlying karst features are highly susceptible to groundwater pollution potential (see map on page 240). Natural surface drainage entering aquifers through sinkholes and containing agricultural and industrial chemicals, livestock waste and other contaminants directly impacts groundwater and threatens the potable water supply. Another common characteristic of karst geology is unpredictable water supply, as new voids open and existing ones go dry.

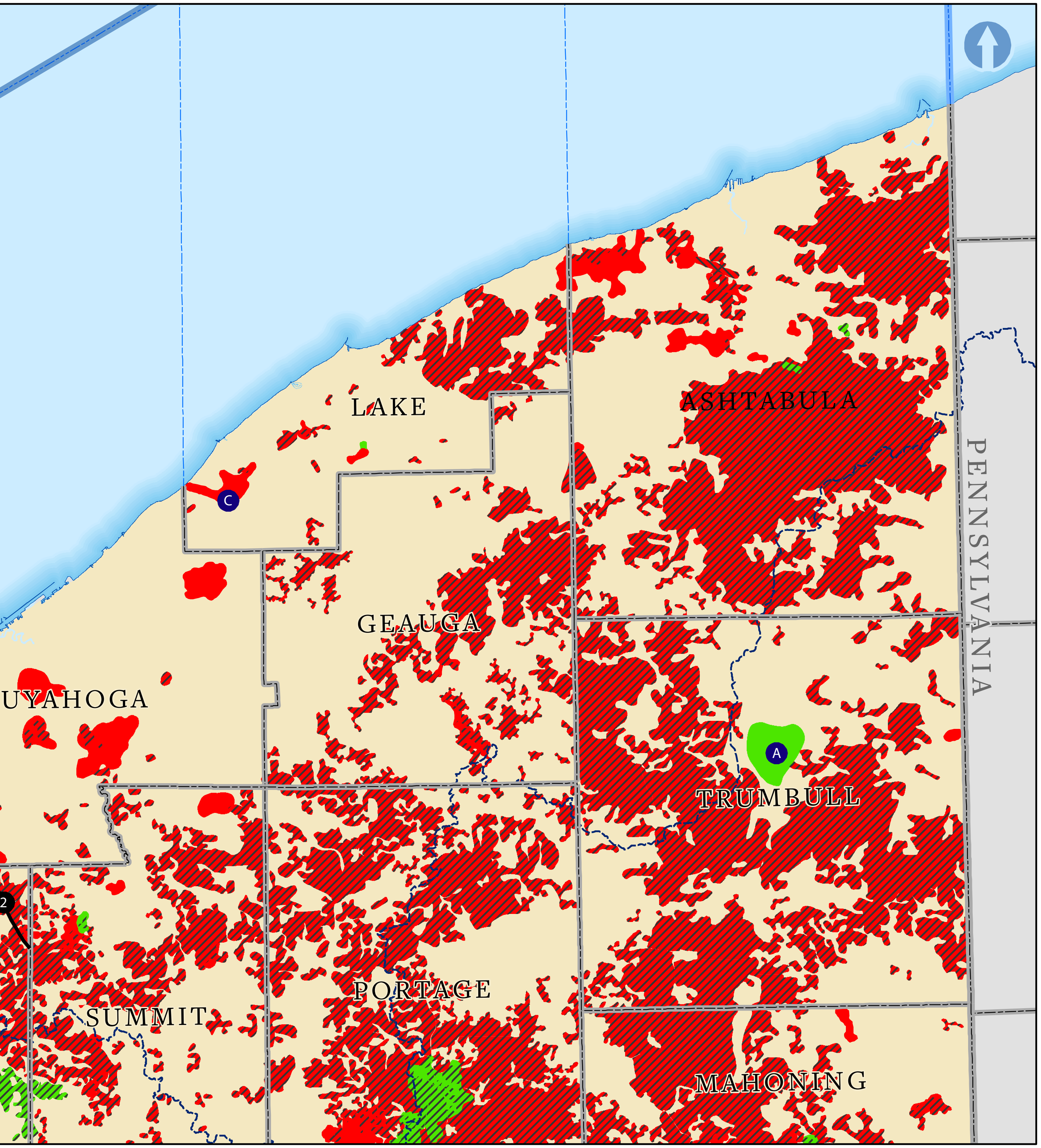
The left map shows the geographic extent of carbonate-dominant lithology (in blue) and probable karst areas (in red). In the Lake Erie Watershed, these rock types are located primarily west of Sandusky and include mostly Silurian- and Devonian-age limestone and dolomite. Carbonate rocks are very common in the U.S. and are most susceptible to dissolution in humid and wet environments. The permeability of these rocks, seasonal precipitation and presence of sinkholes greatly increases aquifer recharge rates.

The right map highlights the Bellevue-Castalia Karst Plain and its many field-verified and suspected karst features. This area contains larger sinkholes (by volume and area) than any other karst region in Ohio. It is underlain by up to 175 feet of Devonian-age carbonate bedrock (Delaware and Columbus limestones) overlying Silurian-age dolomite, anhydrite and gypsum of the Bass Islands Dolomite and Salina Group (see map on page 232). Surface drainage is very limited and streams often disappear into sinkholes, called "swallow holes."

Located within the karst plain is one of Ohio's largest underground cave systems, Seneca Caverns. Discovered in 1872, the caverns comprise an unknown number of stacked levels—each consisting of at least one irregularly shaped "room" and connecting passageways. The topmost seven layers are open for public tours (fee admission). Flowing through the deepest reaches of the cave—and part of the surrounding aquifer network—is an underground stream known as the Ole Mist'ry River. Seneca Caverns was designated an Ohio Registered Natural Landmark in 1997.

OIL AND GAS FIELDS





Ohio's oil and gas industry began in 1859 when the first commercial oil well was drilled just outside the Lake Erie Watershed in Mecca Township (Trumbull County; "A" on map). Commercial quantities of petroleum have been found in 67 Ohio counties. Current production is concentrated in the eastern third of the state.

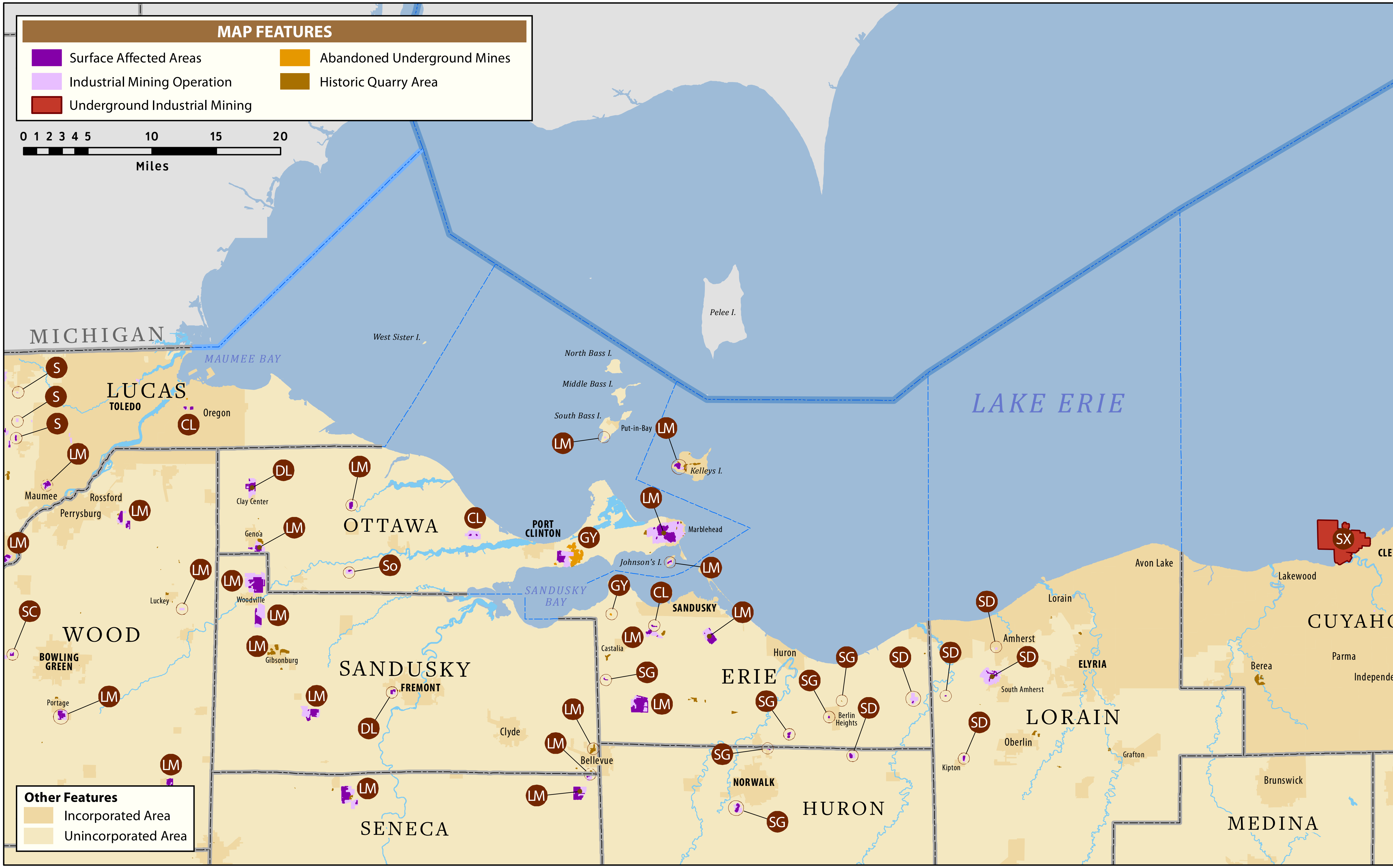
Subsurface petroleum-producing reservoirs are called "fields." This map displays combined oil (green) and natural gas (red) fields in northern Ohio. A concentration of oil and/or gas fields in the same region that exhibit similar geologic conditions, such as bedrock layering and/or structural settings, is called a "petroleum play," or just "play," for short. The two most widespread petroleum-producing plays in the mapped area are from "Clinton" sandstone formations (in eastern Ohio) and Trenton limestone (in western areas). These are both illustrated with distinct gray hatching. Less extensive plays are not highlighted on the map.

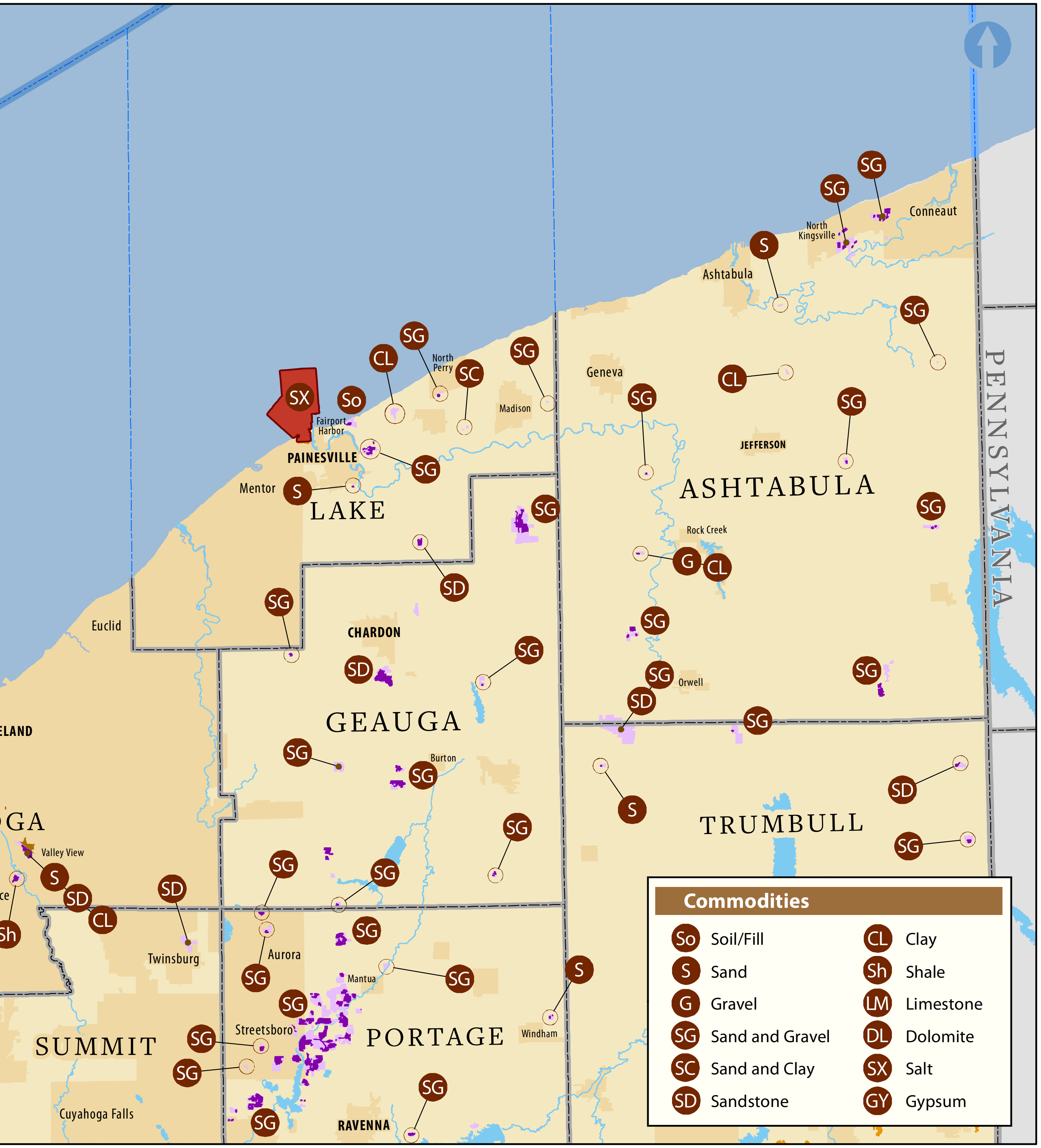
Oil and natural gas are generally believed to have formed through geochemical alteration of decayed organic remains that have been deeply buried and subjected to high temperatures and pressures. Once formed, these "hydrocarbons" commonly migrate with and atop other formation fluids (brine) through fractures and voids in the bedrock.

Hydrocarbons that do not naturally seep to the surface due to impenetrable layers of rock accumulate in either "structural traps" or "stratigraphic traps." Structural traps occur in higher portions of deeply buried structures (e.g. the Findlay Arch) or in the upper margins of a sealed fault system. The fractured limestone in the Bowling Green Fault System is a good example of a structural trap. Stratigraphic traps occur where rock layers laterally transition from a permeable to impermeable state. In northeast Ohio, a series of permeable sandstone fields extend from Ashtabula County to Medina County and abut nonpermeable dolomite and shale, causing stratigraphic traps.

Much of the drilling in northern Ohio took place from the late 1800s through the 1950s—prior to large-scale development of lakefront communities. In northwest Ohio, petroleum fields were discovered in Wood County in the 1880s, prompting a major oil boom. Drilling from the Toledo Field ("B" on map), located mostly in Oregon and eastern Lucas County, began in 1887. The Lima-Indiana oil and gas fields ("D" on map) have produced more than 380 million barrels of oil and approximately two trillion cubic feet of gas. Ohio led the nation in oil production from 1895 to 1903. Large-scale oil production continued into the 1930s, however, due to unsustainable drilling practices—causing oil fields to lose pressure—the number of active wells significantly decreased. In northeast Ohio, drilling in Cuyahoga County began in the early 1900s and continued through the 1930s. Lake County's Willoughby Field ("C" on map) was discovered in 1957. Recently, there has been significant drilling activity in Ashtabula and Lake counties targeting deeper gas-producing layers.

MINERAL INDUSTRIES





The abundance of mineral resources has greatly impacted, and continues to impact, economic development in Ohio. Many mining operations are located throughout the Lake Erie Watershed. This map shows the locations of industrial mining operations (surface and underground), abandoned underground mines and historic quarry areas.

Sand and gravel production in Ohio began in 1904. It is the state's second-largest mining industry, by tonnage. Deposits were transported and placed by glaciers and/or rivers. In the Lake Erie Watershed, extensive sand and gravel mining is found east of Streetsboro in Portage County. These materials were deposited in an ancient river valley now occupied by the upper Cuyahoga River.

Sandstone is a sedimentary rock primarily composed of sand-sized grains of mineral or rock. "Conglomerate" is a coarse-grained rock formed by the cementation of sand and gravel. Deposits of both are mostly found in eastern Ohio. Devonian-age Berea Sandstone, named for outcrops near Berea in Cuyahoga County, is an abrasive and durable rock. It has been quarried for grindstones and construction stone. Quarries are located throughout Erie, Lorain and Cuyahoga counties, including one of the world's largest in Amherst (Lorain County). Berea Sandstone has been used for structural foundations, sidewalks, bridge abutments and buildings.

Limestone and dolomite are versatile minerals. Both are fine- to medium-grained crystal-like rocks primarily composed of calcite, a carbonate mineral. Dolomite also contains magnesium. Most production comes from Silurian- and Devonian-age rocks. Deposits of high-calcium limestones (e.g. Columbus Limestone) are extensively mined in Wood, Ottawa, Sandusky, Seneca and Erie counties. Quarries have produced cement, building stone, construction aggregates and lime since the mid-1800s. Both magnesium-rich and high-calcium limes are used in various chemical, glass, paper and steel industries, as well as in cosmetics and for agricultural purposes and water treatment.

Massive salt deposits underlie much of Ohio and are found in a grouping of rock known as the Salina Group. These deposits formed during the late Silurian Period when Ohio was located south of the equator and submerged under a shallow, saltwater sea. As the water evaporated, rock salt (halite), anhydrite, gypsum and other evaporate minerals were left behind. Today, salt is extracted from underground mines in Cleveland and Fairport Harbor. Both mines are located about 2,000 feet under Lake Erie. In 2015, Cuyahoga and Lake counties ranked first and second in Ohio, respectively, for salt production (by sales). According to the Lake Carriers' Association, these mines move 1.5 million tons (on average) of salt annually. Most rock salt is used to clear roads of snow and ice during winter months. Gypsum is a soft sulfate mineral with little durability. It is used to produce cement, plaster of Paris and plasterboard. Gypsum was discovered along the north shore of Sandusky Bay in 1821; mining began the following year.

Map 9-8: Mineral Industries