Potato Patch Falls, Lake Superior, Munising, Michigan. Cross-bedded sandstone, Chapel Rock Member, Cambrian Munising Formation. Wave-cut platform and undercut rock ledges. Trees on older wave-cut platform formed during a higher, post-glacial lake stage. Dark-colored, basaltic glacial erratic on shoreline.

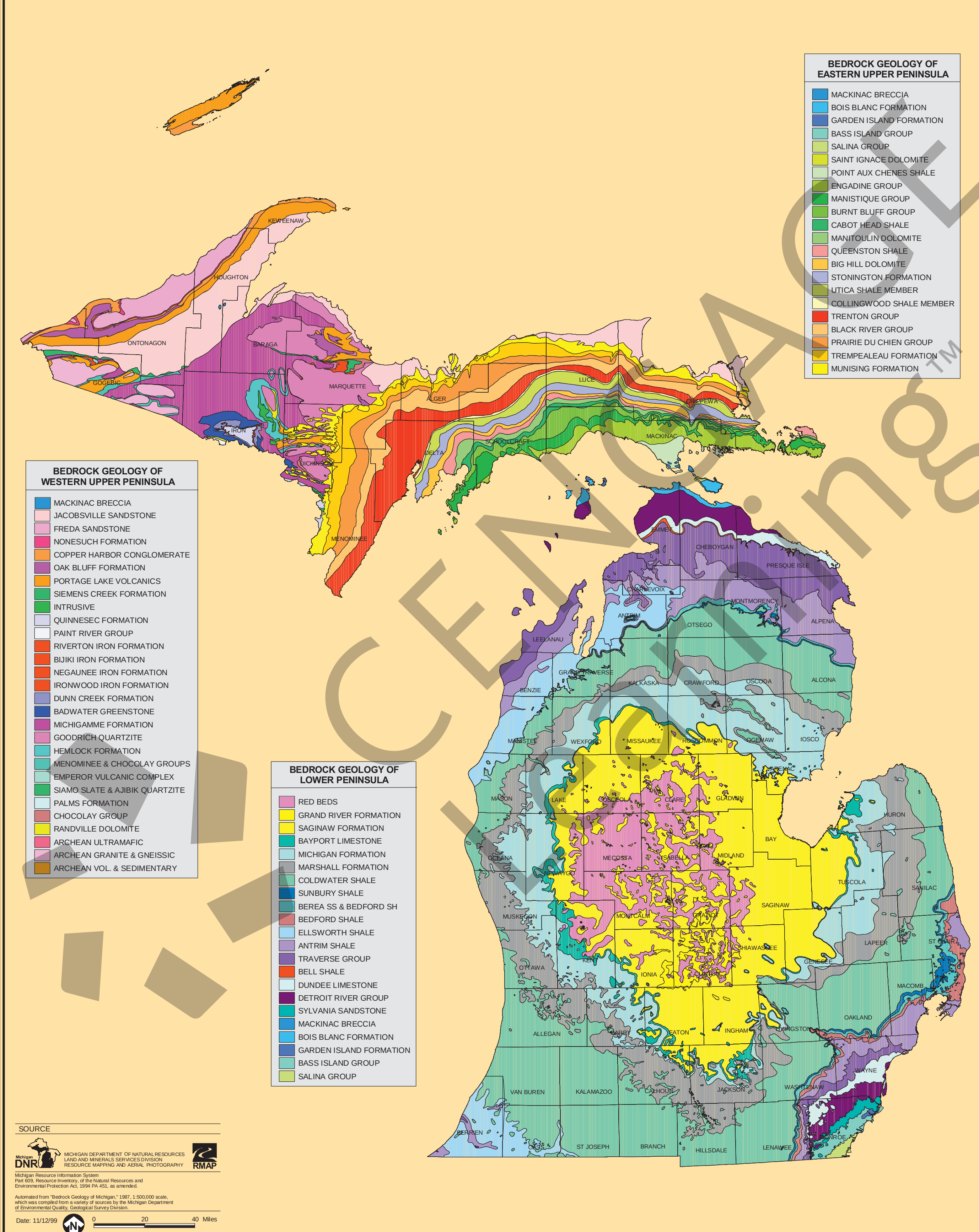
Michigan

Geology of Michigan and the Great Lakes

Robb Gillespie, William B. Harrison III, and G. Michael Grammer

Michigan Geological Repository for Research and Education
Western Michigan University

1987 BEDROCK GEOLOGY OF MICHIGAN



State of Michigan: Bedrock Geology Map

ESSENTIAL QUESTIONS TO ASK

Michigan.1 Introduction

- *Why is the geology of Michigan important to students of physical geology and to all the inhabitants of the state today?*

Michigan.2 Precambrian and Paleozoic Geology

- *What is the structural pattern of the sedimentary rock layers of the Michigan Lower Peninsula that makes it a basin?*
- *What are the various regional structural or geologic elements that define the margins of the Michigan Basin?*
- *What are the ranges of ages for sedimentary rocks in Michigan's Lower Peninsula?*
- *Describe the main geologic differences in rock in Michigan's Eastern and Western Upper Peninsula.*

Michigan.3 Quaternary Geology

- *What were the main controlling factors during formation of the Great Lakes basins?*
- *When was the last glacial (Wisconsinan) event?*
- *Where did erosional and depositional glacial landscapes develop in the Great Lakes watershed?*
- *What types of depositional landforms are found throughout Michigan?*
- *What types of modern-day coastal features are currently evolving along Michigan's shorelines?*
- *How did the inland lakes in Michigan form?*

Michigan.4 Modern-Day Geologic Processes

- *What are the two main types of shoreline found around the Great Lakes in Michigan?*
- *Name three processes that reshape the Michigan shoreline and a depositional feature produced by each process.*

Michigan.5 Geology of Water Resources

- *What are the two types of geologic materials that contain groundwater in Michigan?*

Michigan.6 Mineral Resources

- *What is "banded iron formation" (BIF)?*
- *What are the main types of copper ore?*
- *Name some of the other non-metallic mineral resources produced in Michigan.*

Michigan.7 Oil, Gas, and Coal Resources

- *When and where was oil first discovered in the Michigan Basin?*
- *What was the significance of discovering oil at the Saginaw, Muskegon, and Mt Pleasant Fields?*
- *What geologic factors controlled the ultimate shape and size of the Albion-Scipio Field?*
- *What oil and gas exploration and development plays were important in Michigan in the 1970s and 1980s? In the 1990s and 2000s?*

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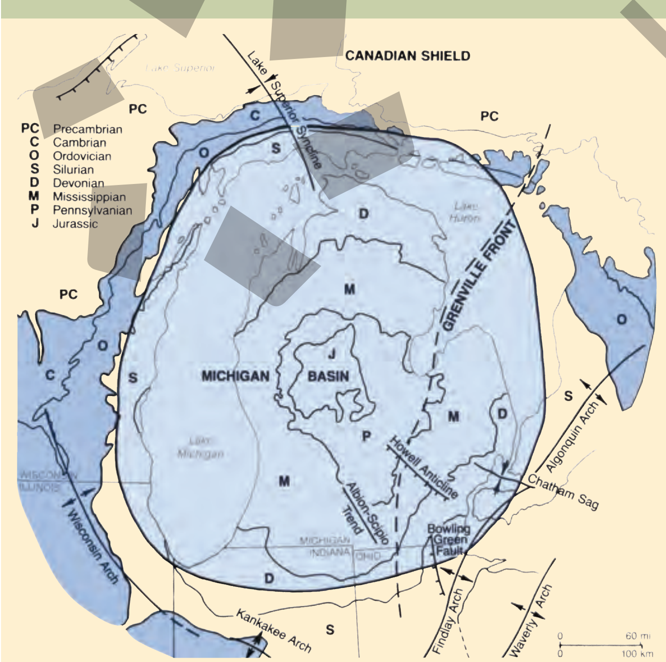
Michigan.1
Introduction

The geology of the State of Michigan is dominated by the Michigan Basin, which is an elliptical, **intracratonic** basin nestled against the southern margin of the Canadian Shield. The Basin occupies approximately 80,000 square miles (180,000 square kilometers), and the sedimentary rocks in the Basin, which are predominantly Paleozoic in age, reach a maximum thickness of 16,000 feet (4,848 meters). Geologic structures define the Basin. The core of the North American Craton, the Canadian Shield, bounds the Basin from the northwest to the northeast. Structural arches define the remainder, with the Wisconsin and Kankakee Arches to the southwest and the Findlay and Algonquin Arches to the southeast (Figure Michigan.1).

The Michigan Basin covers all of Michigan's Lower Peninsula and the eastern half of the Upper Peninsula. The western half of the Upper Peninsula consists of all Precambrian-age rocks with affinities to the southern margin of the **Canadian Shield**. Strata from Middle Cambrian through Upper Pennsylvanian Periods are well represented throughout the subsurface as seen in the many oil and gas wells drilled throughout the Basin. There are also limited outcrops throughout the Basin, especially at the margins near the Great Lakes. Mesozoic rocks are poorly preserved in the Basin, with Jurassic red sandstones known only from well samples in isolated wells in the Basin center. Most of the rocks of the Michigan Basin are buried beneath thick deposits of Pleistocene **glacial drift** that are the only Cenozoic deposits known from the Basin. These sands, gravels, and clays are stacked in complex **facies** relationships and control the patterns of topography seen in much of the Basin. Beneath this veneer of glacial sediments is the eroded bedrock. The **subcrop** of the various formations forms a series of concentric patterns that mimic the Basin margin and that are youngest near the center and oldest at the margin (State Bedrock Map, inside front cover). The locations and shapes of Lakes Michigan and Huron are also controlled by the Basin's bedrock geology. Geographically, the Michigan Basin is centered on Michigan's Lower Peninsula, but also occupies portions of Michigan's Upper Peninsula, Wisconsin, Illinois, Indiana, Ohio, and Ontario, Canada.

Figure Michigan.1 The Michigan Basin: Basement Structural Features.



Modified from Catacosinos, Daniels, and Harrison 1991.

Natural resources abound in the Michigan Basin. Oil and natural gas have been produced from subsurface formations in the Basin in Michigan, Ohio, Indiana, and southwest Ontario. Almost 2 billion barrels of oil and 10 trillion cubic feet of natural gas have been produced since the late 1800s. Underground mines near Detroit have produced large quantities of rock salt from Silurian-age evaporite deposits. **Solution mining** of these salts has occurred nearer the Basin center. Large amounts of potash, bromine, sodium, and chloride have been solution mined from these layers. Limestone, dolomite, and gypsum have been extensively mined from surface quarries in the outcrop areas. Sand and gravel for construction and clay for ceramics and bricks are mined statewide from surficial glacial deposits.

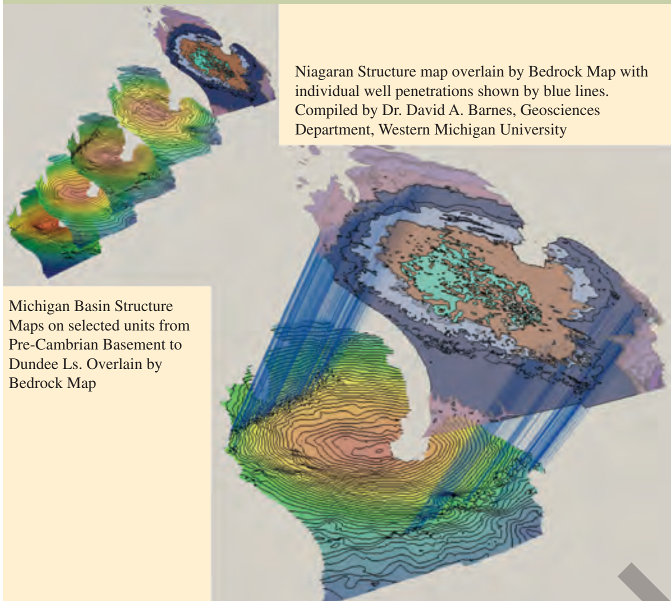
The Great Lakes of Michigan, Huron, and Erie represent the greatest fresh water resources in the region. Along with Lakes Superior and Ontario (which are not geologically part of the Michigan Basin), these five Great Lakes comprise the largest accumulation of fresh water on the earth's surface. There are also vast volumes of fresh water in the glacial drift and shallow bedrock throughout the Basin. The Great Lakes owe their origin to the erosional processes of lobes from the **Laurentide ice sheet**. The moving ice scoured the areas of softer bedrock, commonly composed of shales.

Michigan.2
Precambrian and Paleozoic Geology

Structures

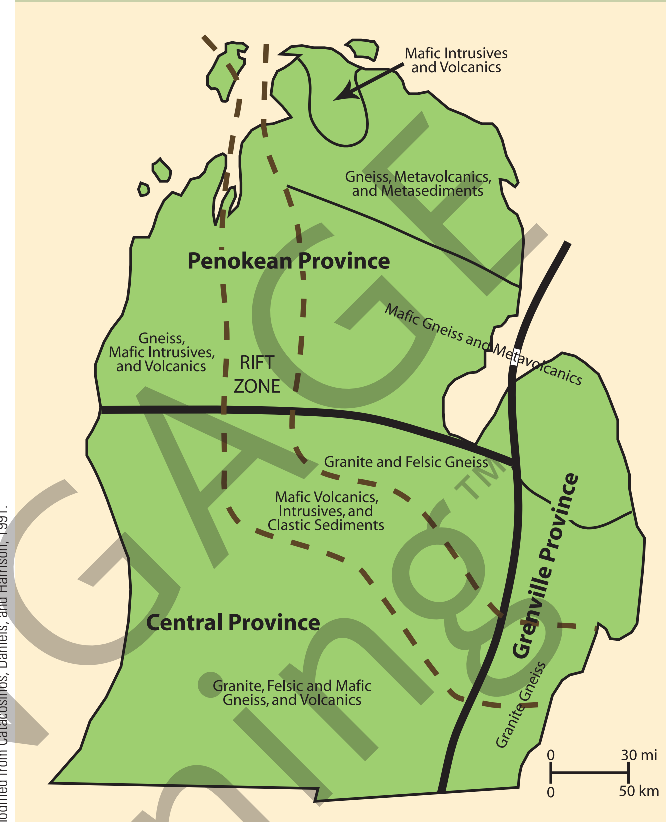
The sedimentary rocks that comprise the Michigan Basin are layered in a pattern like a set of nested bowls (Figure Michigan.2). The oldest layers are at the bottom, and the layers become progressively younger moving upward. The oldest layers outcrop at the Basin margin and occur deeper in the Basin toward its center. All the **strata** in the Paleozoic sedimentary rock section dip at one degree or less in all directions toward the approximate center of the Basin, which is located just west of Saginaw Bay. The exact center of the Basin shifts slightly throughout deposition of the

▶ **Figure Michigan.2** Structural maps of several formations in the subsurface of the Michigan Basin—color patterns create a pseudo-three-dimensional effect.



Compiled by David Barnes.

▶ **Figure Michigan.3** Michigan Basement Provences.



Modified from Catacosinos, Daniels, and Harrison, 1991.

Paleozoic sediments. The entire Basin is underlain by Precambrian rocks of varying **lithologies** and ages that were brought together as this part of the North American plate was assembled during middle and late Precambrian time. These basement **terranes** (Catacosinos, Daniels, and Harrison 1991, fig. 30–2) are mixes of **plutonic** and volcanic igneous rocks, along with **high-grade metamorphic rocks** and **metasediments**.

The mid-Michigan gravity anomaly is a major piece of the basement that follows a wide swath from the northwestern part of the Lower Peninsula through central Michigan and then bends dramatically to the east and intersects the Grenville Front (Figure Michigan.3). The Grenville Front is a major plate suture boundary that extends from the Canadian Shield in central Ontario through eastern Michigan and into northwest Ohio. This anomaly, which is a strong gravity high, has been modeled as a partly developed crustal rift with block faulting, extensive volcanic layers, and sedimentary red bed fills. Analysis of seismic data across the anomaly and samples from Michigan's deepest borehole (McClure-Sparks et al. 1-8, in Gratiot County, at 17,466 feet [5,327 meters] deep) provide good evidence as to the origin of this anomaly (Fowler and Kuenzi, 1978). This mid-Michigan rift is also thought to be connected to the Mid-Continent Rift that runs southwesterly from the Upper Peninsula of Michigan through Wisconsin, Iowa, and Kansas. The basalt flows and volcaniclastic sediments on the Keweenaw Peninsula and through the western Upper Peninsula are part of this geologic feature.

Major structural features that occur in the Michigan Basin are a series of arches to the southeast and southwest. These arches define the margins of the Basin in those areas by dictating the dip direction of the sedimentary rock layers. The Findlay and Waverly Arches in northwest Ohio and the Algonquin Arch in southwest Ontario, Canada, separate the Michigan and Appalachian Basins. The Kankakee Arch in Indiana and the Wisconsin Arch in Illinois and Wisconsin separate the Michigan and Illinois Basins (see Figure Michigan.1).

The Bowling Green Fault, extending into southeast Michigan from northern Ohio, and the Howell Anticline are two major structural features that dominate the geology in the southeastern part of the state. Small **anticlines** with less than 100 feet (30 meters) of relief are common throughout the central part of the state and serve as structures to trap oil and gas. Many of these anticlines show a northwest to southeast trend to their axes. Most of these anticlines are thought to be produced by shearing forces associated with local basement faults or fracture zones that are transmitted up through the sedimentary section during times of crustal deformation due to continent-scale plate collision along the eastern edge of the North American plate.

Lower Peninsula Sedimentary Rocks

Much of the knowledge about the geologic section in Michigan's Lower Peninsula is developed from **cores** (Figure Michigan.4), samples, and **wireline logs** in wells and boreholes drilled during oil and gas exploration and

► **Figure Michigan.4** Michigan Geological Repository for Research and Education is the principal facility in Michigan that houses cores, samples, and other information about subsurface geology.

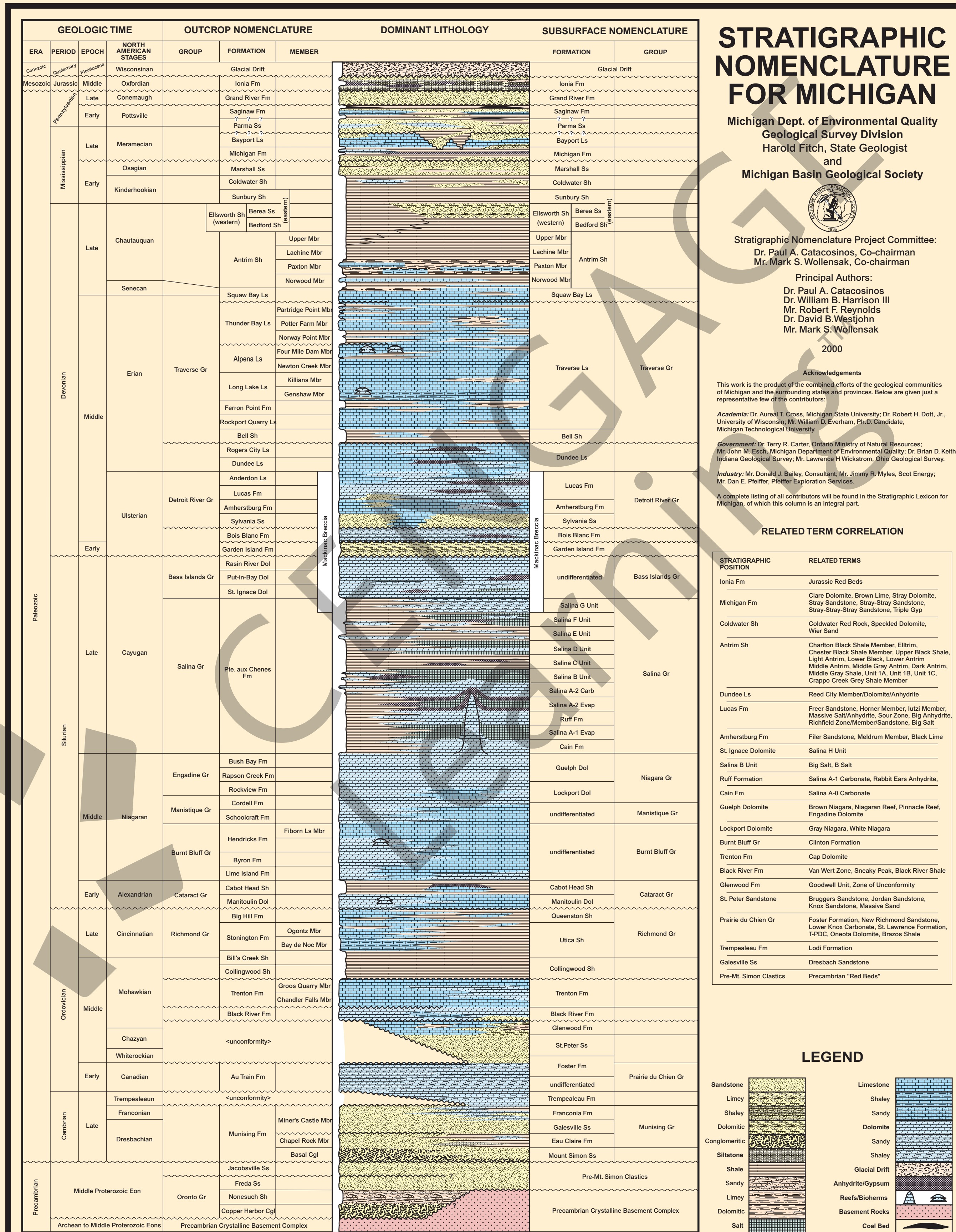
Photograph by Linda Harrison.

mineral resource development. More than 50,000 such wells have been drilled in the Michigan Basin since the early 1900s. Additionally, hundreds of thousands of shallow private and municipal water wells have been drilled statewide. These water supply wells provide data about the glacial drift and shallow bedrock layers. Using this extensive shallow and deep well data, and the local outcrops that mainly occur near the Great Lakes shorelines, it is possible to reconstruct the details of Michigan's subsurface geology.

Michigan has a great thickness (>16,000 feet [>4,880 meters]) of sedimentary rocks deposited in a subsiding basin during late Precambrian through Pennsylvanian time. Jurassic red beds and Pleistocene glacial deposits cover these sedimentary rocks with thickness that varies from a few feet to over 1,200 feet (Figure Michigan.5). As the last billion years of earth's history has unfolded, Michigan has gone through many changes in environment and climate. As the North American continent drifted across the globe, continental collisions and plate movements resulted in greatly varied conditions producing different types of sedimentary deposits throughout Michigan. Continental fluvial, terrestrial, and lacustrine deposits occurred in the late Precambrian age of central Michigan. Shallow marine settings dominated during most of the Paleozoic Era until deposition of fluvial and deltaic deposits returned in the Pennsylvanian Period in response to Appalachian mountain building (Allegheny Orogeny).

The Middle Cambrian Mt. Simon Sandstone represents the beginning of Paleozoic deposition in Lower Michigan. These coastal and shallow marine deposits are the start of a thick **transgressive** interval of sandstone, siltstone, and shale that continues into the Upper Cambrian. Thick, shallow marine shelf deposits of dolomitic carbonates overlie these **siliciclastic** strata in the Lower Ordovician Trempealeau and Prairie du Chien intervals. The strata from the Mt. Simon to the Prairie du Chien represent the Sauk Megasequence of Sloss (Sloss 1963) (Figure Michigan.6). The Tippecanoe Megasequence (Sloss 1963) starts with the Middle Ordovician shallow marine and eolian St. Peter Sandstone and continues upward to the base of the Devonian. This megasequence includes shallow shelf limestones of the Middle Ordovician Trenton-Black River Formations and the Middle Silurian Niagaran reefs and overlying Salina evaporites. These evaporites, which are mostly halite with secondary amounts of anhydrite and potash salts, attain a thickness of over 1,000 feet (305 meters) in the Basin center and are of significant commercial value. The Kaskaskia Megasequence includes most of the rest of Michigan's Paleozoic strata. Ranging from Lower-Middle Devonian to the top of the Mississippian, restricted carbonates and interbedded evaporites (mostly halite and anhydrite) of the Lucas Formation; open marine carbonates of the Dundee and Traverse Formations; the black, **euxinic**, Antrim Shale; the fine-grained sandstones and shales of the Mississippian Berea and Bedford Formations; and the sandstones of the Michigan Formation are all included in the Kaskaskia sequence. The Pennsylvanian Saginaw Formation sandstones, shales, and coals are part of the subsequent Absaroka Megasequence and present only in the Basin center. Spotty occurrences of **terrestrial red bed deposits** are known in the central Basin from well samples. These red beds have been identified as Jurassic in age from **palynological** analysis (Cross 1998). Pleistocene glacial drift covers most of the bedrock strata in the Lower Peninsula. Bedrock exposures are more common in the Upper Peninsula. The best bedrock exposures are found around the shores of the Great Lakes and in some river valleys (Figure Michigan.7).

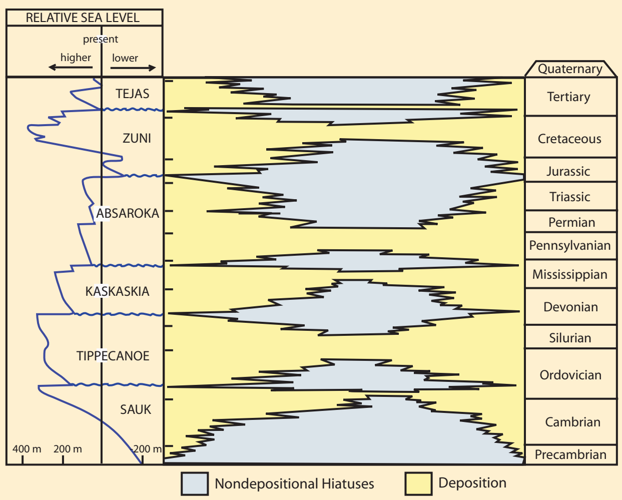
▶ Figure Michigan.5 State of Michigan: Stratigraphic Column and Nomenclature.



STRATIGRAPHIC POSITION	RELATED TERMS
Ionia Fm	Jurassic Red Beds
Michigan Fm	Clare Dolomite, Brown Lime, Stray Dolomite, Stray Sandstone, Stray-Stray Sandstone, Stray-Stray-Stray Sandstone, Triple Gyp
Coldwater Sh	Coldwater Red Rock, Speckled Dolomite, Wier Sand
Antrim Sh	Charlton Black Shale Member, Elltrim, Chester Black Shale Member, Upper Black Shale, Light Antrim, Lower Black, Lower Antrim Middle Antrim, Middle Gray Antrim, Dark Antrim, Middle Gray Shale, Unit 1A, Unit 1B, Unit 1C, Crappo Creek Grey Shale Member
Dundee Ls	Reed City Member/Dolomite/Anhydrite
Lucas Fm	Freer Sandstone, Horner Member, Iutzi Member, Massive Salt/Anhydrite, Sour Zone, Big Anhydrite, Richfield Zone/Member/Sandstone, Big Salt
Amherstburg Fm	Filer Sandstone, Meldrum Member, Black Lime
St. Ignace Dolomite	Salina H Unit
Salina B Unit	Big Salt, B Salt
Ruff Formation	Salina A-1 Carbonate, Rabbit Ears Anhydrite,
Cain Fm	Salina A-0 Carbonate
Guelph Dolomite	Brown Niagara, Niagaran Reef, Pinnacle Reef, Engadine Dolomite
Lockport Dolomite	Gray Niagara, White Niagara
Burnt Bluff Gr	Clinton Formation
Trenton Fm	Cap Dolomite
Black River Fm	Van Wert Zone, Sneaky Peak, Black River Shale
Glenwood Fm	Goodwell Unit, Zone of Unconformity
St. Peter Sandstone	Bruggers Sandstone, Jordan Sandstone, Knox Sandstone, Massive Sand
Prairie du Chien Gr	Foster Formation, New Richmond Sandstone, Lower Knox Carbonate, St. Lawrence Formation, T-PDC, Oneota Dolomite, Brazos Shale
Trempealeau Fm	Lodi Formation
Galesville Ss	Dresbach Sandstone
Pre-Mt. Simon Clastics	Precambrian "Red Beds"

From State of Michigan, Department of Natural Resources.

Figure Michigan.6 Cratonic sea level megasequences. Blue area represents relative global area of continental exposure above sea level at different geologic times.



Adapted from Sloss 1963.

Figure Michigan.8 Quarry with Engadine Dolomite at the outcrop of the Niagaran escarpment, State Rd. 123, Mackinac Co., MI.

Photograph by Linda Harrison.

Figure Michigan.7 Rocky Beach outcrop of Traverse Limestone with large glacial erratic boulders. U.S. Highway 31, roadside park north of Charlevoix, MI.

Photograph by Linda Harrison.

Upper Peninsula Sedimentary Rocks

Knowledge of bedrock geology in Michigan's Upper Peninsula is less dependent on borehole data, since there are many more outcrops (Figure Michigan.8) to help define the rock types and their distribution. There are, however, many relatively shallow boreholes and some cores that have been drilled throughout the Upper Peninsula, especially in areas of mineral exploration. The Eastern Upper Peninsula is part of the Michigan Basin and contains the older strata that also occur deeper in the center of the Basin. Many outcrops and shallow boreholes show the bedrock in the Upper Peninsula to consist of Cambrian through Upper Silurian age rocks. Many of these units are quite similar to formations known from the deep subsurface in the Lower Peninsula.

Cambrian sandstones of the Munising Formation underlie much of the Eastern Upper Peninsula and outcrop along the Lake Superior shore, especially at the famous Pictured Rocks National Lakeshore (Figures Michigan.9 and Michigan.10). The **cross-bedded sandstones** are colorfully stained by mineral oxides of copper, iron, manganese, and other metal **cations** that have precipitated from groundwater flowing through the **porous** sandstone. The Munising Formation is thought to be slightly younger than the Mt. Simon Cambrian sandstone in the Lower Peninsula. The Au Train Formation, overlying the Munising Formation, is a glauconitic or dolomitic sandstone that completes the Sauk Megasequence in the Upper Peninsula.

Tippecanoe Megasequence strata are nearly the same in the Upper Peninsula as seen in the Lower Peninsula, except most units are thinner due to their location near the Basin margin where less subsidence allowed for less depositional space to accumulate sediments. Unconformities at Basin margins also have more impact on the preserved stratigraphic record. During regional sea level falls, erosion at Basin margins begins sooner and lasts longer than in the Basin interiors. During the subsequent sea level rise, deposition occurs last at the Basin margins. The St. Peter Sandstone, a transgressive sandstone unit deposited after the major regional unconformity at the Sauk-Tippecanoe Megasequence boundary, is over 1,000 feet thick (305 meters) in the center of the Basin (Lower Peninsula), but does not occur anywhere in the Upper Peninsula.

An unusual geologic formation called the Mackinac Breccia caps the Tippecanoe Megasequence in the Upper

▶ Figure Michigan.9 Pictured Rocks National Lakeshore: Lake Superior Shoreline, Chapel Rock member of the Munising Formation.

Photograph by Linda Harrison.

▶ Figure Michigan.10 Miner's Castle is a developing sea stack along the Lake Superior shoreline east of Munising, Michigan. Note the sea cave near the waterline that has eroded through the peninsula to the other side, beginning the formation of a sea arch. The undercut, notched cliff face is due to two conditions. First, the notched section was situated right at lake level, and subjected to wave pounding, prior to the recent drop of the Lake Superior water level. Second, the Chapel Rock sandstone, lower in the section at the notch, is less resistant than the overlying Miner's Castle sandstone (both units are members of the Munising Formation). The columns remaining on top were formed as sea stacks on a wave-cut platform during an earlier and higher glacial lake stage.

Photograph by Linda Harrison.

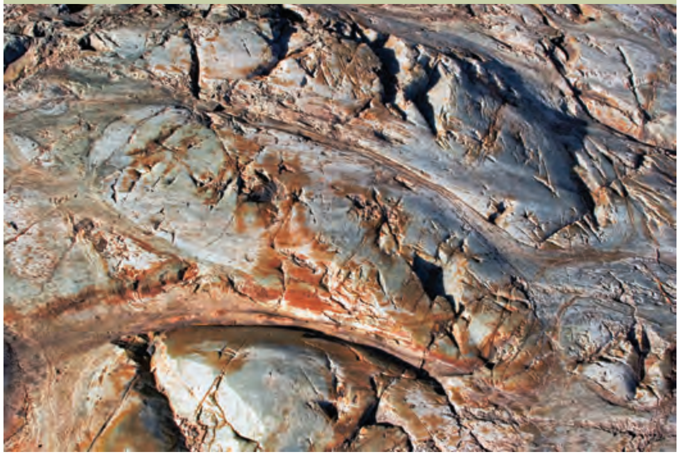
Peninsula. The Mackinac Breccia is a collapse **megabreccia** resulting from the dissolution of Upper Silurian salts along the northern margin of the Basin, principally in the region of the Straits of Mackinac. It contains randomly oriented blocks of Upper Silurian and Lower Devonian carbonate formations that were turned to rubble when evaporite deposits beneath them dissolved by fresh water influx during times of sea level drawdown. There are no deposits younger than Lower Devonian in the Upper Peninsula.

Upper Peninsula Precambrian Rocks

Abundant bedrock exposures occur in the western part of the Upper Peninsula due to thin or absent glacial drift and extensive mining operations. Rocks here are not part of the Michigan Basin, but instead are related to the Lake Superior Basin and several terranes and structural complexes affixed to the southern margin of the Canadian Shield. The oldest formations are middle Precambrian (>2.5 billion years old) **metavolcanic** and **metasedimentary** rocks in the Marquette Trough. This area also contains large deposits of **banded iron formations** that have been extensively mined. The Mona Schist is among the oldest of these formations. It contains large areas of basalt with obvious **pillow lava** patterns (Figure Michigan.11) that have now been altered to greenstone through metamorphic processes. Slightly younger metasedimentary rocks include cross-bedded sandstones of the Mesnard Quartzite and **stromatolite**-rich, shallow water carbonates of the Kona Dolomite. The Banded Iron Formations, most notably the Negaunee Iron Formation, at about 2.1 billion years old are even younger. Less significant iron formations, metavolcanics, metasediments, and intrusive igneous rocks are distributed throughout the region and range in age from 1.6 to 2.0 billion years old.

Late Precambrian (Keweenawan age) volcanic and volcaniclastic sedimentary rocks occur in the far western part of the Upper Peninsula, especially on the Keweenaw Peninsula. The Copper Harbor Conglomerate is a volcaniclastic unit derived from weathered and eroded rubble interbedded with basalt flows of the Portage Lake Lavas. Vast native copper deposits were precipitated in **intergranular** space in these **conglomerates** or in **amygdaloidal** vesicles within

▶ **Figure Michigan.11** Pillow Lavas in the Upper Peninsula of Michigan. These pillows are approximately 2 feet long and indicate deposition below water. They have subsequently been eroded by overriding glaciers that have polished, striated, and plucked the exposed surface.



Photograph by Linda Harrison.

the basalt. These native copper deposits were extensively mined in the nineteenth and early twentieth centuries. Disseminated copper also occurs in commercial amounts in the black, **petroliferous** Nonesuch Shale.

Michigan.3 Quaternary Geology

Formation of the Great Lakes Basins

Episodic glaciation was the major process responsible for creating the Great Lakes basins (Figure Michigan.12); however, bedrock (type and distribution), regional structure and paleo-drainage patterns have all influenced the present-day configuration.

The watershed can be divided into two regions (Figure Michigan.13). The northern upland region (the Canadian Shield) is underlain by Precambrian granites, gneisses, and metavolcanic and metasedimentary rocks. These rocks, in the Lake Superior area, were folded during the Penokean Orogeny (middle Precambrian time) into a northeast–southwest-trending regional syncline. During the Quaternary, this structural trough helped funnel advancing glacial ice southwestward, which scoured and deepened the synclinal basin even more, eventually forming Lake Superior.

The northern upland region also includes the Georgian Bay basin (eastern portion of Lake Huron) and part of the Lake Ontario basin. The underlying syncline of the Lake Superior area is not present in these areas. Only the regional **joint** pattern, northeast–southwest- and northwest–southeast-trending **conjugate joints**, provides any bedrock influence, sometimes producing straight erosional **lineaments** in an otherwise random, glacially eroded pattern (Figure Michigan.14). Topography throughout the northern region is dominated by exposed Precambrian bedrock that has been scoured and sculpted by repeated glacial events. Some thin, discontinuous glacial sediments are only locally present.

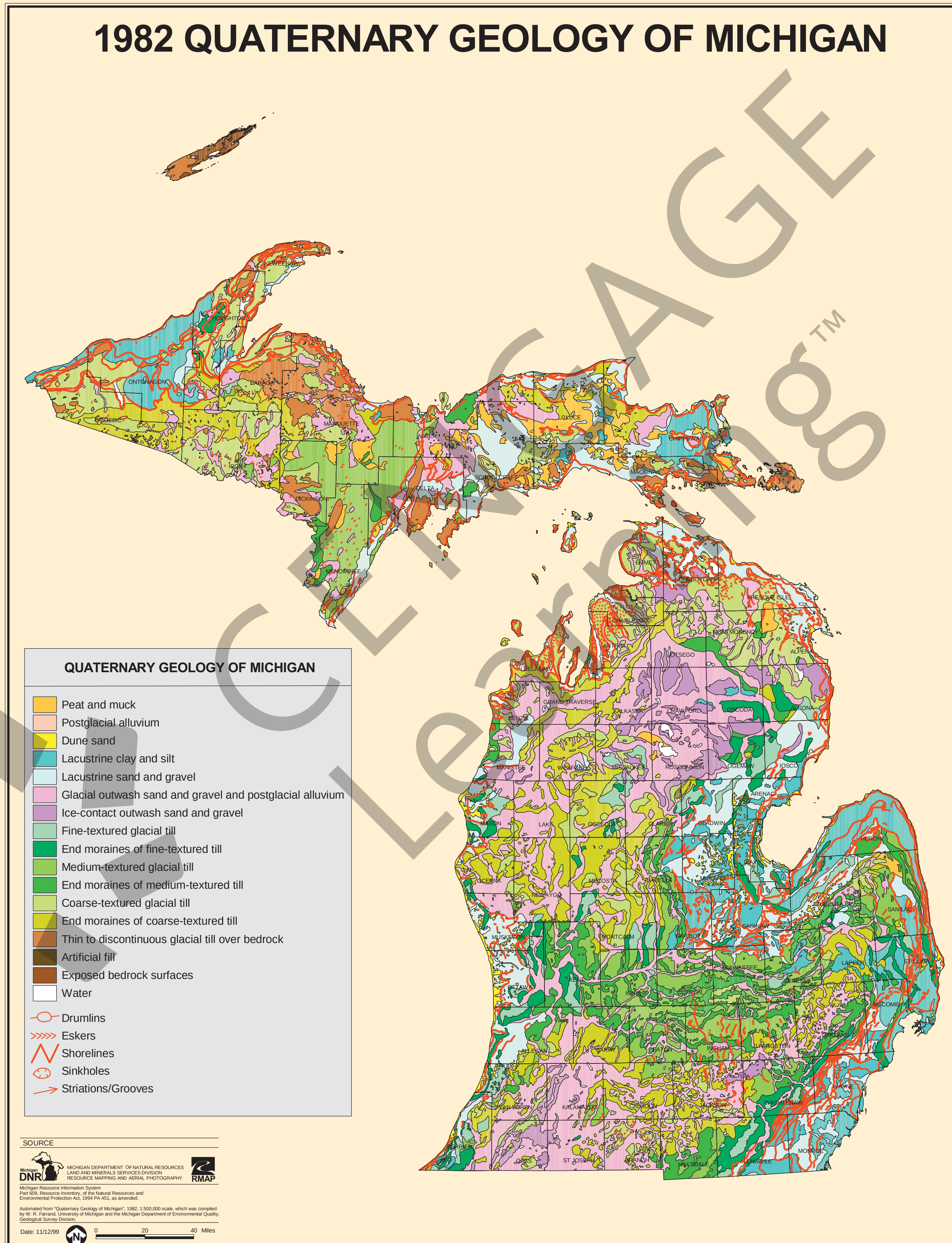
The southern lowland region (the Michigan Basin) is underlain by relatively soft, Paleozoic sedimentary rocks. These rocks all dip toward the center of the state of Michigan into the structural basin. These rock layers appear as a series of stacked bowls with their truncated edges forming a circular pattern encompassing and forming the state of Michigan (much like a bull's-eye). This region includes the Lake Erie, the Lake Michigan, the western portion of the Lake Huron, and a portion of the Lake Ontario basins. Glacial erosion has scoured out these lake basins following the circular, structural pattern where the Paleozoic rocks crop out at the surface around the Michigan Basin. Here, the pattern is much more controlled and better developed than that formed by glacial erosion on the Canadian Shield granite, gneisses, and metasedimentary rocks. This difference is particularly apparent when observing the semi-circular shape of the western portion of Lake Huron carved out of the Paleozoic rocks, in comparison to the more random shape of the eastern portion (Georgian Bay) glacially scoured from the Precambrian Shield (see Figure Michigan.14). This semi-circular pattern continues through the western end of Lake Erie along the Bass Islands, and is reflected in the curvilinear shape of Lake Michigan to the west and Straits of Mackinac to the north. The Great Lakes basins simply conform to the outcrop pattern of the soft limestones and shales of Upper Silurian, Ordovician, and Devonian age.

The Great Lakes watershed was subjected to long-term **subaerial** erosion prior to Quaternary glacial events. Glacial ice was then channeled through the region by this pre-existing drainage system. Relatively weak bedrock, already exploited by valleys of the paleo-drainage system, was increasingly scoured and eroded, thereby exerting one more control upon the formation of the present-day landscape.

Even the Lake Superior Basin, which is located entirely within the Canadian Shield and was initially developed along the length of a structural syncline, owes much of its current shape to the bedrock. Rocks within the syncline included Precambrian sandstones and slightly metamorphosed sedimentary rocks that are less resistant to glacial erosion than the underlying volcanic rocks. Glacial scouring and erosion removed these weak rocks, greatly accentuating the Basin initially formed by the syncline.

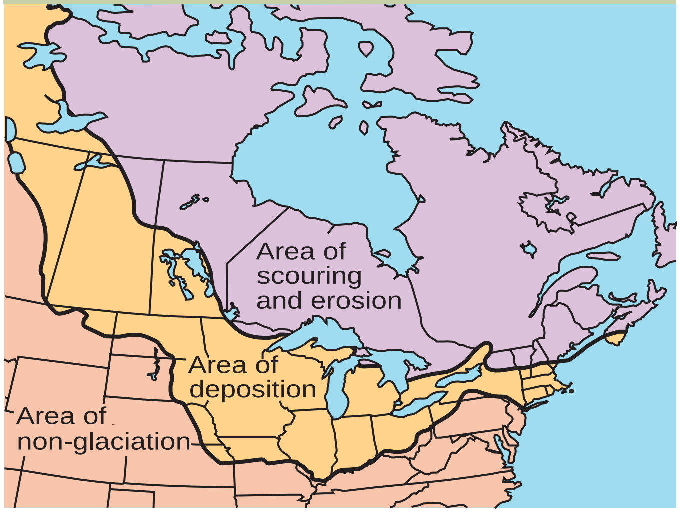
Just the opposite holds true for the islands and peninsulas throughout the Great Lakes. More resistant rock types underlie these areas. Many examples can be observed. Resistant Silurian dolomite forms the Door and Garden Peninsulas separating Green Bay from Lake Michigan. The Niagaran Series of resistant limestones and dolomites of Silurian age occurring along the northern shore of Lake Michigan form the islands separating the North Channel and Georgian Bay from Lake Huron, form the Bruce Peninsula, and can be traced eastward as a long escarpment which the Niagara River flows over at Niagara Falls. Resistant Precambrian Portage Lake Volcanics form the backbone of the Keweenaw Peninsula and Isle Royale in Lake Superior within the northern section of the Great Lakes watershed. Glacial scouring varies considerably from lake to lake

Figure Michigan.12 State of Michigan: Quaternary Geology.



From State of Michigan, Department of Natural Resources.

▶ **Figure Michigan.13** The Great Lakes Watershed: Glacial Erosion vs. Deposition.



Modified from Marshak 2005.

(Figure Michigan.15). Lake Superior, the deepest of the five lakes, is 1,333 feet (406 meters) deep. Lake Erie, the shallowest, is only 210 feet (64 meters) deep. The floors of Lakes Superior, Huron, and the northern portion of Michigan tend to be somewhat irregular.

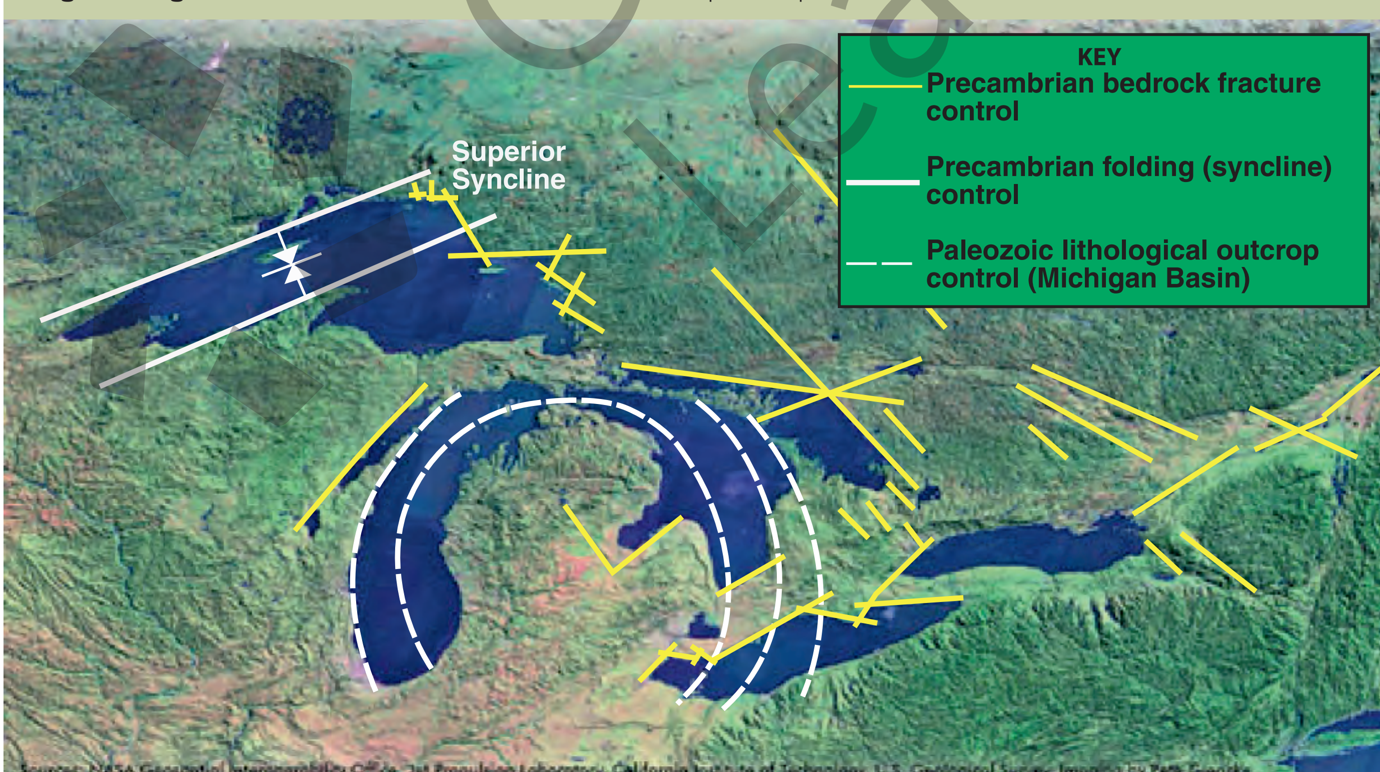
Glacial sediments, often greater than 165 feet (50 meters) thick, and in places over 1,150 feet (350 meters) thick, blanket the region. Broad, low, glacial moraines and a few Paleozoic bedrock **escarpments** provide moderate relief. Quaternary glacial sediments also occur in the basins, often exceeding 330 feet (100 meters) in thickness. Portions of Lake Superior contain glacial sediments greater than 850 feet (250 meters) thick. These glacial sediments indicate that the present-day Great Lakes Basins are the product of both glacial erosion and post-glacial deposition.

Glacial Events

The glacial history of the Michigan Basin is very complex. Six major ice sheets advanced across the Michigan region probably beginning as early as 2.4 million years ago (2.4 Ma). The oldest advances, previously called the Kansan and Nebraskan events, must have advanced across Michigan because sediments from these events are found much farther south across Ohio, Indiana, Illinois, and into Kansas and Nebraska. Geologists now know that these events were much more numerous and complex than originally thought, and the terms Kansan and Nebraskan are no longer used.

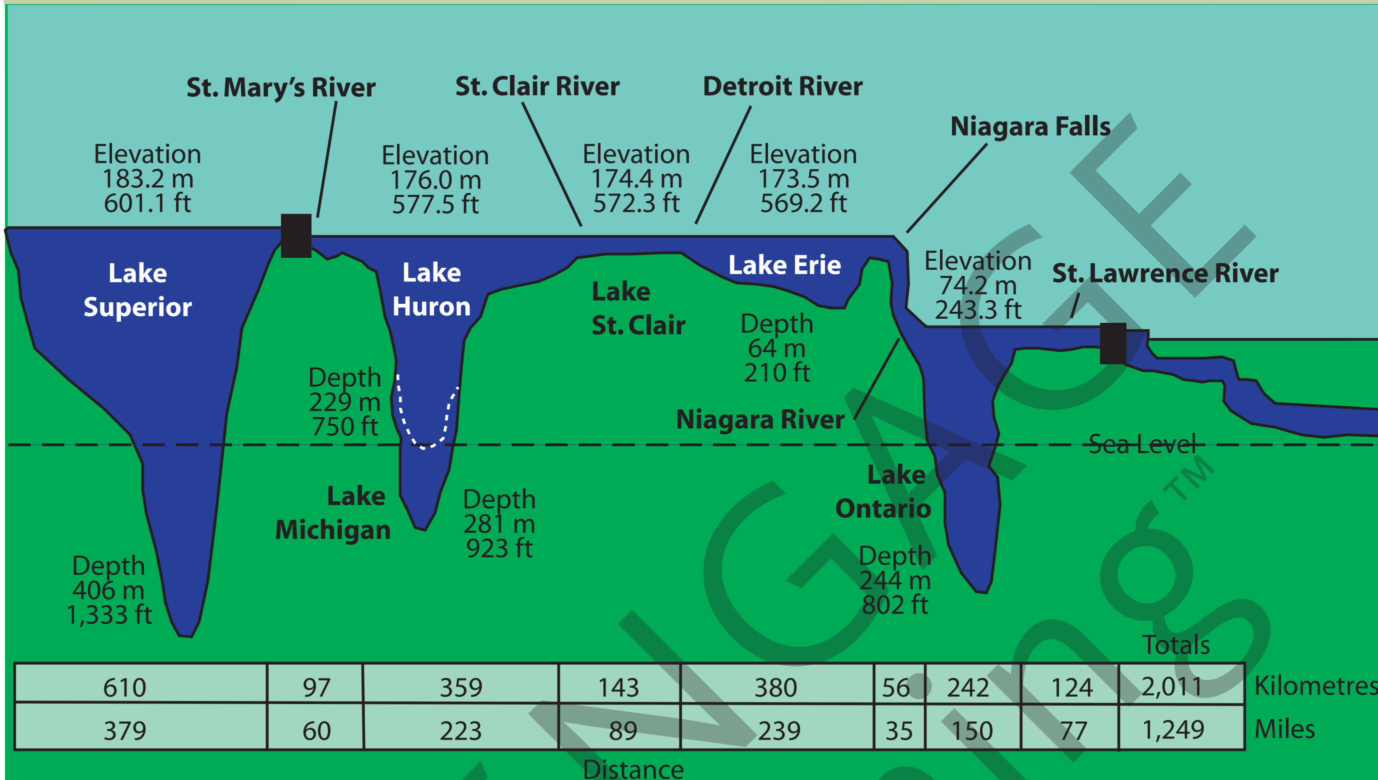
The last two events, the Illinoian and Wisconsinan events, are much better documented and understood, and this terminology is still in use. Illinoian events are inferred from deposits found primarily in Illinois. Glacial sediments in the Michigan Basin once thought to be Illinoian, are now thought to actually be younger Wisconsinan deposits. Currently, indisputable and direct evidence of Illinoian glacial events in the Michigan Basin has yet to be discovered. Warm conditions much like today, in a period 125–179 thousand years ago known as the Sangamon interglaciation, existed between the Illinoian and Wisconsinan glacial events.

▶ **Figure Michigan.14** The Great Lakes Watershed: Patterns of Landscape Development.



Photograph modified from NASA, JPL, Cal Tech, USGS.

Figure Michigan.15 Profile of the Great Lakes.



Modified from United States Army Corps of Engineers, Detroit Office.

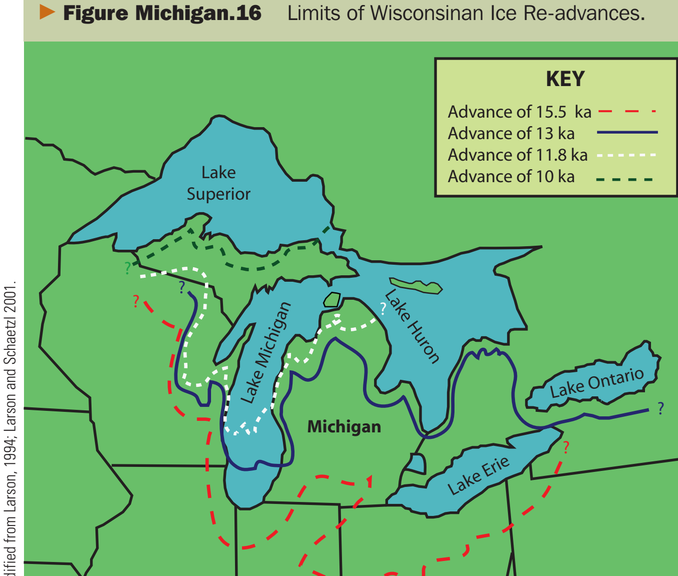
The last glacial episode, the Wisconsinan advance of the Laurentide Ice Sheet, is well documented throughout the Michigan Basin. Three separate sublobes of this last glacial ice sheet advanced and retreated across the Basin (the Michigan, Saginaw, and Erie Lobes) (see Figure Michigan.12). Although no compelling evidence exists, it is thought that advance and retreat of these sublobes was not always synchronous.

Wisconsinan glaciation began sometime between 65 and 79 thousand years ago (65–79 ka). Glacial ice first invaded the eastern section of the Great Lakes watershed where the ice margin oscillated until approximately 25 ka. During this time, a boreal forest-tundra environment covered most of the western portion of the watershed (the Michigan Basin). After 25 ka, the ice sheet advanced from both the north and the east, overriding the western forest-tundra landscape, and covered the entire watershed. Ice eventually reached the Ohio River to the south and northern Wisconsin and east-central Minnesota to the west. The ice front fluctuated there for nearly 4,000 years. After 18 ka, the ice margin began to retreat, but experienced a series of re-advances about 15.5, 13.0, 11.8, and 10.0 ka (Figure Michigan.16). Ice finally continued its retreat about 10.0 ka, and the watershed was completely ice-free by 9.0 ka.

Glacial Lakes

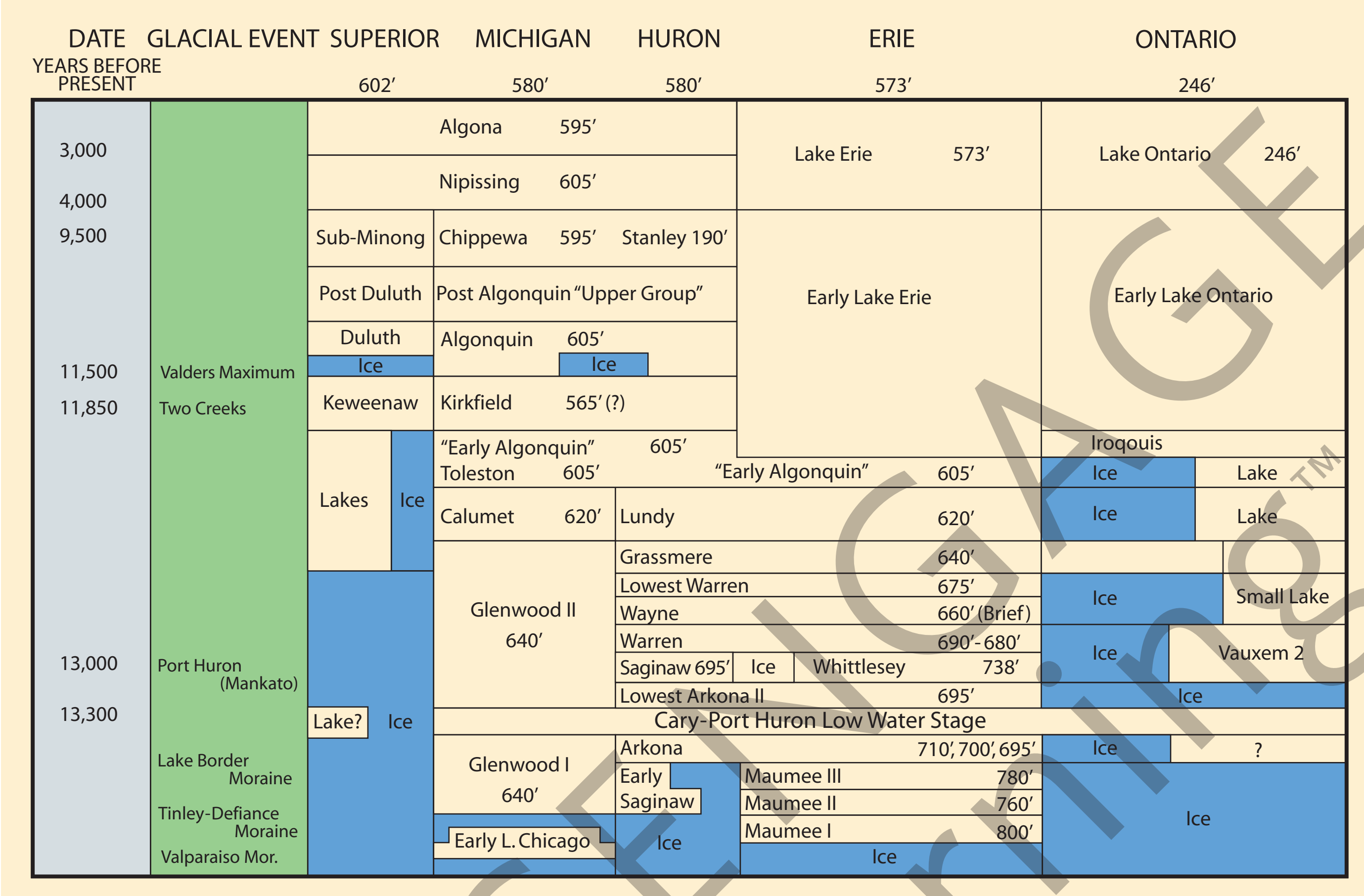
Large, glacial, ice-margin lakes (proglacial lakes) were developed during each retreat of the ice sheet. These lakes filled the newly scoured Great Lakes basins. The northern margin of each lake was established by the southern edge of the glacial ice sheet. The extent and elevation of these lakes varied as outlets were blocked by ice or uplifted by **isostatic rebound**. New outlets formed as rising lake levels found new low spots through ridgelines. Channels were eroded and downcut or melting ice re-opened old channels. Occasionally, catastrophic influx of water from neighboring

Figure Michigan.16 Limits of Wisconsinan Ice Re-advances.



Modified from Larson, 1994; Larson and Schaetzl 2001.

Figure Michigan.17 Chart: Evolution of Glacial Lakes throughout the Great Lakes Basins.



Modified from Dorr and Eschman 1970.

glacial lakes to the west affected the lake levels. This series of glacial lakes left a legacy of lake sediments, abandoned spillways and channels, wave-cut cliffs, beach ridges, deltas, and abandoned shorelines. Some of those old shorelines can still be traced from one lake basin to another.

The history of the proglacial lakes that occupied the Great Lakes watershed is summarized in Figures Michigan.17 and Michigan.18a–d. Fed by glacial meltwater during ice retreats, these lakes expanded, often to the point where they merged with one another. Conversely, the lakes contracted as water levels fell due to the opening of new drainage channels, or as glacial ice once again advanced through the various basins of the watershed.

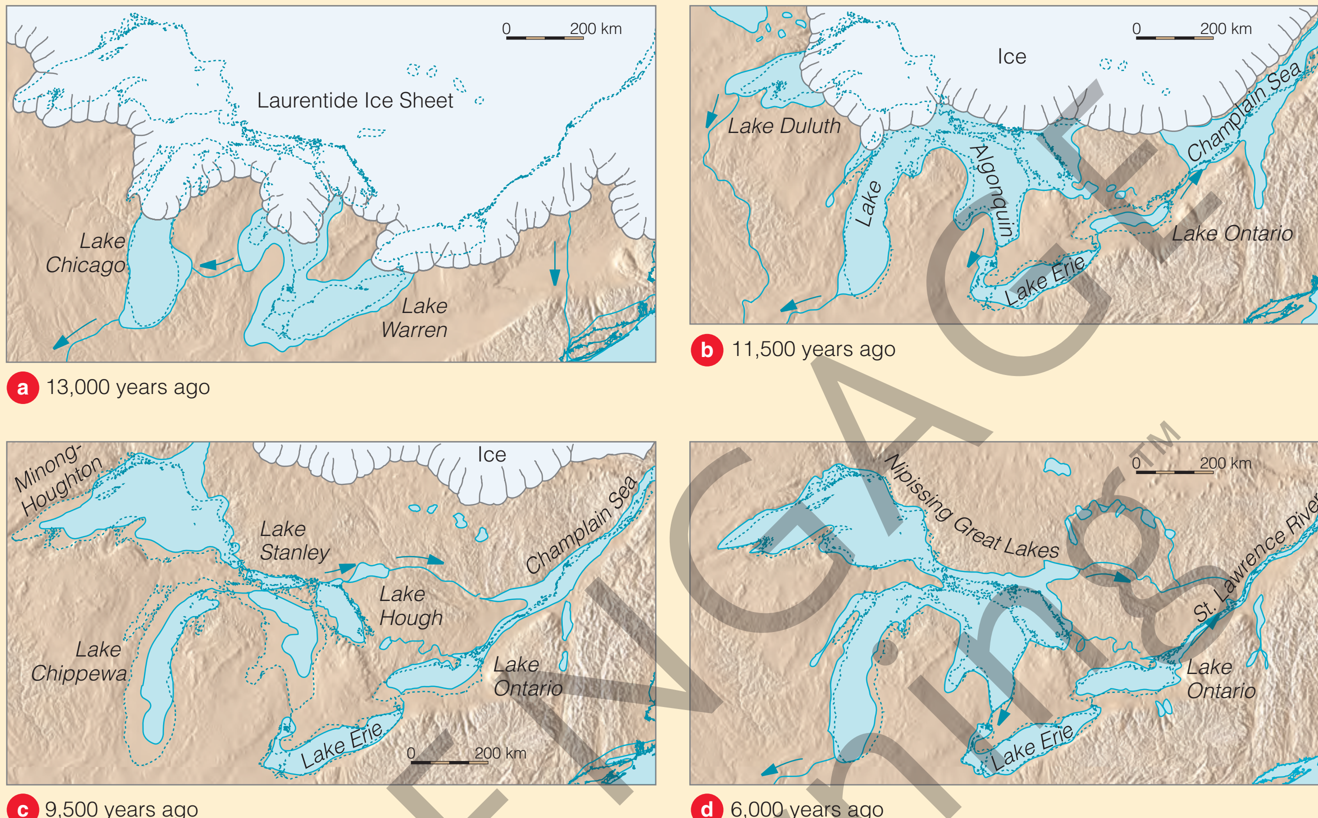
The Lake Superior Basin remained ice covered until approximately 12 ka. Then, as glacial ice retreated from the Basin, a series of relatively small proglacial lakes formed. These lakes expanded and merged with lakes in the Michigan and Huron Basins to eventually form glacial Lakes Nipissing and Algoma.

The Lake Michigan Basin became ice free early in its history. Ice retreated from the southern portion of the basin about 16 ka, and the first of a series of proglacial lakes formed. This early lake, termed Lake Chicago, expanded and contracted in conjunction with a series of glacial retreats and re-advances. Glacial Lake Algonquin formed approximately 12 ka as ice retreated, the Straits of Mackinac opened, and Lake Chicago (Kirkfield Stage) expanded and merged with waters occupying the Huron Basin. Eventually, with continued ice retreat, waters in the Lake Michigan Basin joined those of Superior and Huron to form glacial Lakes Nipissing and Algoma.

High rates of bluff erosion, development of strong cliffs, and formation of very large sand dunes occurred in association with the Lake Nipissing Great Lakes stage (see Figure Michigan.18d). Tower Hill, in Warren Dunes State Park south of Benton Harbor, and Mt. McSuba, just east of Charlevoix, are two examples of these large Lake Nipissing dune fields. Sleeping Bear Dune, north of Frankfort, Michigan, is partially glacial moraine and outwash deposits covered by windblown sand dunes formed during this same time.

The Lake Huron Basin (particularly the southern portion of the basin), much like the Lake Michigan Basin, became ice-free early in its history. There were at least thirteen different proglacial lakes that occupied the basin before merging into glacial Lake Algonquin. These early lakes, for the most part, drained westward across the center of the state of Michigan. This drainage pattern eventually developed into the present-day Grand River Valley system. Huron Basin waters expanded as the northern portion of

▶ **Figure Michigan.18a–d** Glacial Lake Stages: Ice Advances and Retreats.



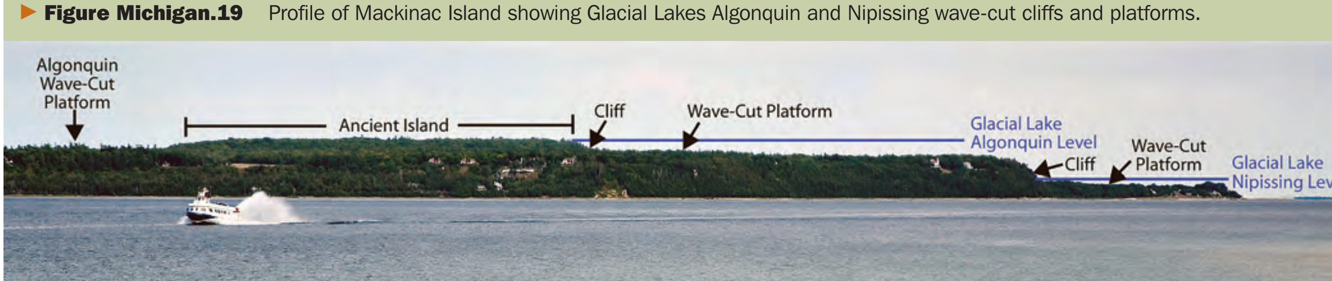
From Monroe, Wicander, and Hazlett 2007.

the basin became ice-free, and merged with waters in the Lake Michigan and Lake Superior Basins to form glacial Lakes Nipissing and Algoma.

The same thirteen proglacial lakes that occupied the Lake Huron Basin early in its history also occupied the Lake Erie Basin. Beginning about 12 ka, the Huron and Erie Basins developed separately as ice retreat and isostatic rebound caused new drainage patterns to develop. Waters from the Huron Basin merged westward with those in the Michigan and Superior Basins to form Lake Algonquin. The presence of glacial Lake Algonquin is evidenced today by numerous wave-cut platforms and other erosional coastal features cut into bedrock, now observed high up along much of the present-day shoreline (Figure Michigan.19). Waters in the Erie Basin fell to a lower level as new eastward drainage developed for that basin, forming the early stages of modern Lake Erie.

Like the Lake Superior Basin, most of the Lake Ontario Basin remained ice covered throughout its early history. Only the southeastern portion of the basin was ice free after 13.3 ka, and was occupied by a series of small proglacial lakes. All these lakes drained eastward, first along the glacial ice front, and later through New York State into the Mohawk River Valley. The early stages of glacial Lake Erie (12 ka) drained eastward into the Ontario Basin where these waters formed glacial Lake Iroquois. When eastward drainage through the present-day St. Lawrence River opened, Lake Iroquois drained to a lower level, forming the early stages of modern-day Lake Ontario.

▶ **Figure Michigan.19** Profile of Mackinac Island showing Glacial Lakes Algonquin and Nipissing wave-cut cliffs and platforms.



Photograph by Linda Harrison.

Glacial Landscapes

Glacial landscapes in Michigan result from two opposing processes: deposition and erosion. Thick deposits of glacial debris capped by associated depositional landforms blanket the entire Lower Peninsula of Michigan and the eastern portion of the Upper Peninsula. Only the western portion of Michigan's Upper Peninsula displays an erosional, Precambrian-aged, bedrock landscape that is scoured clean. Northward, the Canadian Shield is deeply eroded and scoured into the Precambrian bedrock with only a scattering of depositional features.

Erosional Glacial Landforms. Despite the blanket of glacial sediments covering most of the Michigan Basin, there are scattered outcrops displaying the erosional power of glacial ice that moved through the region. **Glacial grooves** are displayed on Late Silurian dolomite bedrock of the Bass Island Group where it crops out along the west side of South Bass Island in Lake Erie near Put-in-Bay. One of the most spectacular, and perhaps the best known, glacially grooved surfaces in the Great Lakes Region is found on Kelly's Island, off Marblehead Peninsula in Lake Erie.

Glacial erratics (of Precambrian age), carried by the glacial ice southward into Michigan from the Canadian Shield, are found in glacial deposits throughout the state. Boulders of Banded Iron Formation (BIF) and pieces of native copper from the Upper Peninsula are occasionally found in Lower Michigan. Although fairly rare, they are easily spotted because they are so distinctive and tend to stand out from the drab sands and gravels. More commonly, rounded pebbles of gray and pink granite, derived from the Canadian Shield, are found in the gravels deposited throughout the Michigan Basin (Figure Michigan.20).

Depositional Glacial Landforms Figure Michigan.21 shows the locations of geologic features discussed in the following sections. Most of the Michigan Basin is blanketed by glacial deposition in the form of **diamictons** (formerly termed "glacial tills") and **glacial outwash**. Landforms, such as **drumlins** and moraine systems, are composed of diamictons deposited directly from the glacial ice. Diamictons are unsorted and unstratified deposits composed of a heterogeneous mixture of materials in all shapes and sizes.

Outwash, on the other hand, is a very general term applied to sorted and stratified deposits laid down by glacial meltwaters. Depositional glacial landforms such as **kames**, **kame terraces**, **eskers**, and ice-channel fillings are indicative of ice-contact and outwash deposition. Landforms such as outwash plains and valley trains, **pitted outwash plains**, kettles, and kettle lakes usually indicate deposition near the ice but farther removed from the immediate ice front (Figure Michigan.22).

▶ **Figure Michigan.20** Erratic pebbles in typical southwestern Michigan gravel (note gray and pink granites, quartz pebbles.)

Photograph by Linda Harrison.

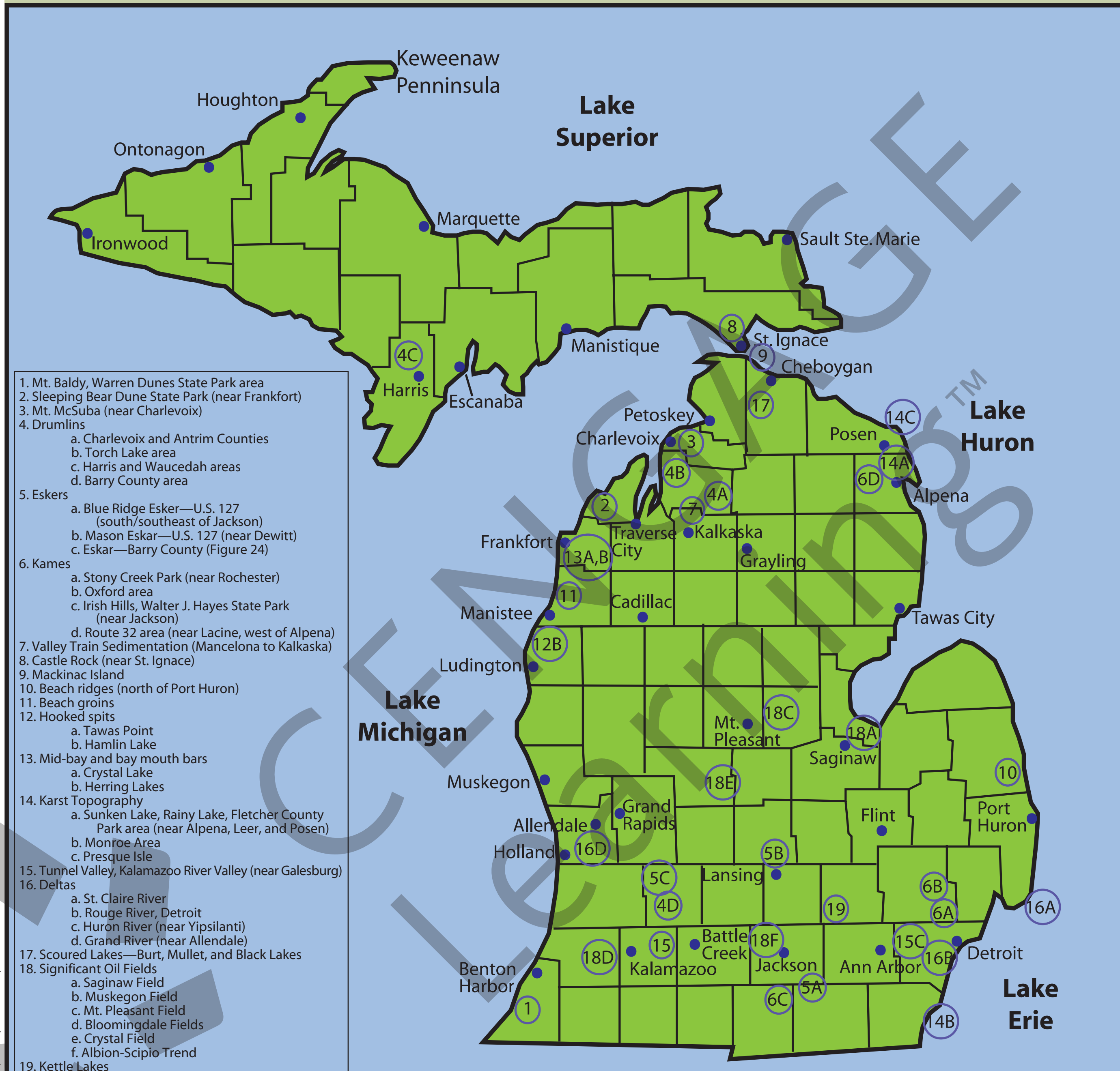
Diamicton and Drumlins

Numerous, well developed drumlins can be observed along both sides of Grand Traverse Bay. Drumlins in Charlevoix and Antrim Counties, just north of Torch Lake, trend south-southwest, indicating the direction of the ice movement. U.S. Route 31 follows the length of two drumlins between Torch Lake and Charlevoix. The exposed interior of these drumlins is composed of unsorted, unstratified clay and boulder diamicton (till). Another drumlin field is situated along U.S. Route 2 between Harris and Waucedah, Michigan, in the Upper Peninsula. Small drumlins are also located in Barry County, 20 miles west of Kalamazoo, in southwestern Michigan.

Moraines. Moraine systems are the most prominent landscape features across Lower Michigan. Three major ice lobes advanced across Michigan during the Wisconsinan glaciation. These advancing ice masses took on lobate forms, fanning outward in radial patterns along their fronts as glacial ice was channeled through the pre-existing Great Lakes Basins. The Michigan Lobe advanced southward through the Lake Michigan Basin. The Saginaw Lobe advanced southwestward as it was channeled through the Saginaw Bay area. The Erie Lobe advanced westward as it was funneled through the Lake Erie Basin (see Figure Michigan.12). These three lobes advanced into northern Illinois, Indiana, and Ohio, developing a pronounced **terminal moraine** (the Cary Border) approximately 16 ka. The state of Michigan was covered by thousands of feet of ice during this time. Retreat from this position lasted until about 13.5–13.2 ka, depositing a series of **recessional moraines** of "Cary" age. The prominent Valparaiso Moraine and Lake Border Moraine that parallel the Lake Michigan coastline through western Michigan, Indiana, Illinois, and Wisconsin formed during this time.

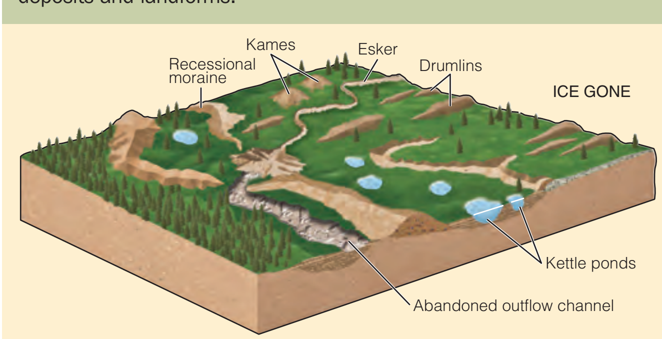
These moraines took on the form of rolling ridges of diamicton and poorly sorted sediments laid down as ice-contact deposits, grading into sloping wedges of outwash deposits farther away from the ice front (Figure Michigan.23). Minor re-advances interrupted the retreat, often smearing out and re-working the just-deposited recessional moraine system

Figure Michigan.21 Location of Geologic Sites



Compiled by Robb Gillespie.

Figure Michigan.22 Generalized block diagram of glacial deposits and landforms.



From Monroe, Wicander, and Hazlett 2007.

as the advancing ice moved over it. This can be seen in one case where thin, weathered, till deposits overlay outwash sediments in the Whittaker-Gooding Pit off Cherry Hill Road, just south of Dixboro, east of Ann Arbor.

Two major, interlobate moraines formed, one between the Michigan and Saginaw lobes, and one between the Saginaw and Erie lobes. The first extends north-south through the center of the state. The other follows the axis of the thumb (east of Saginaw Bay). These areas contain much sand and gravel in the form of kames and extensive outwash plains (called the Sand Barrens) laid down by meltwater deposition.

▶ **Figure Michigan.23** Outwash in Barry County gravel pit (near Hastings).

Photograph by Alan Kehew.

The Port Huron Border Moraine, immediately adjacent to the Saginaw Bay shoreline, is the terminal moraine of the ice that began re-advancing approximately 13.2 ka. Intermittent retreat from this position quickly resumed, lasting until 11.8–11.5 ka. This period of retreat is termed the Two Creeks **interstadial**.

The last major advance of Wisconsinan glacial ice occurred 11.8 ka (termed the Valders **stadial**). Ice, advancing from the north through the Lake Michigan Basin, picked up large quantities of red silt and clay from the Lake Superior Basin (evidence that the Lake Superior Basin must have been a proglacial lake prior to this event) and from the Precambrian iron formations of the Upper Peninsula. The resulting Valders-aged moraines and diamicton deposits, all of which lay north of the older Port Huron Border, are a distinctive red color as a result. This Valders ice advance is also responsible for the formation of the drumlins located in Leelanau and Charlevoix counties.

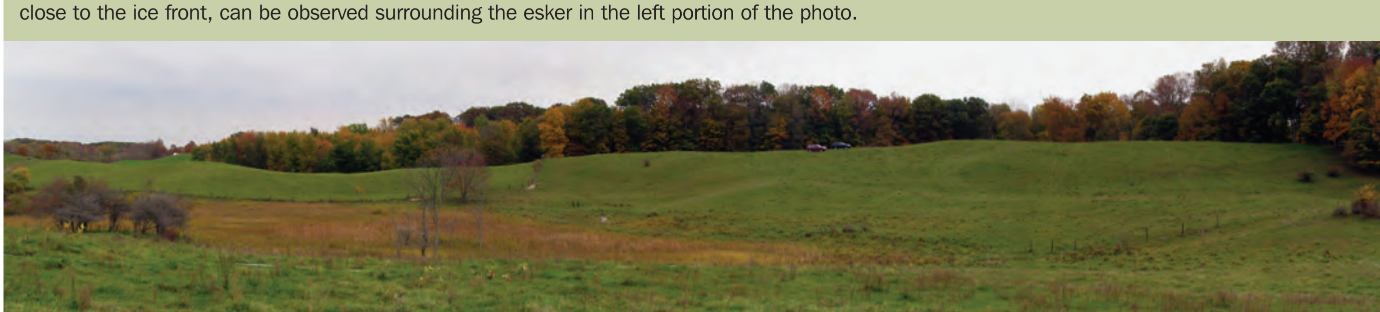
Outwash, Ice-channel Deposits, and Eskers. Sinuous, elongate ridges of outwash materials, flanked by slopes composed of ice-contact sediments, result when glacial debris is laid down within ice-bounded channels. Three excellent examples of such ridges occur in central Michigan. The first is the Blue Ridge Esker that is cut by U.S. 127 about 6.5 miles south-southeast of Jackson, Michigan. The second example is the Mason Esker, located just east of U.S. 127 and extending from Mason to DeWitt, in Ingham County. Barry County is home to the third example. Here, a large esker is observed associated with a field of kames (Figure Michigan.24).

Kames. Kames are hills of outwash flanked by slopes of ice-contact materials. They initially form in low areas between ice blocks, or holes within the glacier. Meltwater deposits flood into these depressions, and ice-contact materials rapidly accumulate around the edges. When the ice melts, the walls of these deposits collapse, leaving behind steeply sloping hills. Groups of Kames can be found in Stony Creek Park near Rochester, the gravel hills near Oxford, and the Irish Hills near Walter J. Hayes State Park southeast of Jackson, Michigan. Isolated kames occur along Michigan Route 32 near Lachine, west of Alpena, and many more can be found scattered throughout the state. Kames are also associated with the previously mentioned large esker in Barry County (see Figure Michigan.24).

Proglacial Outwash and Valley Trains. Proglacial outwash is deposited as a sloping, apron-like fan of meltwater-laid sediments out in front of an ice-contact recessional moraine being deposited along the ice lobe. Most recessional moraines throughout Michigan occur in association with proglacial outwash aprons that were initially deposited away from the glacial margin. The term "**valley train**" is applied to these sloping proglacial aprons when they are confined within valley walls. Good examples of valley trains can be observed in the valley extending from Mancelona to Kalkaska, Michigan.

Pitted Outwash, Kettles, and Kettle Lakes. Outwash sediments are frequently laid down around separate blocks of stagnant ice left in front of the retreating ice sheet. Large depressions in the outwash plain result when these ice blocks finally melt. These depressions are termed **kettle holes**, and the resulting outwash fan, pock-marked by a number of kettle holes, is termed a pitted outwash plain. Kettle holes

▶ **Figure Michigan.24** Esker: Barry County Michigan. The esker is seen as a large ridge (note cars sitting on esker, for scale). Kames, deposited close to the ice front, can be observed surrounding the esker in the left portion of the photo.



Panoramic photograph by Alan Kehew.

become **kettle lakes** when they fill with water. Most of the numerous, small, inland lakes throughout Michigan are kettle lakes, and are associated with pitted outwash plains.

Michigan.4 Modern-Day Geologic Processes

The geologic history of the Michigan Basin does not end with the retreat of the most recent glaciers. Rather, landscape development is an evolutionary, ongoing process. For example, several distinct types of shorelines exist along the Great Lakes.

Bedrock cliffs are most common along the shores of Lakes Superior and Huron. Cliffs 1,312–2,625 feet (400–800 meters) in height are common along the north shore of Lake Superior. Beaches of sand and gravel are common along the southern shore. Limestone bedrock and gravel form much of the Lake Huron shoreline east of the Mackinac Bridge. High dolomite cliffs are common along the Lake Huron and Lake Michigan shorelines wherever they intersect the Niagaran Series of rocks. The eastern margin of the Door Peninsula, the Garden, Bruce, and Presque Isle Peninsulas, and the western margin of Manitoulin Island are examples of such areas. Rocky headlands and small pocket beaches composed of rounded limestone gravel and sand are found along these shores. Bluffs cut into glacial sediments are especially prominent along the southeastern shore of Lake Huron, the central section of Lake Michigan, and the shores of Lake Erie. Many of the Lake Erie shores are low and marshy.

Erosional Shorelines

Mackinac Island continues to be, after more than a century, a favorite tourist destination in Michigan. The well developed shoreline features of this island, as they relate to the various glacial lake stages, can easily be observed from the Mackinaw Straits Bridge (see Figure Michigan.19). The Algonquin wave-cut cliff and terrace dominate the upper portion of the island. The Nipissing wave-cut cliff and terrace dominate the lower portion. More than 14 different beach ridges are situated between the Algonquin and Nipissing terraces and can be explored all across the island. Associated with these two major wave-cut cliffs are a number of erosional shoreline landforms. Arches, **sea stacks**, and caves have all been eroded from the weak Mackinac Breccia bedrock. The best-known **sea arch** on the island is Arch Rock, formed during Glacial Lake Nipissing time (see Figure Michigan.25). Sugar Loaf, a prominent sea stack, is located 300 feet (91 meters) east of the Algonquin wave-cut cliff at Point Lookout. Skull Cave is cut into a second stack formed by Glacial Lake Algonquin.

Sea cliffs and sea stacks can be observed at Miner's Castle (see Figure Michigan.10) in the Pictured Rocks area along

► Figure Michigan.25 Arch Rock, on Mackinac Island, was eroded from the Mackinac Breccia bedrock at the time of Glacial Lake Algonquin. Modern Lake Huron, to the east, is visible in the background through the arch.

Photograph by Linda Harrison.

Lake Superior east of Munising. Also, sea cliffs cut into Mississippian age sandstones are visible at Pointe Aux Bargues at the tip of Michigan's "thumb." Castle Rock, a wave-cut stack of Mackinac Breccia, formed during Glacial Lake Nipissing time, and can be observed along I-75 just north of St. Ignace (Figure Michigan.26).

Coastal bluffs, composed of glacial sediments, are subject to erosion (Figure Michigan.27). Recent studies by Dr. Alan Kehew and Dr. Ronald Chase of Western Michigan University (United States Army Corps of Engineers grant) of bluffs along Lake Michigan's shoreline north of South Haven have shown that bluffs are most susceptible to erosion during periods of high water. Low lake levels, as experienced during recent years, have greatly reduced the rate of slope failures along the Michigan coastline. Also, water content of bluff materials is a major controlling factor. Bluff stability is greater, displaying little to no slope movement, during dry periods when water tables are low. Pumping, to dewater bluff areas, helps increase slope stability, thereby reducing erosion.

Depositional Shorelines

Sand Dunes. Beaches along the shores of the state of Michigan are some of the best-developed, quartz-rich, sand beaches in the world. Numerous areas of irregular sand accumulations and dune fields occur well inland from current lake shorelines (Figure Michigan.28). These areas

▶ **Figure Michigan.26** Castle Rock is a wave-cut sea stack located along I-75 just north of St. Ignace, Michigan. It was cut from Mackinac Breccia bedrock along the Glacial Lake Nipissing shoreline.

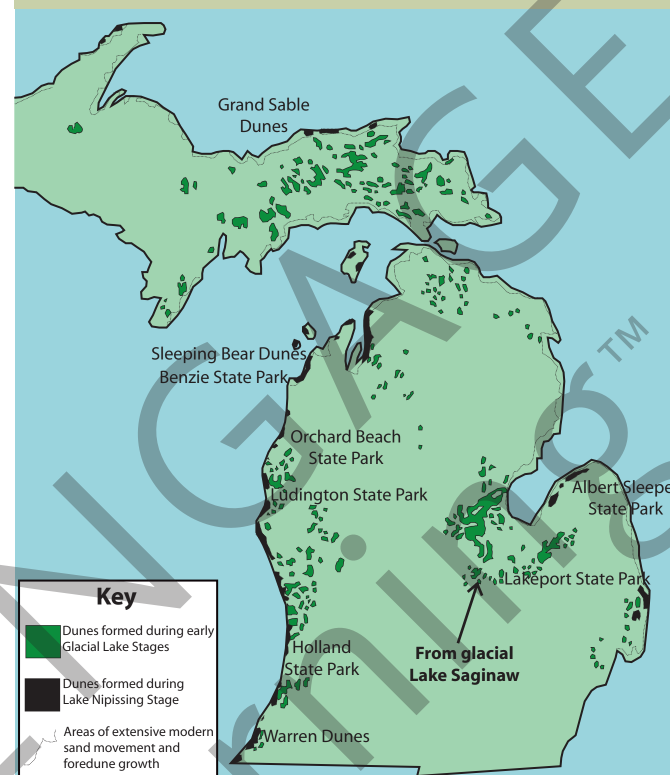
Photograph by Linda Harrison.

▶ **Figure Michigan.27** Slumps along the Lake Michigan shoreline. Located about 4 miles north of South Haven, the view is southward along a part of the coast that is dominated by a sandy bluff with some clay layers on top. This slump structure is typical of bluffs with interbedded clays and sands.

Photograph by Ronald Chase.

originated in conjunction with earlier proglacial lakes standing at much higher elevations, and are generally the oldest dunes in the state of Michigan. The dune field deposited on the old lake plain of Glacial Lake Saginaw (southwest of present-day Saginaw Bay), in particular,

▶ **Figure Michigan.28** Blown Sand and Dune Areas in Michigan. Dotted lines delineate areas of extensive modern-day sand movement and foredune growth. Black areas are older, high dunes related mostly to Glacial Lake Nipissing. Dark green colored areas inland are still older dunes related to earlier, higher glacial lake levels. Note the dune field southwest of Saginaw Bay which was created by Glacial Lake Saginaw.



Modified from Dorr and Eschman 1970.

stands out. These dunes can be observed along U.S. Highway 10 between Midland and Clare, Michigan.

Inland, high dunes are common along all the shorelines that ring the state of Michigan. Many of these high dunes are related to high-water levels of Early Glacial Lake Nipissing (9–2.2 ka). Along the western side of the state, many of the inland, high dunes are related to the high stages of Glacial Lake Chicago that occupied the Lake Michigan Basin. Generally, these inland dunes are no older than about 13,000 years. They were stabilized by vegetation long ago and are no longer sites of extensive dune growth.

Coastal dunes are younger than inland dunes, having formed along the modern Great Lakes shoreline. They are generally less than 4,500 years old, and are mainly related to Late Glacial Lake Nipissing water levels. Coastal dunes can be divided into two categories. **Foredune** ridges are low dunes (30–50 feet [9–15 meters]) that are found close to the water's edge. High dunes (greater than 100 feet [31 meters]) are generally found slightly farther inland behind the foredunes. High dunes may also be found at the water's edge in a few instances. Some of the older high dunes may have been deposited on the tops of glacial moraines and outwash deposits during periods of higher lake levels. These are termed perched dunes. Sleeping Bear Dune is just such a complex, standing 450 feet (137 meters)

Figure Michigan.29 Sleeping Bear Dunes (view northward along coast). This Pearched Dune (right portion of photo), 450 feet above the current level of Lake Michigan, is partially stabilized by vegetation. It sits atop an older glacial moraine (left portion of photo). Coarse cobble and pebble lag, weathered from the moraine by the wind, covers the moraine's surface. The depression (center) is a wind-generated blowout where sand is being scoured from the dune and blown inland.

Photograph by Linda Harrison.

Figure Michigan.30 Sands are constantly being blown inland along the east shore of Lake Michigan. Here, in Indiana Dunes State Park, the lee-side of Mt. Baldy Sand Dune is encroaching upon the trees. Note the angle of repose for the sand face is approximately 35 degrees.

Photograph by Alan Kehew.

above the current Lake Michigan water level (Figure Michigan.29). Grand Sable Dunes in the Upper Peninsula is another such system, standing 380 feet (116 meters) above Lake Superior. Perched dunes tend to be less thick than other foredune types.

Foredunes are the youngest and most active dunes along the Michigan coast. Blowouts occur where dunes lack the stabilizing effects of vegetation. Sand is blown from the windward side of the dune, up and over the crest, to be deposited on the dune's lee side. (Figure Michigan.30). The dune is observed to "march inland" as this process continues. However, the coastal dunes eventually stabilize as (1) they move away from the beach; (2) the source of sand supply diminishes; (3) they become more protected from the shore winds; (4) they encounter the fronts of the inland high dunes; and (5) vegetation takes hold and provides stabilization. Unfortunately, in some areas, these sand dune systems are being threatened, not only by the flux of nature, but more and more by human interference and lack of sound environmental stewardship.

Beach Ridges. Many beaches along Michigan's shores are marked by a series of recessional **beach ridges**. These ridges, composed of gravel and coarse sands, were formed along the shorelines by progressively dropping glacial lake water levels. One set of well developed beach ridges can be observed along the Lake Huron shoreline just north of Port Huron (Figure Michigan.31). Another example of beach ridges can be observed at Sturgeon Point on Lake Huron just north of Harrisville. Here, closely spaced lines of trees parallel the present-day shoreline. These tree lines reflect former beach ridges, where sediments that favor tree growth have accumulated.

Hooked Spits. Sands necessary for the growth of **spits** and mid-bay and bay-mouth bars are supplied as beach drift. This beach drift develops as **longshore currents** erode sands from the beaches they are moving along (Figure Michigan.32). Groins, built at 90 degrees to the shore out into the water, help prevent erosion by trapping beach drift moving along the beach. Examples of such groins can be observed along the Lake Michigan shoreline near Ludington, Michigan.

Sand bars and spits grow as beach drift, moving along a shoreline, is deposited into an open embayment as it attempts to extend the beach. Waves, coming into the embayment from offshore, redistribute sediments near the end of the spit, carrying those materials farther into the embayment. This results in the formation of a hooked spit

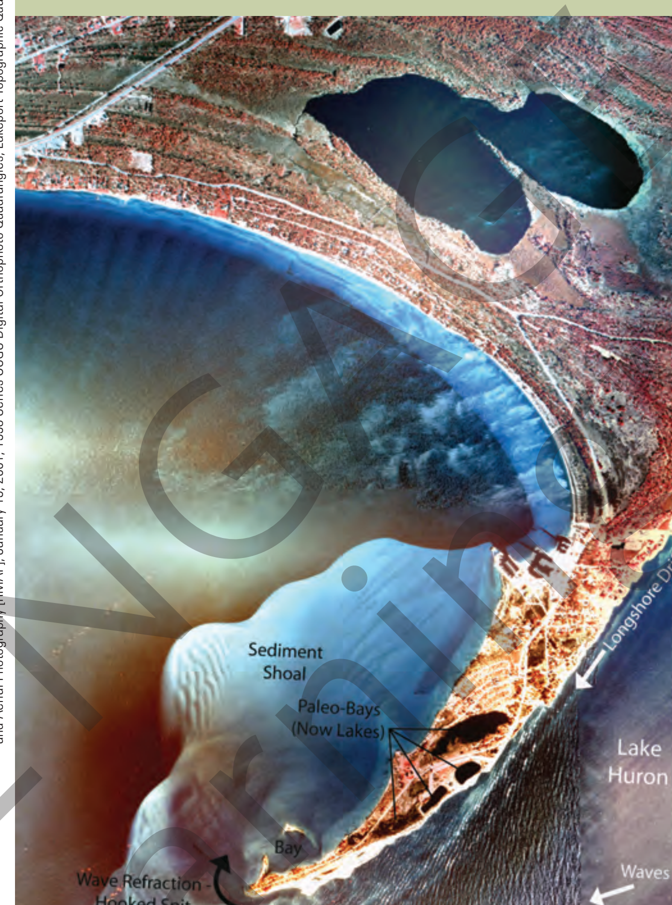
▶ Figure Michigan.31 Recessional Beach Ridges, north of Port Huron, were formed by progressively dropping glacial lake levels in the Lake Huron basin.

Photograph modified from Michigan Department of Natural Resources [MDNR], Forestry, Mineral and Fire Management Division, Resource Mapping and Aerial Photography [RMAP], January 15, 2001, 1998 Series USGS Digital Orthophoto Quadrangles, Lakeport Topographic Quadrangle.

▶ Figure Michigan.32 Northward view of groins along the Lake Michigan beach north of Manistee. The groins were originally used to capture sand moving along the beach, but they now reside high in the dune line due to the significant drop in lake levels during the last 5 years. This is just one of many public beach access points along the coast.

Photograph by Linda Harrison.

▶ Figure Michigan.33 The hooked spit at Tawas Point has a long and complex history. Waves from Lake Huron refract around the southern point of the spit, carrying sediment into the bay, and creating a shoal behind the spit. The numerous lakes observed within the spit are the remnants of previous bay areas surrounded and cut off by the growing shoal and migrating spit.



Photograph modified from Michigan Department of Natural Resources [MDNR], Forestry, Mineral and Fire Management Division, Resource Mapping and Aerial Photography [RMAP], January 15, 2001, 1998 Series USGS Digital Orthophoto Quadrangles, East Tawas SW Topographic Quadrangle.

as the end of the spit "bends" around toward the inner shore of the embayment. Tawas Point, a hooked spit currently evolving near Tawas City on Lake Huron, has a long and complex history (Figure Michigan.33). Nine separate hooks (points) and associated sub-bays have developed, and subsequently, have been highly modified, as this large hooked spit continues to evolve.

Mid-Bay and Bay Mouth Bars. Waves, longshore currents, and wind action constantly re-shape the shorelines of Michigan. The Upper and Lower Herring Lakes, located in Benzie County about 6 miles south of Frankfort, are good examples of such evolving shorelines (Figure Michigan.34). The two lakes lie within a U-shaped depression. This depression is enclosed on the north, east, and south by the Manistee Moraine, but was originally open toward the west as an embayment to Lake Michigan. During late Lake Algonquin time, mid-bay bars developed within the embayment. These bars isolated Upper Herring Lake in the mid-eastern portion of the embayment and another small basin in the very eastern section. This eastern basin was a short-lived lake and is now filled with sediment and vegetation.

Figure Michigan.34 Upper and Lower Herring Lakes formed as mid-bay and bay mouth bars isolated an estuary, located between two east-west trending glacial moraines (ridges), from Lake Michigan. The eastern-most portion of the embayment is now a depression filled with sediment and vegetation.

Photograph modified from Tucker, C. J., D. M. Grant, and J. D. Dykstra. 2004. NASA's global orthorectified landsat data set. Photogrammetric Engineering and Remote Sensing 70, no. 3:313–322.

Figure Michigan.35 Crystal Lake, north of Frankfort, Michigan, formed in a low area between two east-west trending glacial moraines (ridges). Originally formed as an estuary open to the west, growth of a bay mouth bar eventually isolated the estuary from Lake Michigan. Sand Dunes, related to Glacial Lake Nipissing, formed on the bar augmenting the closure. Note that Betsie Lake, to the south, has formed by the same process. Offshore jetties and human intervention are the only things keeping the remaining channel open.

Photograph modified from Tucker, C. J., D. M. Grant, J. D. Dykstra. 2004. NASA's global orthorectified landsat data set. Photogrammetric Engineering and Remote Sensing 70, no. 3:313–322.

The remaining western portion of the embayment drained during the early stages of Glacial Lake Nipissing, but during late Nipissing time, the embayment was once again flooded. During post-Nipissing times, the current bay-mouth bar formed, isolating Lower Herring Lake in the western portion of the embayment. Eventually, during recent times, low foredunes developed on top of this bar and adjacent shorelines. Presently, the two Herring Lakes are isolated from Lake Michigan, being drained only by narrow Herring Creek that cuts across the mid-bay and bay-mouth bar systems.

Crystal Lake, located immediately north of Frankfort, formed in a similar manner (Figure Michigan.35). The area originally occupied a topographic low, situated between two east-west trending glacial moraines, and opened to Lake Michigan to the west. Development of a bay-mouth bar isolated the embayment, and complete closure was assured as dunes related to Glacial Lake Nipissing covered the bar.

Hamlin Lake, in Ludington State Park on Big Sable Point (just north of Ludington, Michigan) is another product of shoreline evolution (Figure Michigan.36). Originally, five rivers entered the Lake Michigan Basin along this portion of the coast. Sands carried into the lake by these rivers fed the growth of two large hooked spits, one from the north and one from the south. These spits formed two arms that eventually enclosed Hamlin Lake, first as an open embayment, and finally as a separate, isolated lake. High dunes related to Glacial Lake Nipissing formed atop these spits, completing the enclosure.

Michigan.5
Geology of Water Resources

Groundwater

Michigan is very fortunate, mostly due to its glacial heritage, that high quality water resources abound throughout the state. The majority of Michigan's water wells tend to be shallow, and can easily be pumped from surficial sands and gravels deposited by glaciers. Much of the groundwater in the Lower Peninsula comes from these glacial deposits, and is "hard" due to the lime ($CaCO_3$) held in solution. Bedrock **aquifers** in the Marshall Sandstone in southern and eastern Michigan and the Saginaw/Grand River formations provide most of

▶ **Figure Michigan.36** Hamlin Lake, on Big Sable Point north of Ludington formed as two hooked spits, one growing from the north and one growing from the south, merged, cutting Hamlin Lake off from Lake Michigan. Ample sediment supply for hook growth was fed into the area by five rivers denoted by stars. The original shoreline extended along these points. Lake Hamlin formed first as a bay, and then developed into a lake as the hooked "arms" merged. Sand dunes related to Glacial Lake Nipissing now cover the spits.

Photograph modified from Tucker, C. J., D. M. Grant, J. D. Dykstra. 2004. NASA's global orthorectified landsat data set. Photogrammetric Engineering and Remote Sensing 70, no. 3:313–322.

the water supply for major municipalities such as Battle Creek and Lansing. Groundwater extracted from bedrock aquifers in the Upper Peninsula tend to contain sulfur, iron, and various salts, which must be chemically removed.

Gravels buried beneath impermeable glacial drift in Michigan are responsible for numerous **artesian** water systems. The municipalities of Ann Arbor, Northville, Alma, St. Louis, and Cadillac are just a few examples of these systems. Some artesian systems are developed in bedrock. There is a large flowing well on Grosse Ile in the Detroit River and a series of non-flowing wells in the Marshall Sandstone that supply water to Battle Creek (the Verona Field).

Karst Topography

Although Michigan is not normally thought of as a region of caves and **karst topography**, there are limited areas within the state where these conditions do exist. Paleozoic carbonates, now near the surface and only buried by a thin veneer of glacial debris, are readily susceptible to dissolution and karst development. The area surrounding Leer and Posen, Michigan, immediately west of Alpena, is such an example. Here, Middle Devonian age Alpena Limestone tends to dissolve and form karst features. Sunken Lake and the Fletcher County Park area have developed east of Leer. Rainy Lake, west of Leer, occupies a sinkhole that occasionally goes dry as bottom sediments are breached, and surficial lake waters drain through the underground karst system. Numerous lakes throughout Presque Isle County are water-filled, karst sinkholes.

West of Monroe, in the southeastern portion of the state, extremely broad and shallow sinkholes have developed. These are now filled with sediments related to previous older, high lake levels in the Lake Erie Basin.

There is evidence of ancient cave and karst development during the Devonian Period near the Straits of Mackinaw. Blocks of roof rock that collapsed into the caves below were later re-cemented to form the Mackinac Breccia. Today, Mackinac Breccia is the bedrock found throughout the area. Before construction of the piers and footings for the Mackinac Bridge could begin, careful geologic studies had to be carried out to ensure that this weak breccia could support the bridge, and that no further collapse would occur.

Surface Water

Rivers. The surface topography of Michigan is primarily the result of glacial events, the last of which ended only 13–9 ka. Therefore, rivers and streams have played a somewhat limited role in the development of Michigan's landscape. The Kalamazoo River Valley, for example, is thought to have originated as a **glacial tunnel valley** (Kozlowski, Kehew, and Bird 2005). The river currently occupying the valley has actually done nothing to initiate, and little to further develop, this pre-established glacial drainage system. Similarly, today's Grand River occupies a valley that was originally used as an outlet for a number of glacial lakes that occupied the Huron and Michigan Basins.

Deltas. Delta growth, where rivers enter standing bodies of water, is an important means of delivering sediments into these glacial lakes. The delta currently forming where the St. Clair River empties into Lake St. Clair is a classic example of a growing, modern delta system.

Many of the delta systems built into earlier glacial lakes have been rejuvenated as water levels dropped and/or as **isostatic rebound** raised the delta complexes in relationship to the water surface. **Distributaries** incised the **delta floodplains** attempting to maintain grade. This has resulted in newly incised river valleys cutting through older, broad, now terraced, deltaic, floodplain deposits. Excellent examples of such rejuvenated deltas in Michigan can be seen at (1) the Huron River near Ypsilanti; (2) the Rouge River in the Detroit area; and (3) the Grand River near Allendale (west of Grand Rapids).

Inland Lakes. The natural beauty of Michigan is in large part due to the hundreds of inland lakes found throughout the state. Kettle lakes abound and are the most common type of all Michigan's inland lakes. Although kettle lakes are scattered throughout the state, a broad, extensive belt of these lakes extends from just north of Pontiac southwestward to Jackson. This belt of kettle lakes was formed within the broad outwash plain formed between the interlobate moraines of the Saginaw and Erie ice lobes.

Other lakes, primarily found in the northern portion of the Lower Peninsula, formed in basins scoured out by the glaciers. Glacial lake levels eventually dropped, causing the shallower portions of these basins to become dry land. Only the deeper portions of the basins remained submerged as inland lakes, now isolated by the shallower dry areas. Burt Lake, Mullet Lake, and Black Lake formed in this manner.

Coastal lakes, as already discussed, are the result of embayments being cut off from the surrounding Great Lakes by mid-bay and bay-mouth bars, and later being modified by the development of sand dune systems. Upper and Lower Herring, Hamlin, and Crystal Lakes are typical examples of these lakes.

Some inland lakes are the result of karst development, such as Sunken and Rainy Lakes near Alpena. Also, a few small lakes evolved as river meander cut-offs that became oxbow lakes. Small depressions sometimes become seasonal ponds, but these quickly fill with sediment and vegetation and prove to be very short-lived.

Michigan.6 Mineral Resources

The latest United States Geological Survey report on non-fuel mineral production in 2004 (http://minerals.usgs.gov/minerals/pubs/state/mi.html) lists Michigan as the ninth most productive state, with an annual produced raw mineral value of $1.67 billion. Michigan produces about 3.7% of the nation's domestic minerals. Michigan is the nation's top producer of magnesium compounds, and is second in iron ore, bromine, and iron oxide pigments. Michigan is third nationally in potash production, and fourth in Portland cement and construction sand and gravel. It is seventh in salt production and tenth in gypsum production. Michigan also produces significant amounts of common clay and crushed stone. Although Michigan's production of these non-fuel minerals has recently declined as other states' sources and foreign sources have increased, however at some point in the past Michigan led the nation in the production of many of these important minerals.

Iron Ore

Michigan, located between the iron fields to the northwest and the coal reserves of Pennsylvania to the east, all linked by easy, accessible Great Lakes shipping, was in the right location during the early twentieth century to become the world's industrial center for automobile manufacturing—all thanks to geology.

Although banded iron formations (BIFs) are present on all continents and are the principal source of iron ore mined today, nowhere are they more plentiful than in the Lake Superior Region of the United States, Canada, and the Labrador trough of eastern Canada. In Michigan, these middle Precambrian iron formations are of great importance to the economy of the Upper Peninsula and to the state of Michigan as a whole. BIFs are chemical sedimentary rocks consisting of banded layers of quartz-rich rock (chert and jasper) and layers of almost pure iron oxides such as hematite (Fe_2O_3) and magnetite (Fe_3O_4). The BIFs are easily identified. The iron forms gray-black bands and makes the rock very dense (heavy), while the silica forms gray (chert) or red (jasper) bands and makes the rock very hard and durable (Figure Michigan.37).

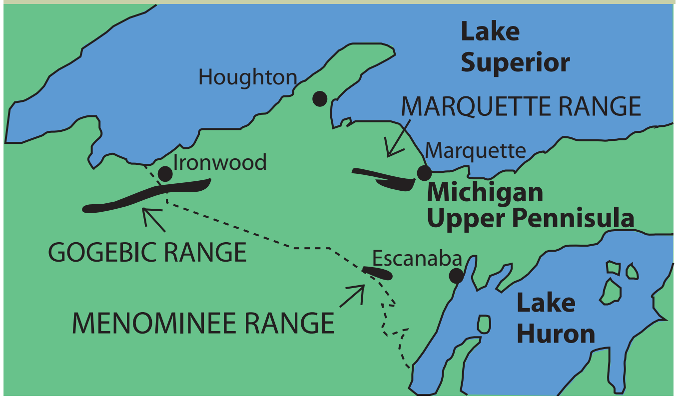
Iron minerals, deformed and metamorphosed, changed into coarser-grained magnetite, or to a shiny variety of coarse-grained hematite, called specularite. Locally, flows of underground water leached or dissolved away some of the silica-rich layers, naturally concentrating the remaining iron ore in those areas. The first deposits to be discovered and worked by humans were the near-surface concentrations of these soft ores, often as rich as 70% iron. Some of these mines followed the rich ore into the depths as the shallow, open-pit works exhausted the easy-to-get high-grade ore.

High-grade ores, those with iron concentrations greater than 50%, can be sent from "mine to mill" without processing, and are known as "direct shipping" ores. Lean-ores

► Figure Michigan.37 Banded Iron Formation (BIF) from Jasper Knob with interbedded red jasper and gray hematite.

Photograph by Linda Harrison.

► **Figure Michigan.38** Location of Keweenaw iron ore ranges.



Modified from Dorr and Eschman 1970.

(25–30% iron) require artificial concentrating (beneficiating) to remove as much as possible of the unwanted silica components to keep shipping and **smelting** costs under control. The higher proportion of silica materials (chert and jasper) also makes the rock harder, making it more difficult (and expensive) to drill and process. Taconite and jaspillite are the two most common lean ores mined and beneficiated today.

Michigan iron ore has been or is currently mined from three main areas: (1) the Marquette Range; (2) the Menominee Range; and (3) the Gogebic Range (Figure Michigan.38). Millions of tons of low-grade ore still remain in all three of these ranges. Modern beneficiation techniques may yet make these ores economically recoverable.

The structure of the Marquette Range, the first Range in Michigan to be opened (1848), is a syncline complicated by folds, faults, and igneous intrusions (both sills and dikes) at depth. This range extends 30 miles westward from Marquette, and encompasses the towns of Negaunee, Ishpeming, Humbolt, Champion, and Michigamme, with a narrow extension to the town of Republic. This range is still being worked.

The Menominee Range, opened in 1872, includes two naturally leached ore bodies: (1) the Vulcan Iron Formation by the towns of Iron Mountain, Quinnesec, Norway, Vulcan, and Loretto, Michigan; and (2) the Riverton Iron Formation in the vicinity of Iron River and Crystal Falls, Michigan, and Florence, Wisconsin. Mines are still active in the northwestern portion of the range.

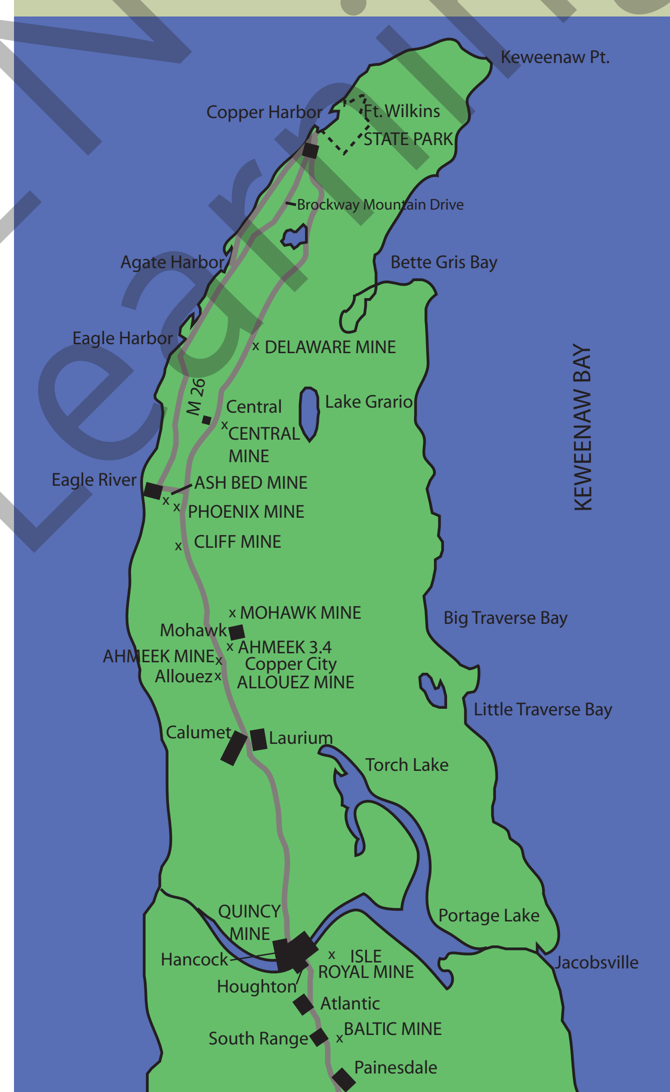
The Gogebic Range, opened in 1884, produced ore from the Ironwood Iron Formation that extends to great depths. These beds are steeply dipping, complexly broken, offset by faults, and cut by igneous intrusions. The Gogebic Range extends from the western tip of Michigan's Upper Peninsula westward into Wisconsin. The last operating mine in this range closed in 1965.

Processing low-grade iron ore takes great quantities of water for washing and separating, so most beneficiating facilities are located along the shores of Lake Superior. Disposal of the silica-rich waste slurry has become an environmentally sensitive issue along the shoreline. Lower grade ores, by-passed in the original open-pit mines, are now being worked due to new beneficiation techniques. Determined environmental stewardship, along with improved beneficiation processes, will play major roles in keeping the Upper Peninsula iron mining industry alive.

Copper Ore

Michigan's famous Keweenawan Copper District in the Upper Peninsula (Figure Michigan.39) produced more than 75% of the nation's copper during the post-Civil War industrial boom, and was the largest producer of copper ore in the United States up through World War I. Douglas Houghton, Michigan's first State Geologist, initially noted "copper bearing rocks" in the Keweenawan Peninsula as early as 1841, and copper mining began at Copper Harbor in 1844. The first "minerals rush" in the United States began in 1846, looking for Michigan copper, three years before the 1849 rush looking for California gold. The growth of the Upper Peninsula copper mining industry led to a rapid influx of immigrant settlers from more than three

► **Figure Michigan.39** Keweenaw Copper District: Major Copper Mines and Points of Interest.



Modified from Dorr and Eschman 1970.

dozen countries, all hardy pioneers facing numerous hardships. Eventually, at the height of production, more than 100 copper companies were actively engaged in mining.

The last large native copper deposit, the Baltic lode, was discovered in 1882. Another, albeit much smaller, copper deposit, the Nonesuch Shale, would not be discovered for 80 years until the early 1960s. High grade Michigan copper ores (lodes) began to be depleted, and as newer deposits in Butte, Montana, and Bisbee, Arizona, came on line, Michigan's contribution began a steady decline. One-by-one, mining companies in the Keweenaw began to close as they were faced with declining high-grade reserves, increasing western competition and contentious labor strikes over pay and working conditions. Most Michigan copper mines were as deep as they could go and were at their economic limits by the 1950s. Only 12 companies were engaged in copper mining in the Keweenawan Peninsula by 1958, only 8 companies by 1967, and only 3 exist today. Today's copper mining industry in the Keweenaw is different. New recovery techniques have been developed and operations have shifted from mining high-grade metallic (native) copper deposits to low-grade chalcocite (copper sulphide) deposits. Today, the once bustling Keweenaw copper industry can be examined by visiting Keweenaw National Historical Park. This national park is a partnership of privately owned heritage sites, museums, memorials, and abandoned mines. The Park Service provides maps, directions, and walking tours that can be obtained at park headquarters (the old offices of the Calumet & Hecla Mining Company) in Calumet, Michigan, or 12 miles (19 kilometers) away at the Quincy Mine unit in Hancock, Michigan.

Although native copper occurs in other parts of the world, nowhere else does it occur in the quantities found in the Upper Peninsula of Michigan. Native copper has been by far the most important ore from an historical mining perspective. Native copper is primarily found in late Precambrian rocks of the Keweenawan Series, and in particular, the Portage Lake Lava Series (approximately 1.2 billion years old). These rocks crop out in a belt roughly 100 miles (160 kilometers) long extending along the western edge of the Keweenawan Peninsula, from its northeastern tip, toward the southwest, and extending through the Porcupine Mountains into Wisconsin. Over 95% of Michigan's native copper has been mined from a zone 26 miles long (42 kilometers) within this belt (mostly within Houghton County).

These rocks dip at angles between 15 to 90 degrees to the northwest, forming the eastern flank of a large regional syncline located beneath Lake Superior. Dips are reversed to the east where the west flank of the syncline crops out on the other side of Lake Superior in Minnesota. The syncline is asymmetric, with the deepest potion of the syncline containing the thickest section of rocks situated approximately 20 miles (32 kilometers) offshore from Michigan under Lake Superior. The tilted strata have been truncated and eroded, exposing Precambrian rocks at the surface.

The middle of the Keweenawan Series includes almost 400 individual basaltic lava flows overlain by 20 to 30 interbedded conglomerate and sandstone layers. These rock layers acted as traps for copper-rich, hydrothermal waters coming up from below. Copper precipitated from these waters as they cooled, forming three main types of native (metallic) copper deposits.

Amygdaloidal copper lodes formed within vesicles (voids) in the upper portions of the individual basaltic lava flows as native copper and other minerals were deposited from the hydrothermal waters. Much of the native copper mined in the Keweenawan Peninsula is the amygdaloidal lode type, being produced from such famous mines as the Kearsarge, Baltic, Pewabic, Osceola, Isle Royale, and Atlantic mines.

Conglomerate lodes formed when copper-rich hydrothermal waters were trapped in conglomerate and sandstone units where they **pinchout**. This copper precipitation fills the openings around the pebbles and sand grains with native copper. The Calumet & Hecla red conglomerate lode produced 40% of all the native copper mined from the Keweenawan Copper District up until 1929. Amygdaloidal and conglomerate lodes parallel the dipping strata, so mines simply follow the lode along the dipping bed, becoming deeper the farther they go. The Calumet & Hecla conglomerate lode was mined for 10,000 feet along the inclined bed, eventually reaching 6,000 feet below the surface, before becoming uneconomic to mine any farther. Throughout the Keweenawan District, one can still see abandoned, mine shaft-houses with their inclined roofs oriented toward the northwest. This roof angle parallels the rock layers which the mine shafts follow at depth.

Vein or fissure lodes, the third type, contain native copper deposited in fractures and fissures that cut across the various Keweenawan Series rock layers. Although the total native copper production from vein and fissure type lodes was relatively small, individual masses of copper from these lodes could often be very large.

Glaciers advanced and retreated throughout the Keweenawan area many times, the latest beginning approximately 35,000 years ago. Native copper, being malleable, was easily ripped from the exposed Precambrian vein and fissure lodes by the glaciers, carried farther south, and eventually deposited along with the other glacial debris throughout the Great Lakes region. These scattered individual pieces of copper are known as "float copper."

Early Native Americans moved into the Great Lakes Basin shortly after the last glaciers retreated, approximately 10,000 years ago. They were the first to find and use these loose pieces of float copper for ornaments, tools, and weapons. Two excellent examples of float copper are on display in the state of Michigan. The largest piece ever recovered in Michigan is a 17-ton (15,422-kilogram) specimen recovered from the bottom of Lake Superior. It is currently on display at Michigan Technological University's Seaman Mineral Museum (the official mineral museum for the state of Michigan) located at the Quincy Mine in Hancock, Michigan. The third largest piece recovered is a 2,240-pound (1.21-ton, 1,016-kilogram) piece. It is called "The Michigan Copper Erratic" because it is shaped similarly to the state of Michigan, and is on display outside the Geosciences Department (Rood Hall) on the campus of

▶ **Figure Michigan.40** The 1.12-ton "Michigan Copper Erratic" at Western Michigan University. Discovered by Brian Schulze in Lake Superior in 45-feet water depth, 1 mile offshore of Eagle River, Michigan. Recovered from the Great Lakes Bottomlands in 2006 by Brian and Paula Schulze, Don and Katie Anderson, and Ben, Kristie and Bella Bigari. On loan from the State of Michigan, Michigan Department of Natural Resources.

Photograph by Linda Harrison.

Western Michigan University in Kalamazoo, Michigan (Figure Michigan.40).

Early Native Americans were also the first to find the original vein and fissure copper deposits exposed at the surface in the Precambrian bedrock, swept clean by the glaciers, and to begin mining these deposits. These early inhabitants discovered all but two of the native copper deposits that would eventually become the giant mining enterprises of Michigan's Keweenawan Copper District.

Native copper from Michigan played a critical role in the industrialization and growth of the United States. It became available in quantity just when the electrical industry first began to grow, and Michigan copper made possible the rapid electrification of the country.

As production of Michigan's native copper ended, large reserves of non-metallic, lower-grade chalcocite were mined. The White Pine Copper Company mined chalcocite in Ontonagon County, just east of the Porcupine Mountains and 6 miles (10 kilometers) south of Lake Superior. This chalcocite occurs as finely disseminated copper sulphide within the Nonesuch Shale. The Nonesuch Shale is a Late Keweenawan Series deposit (latest Precambrian) overlying the red sandstones, Copper Harbor or "Outer" Conglomerate, and the Portage Lake lava flows that contain the native copper deposits. Minor amounts of finely divided native copper are associated with the chalcocite. Although the Nonesuch Shale is more than 600 feet thick, chalcocite only occurs in the basal 20–25 feet (6– 7.6 meters) of the unit in sufficient concentrations to be profitably mined. Mining operations for chalcocite in Michigan were suspended in 1995.

Halite and Other Evaporitic Minerals

Thick deposits of Upper Silurian evaporite deposits occur in the central Michigan Basin. These Salina salts have been mined for more than a century. Much of the early exploratory well drilling in Michigan was in the search for various types of salt deposits. The area around Detroit and neighboring Windsor, Ontario, Canada, have underground, room and pillar mines that dig coarse rock salt for winter ice control and other industrial purposes. Solution mining of the salts is common deeper in the basin and is the primary industrial raw material for many major industries in Michigan. Dow Chemical Company began in Michigan as a producer of bleach, using the chlorine extracted from salt. It also produced potassium, bromine, and magnesium, key ingredients in many industrial chemicals and some fertilizers. Not only is the Salina salt mined for industrial chemicals, but it is a common source for food grade salt. Much of the common table salt we use comes from the mining of ancient salt deposits.

Gypsum and anhydrite are calcium sulfate minerals also formed during the evaporation of seawater. Although nowhere nearly as abundant as halite, these sulfate minerals occur in significant commercial quantities. Gypsum has been mined in Michigan in underground room and pillar mines near Grand Rapids and in open pit mines near the town of Alabaster near Lake Huron. Gypsum is the primary ingredient in drywall construction materials and plaster. It is also an important ingredient in some health and beauty products and is sometimes used as a food additive. It can be an important source of dietary calcium.

Limestone and Dolostone

Limestone and dolostone are mined from Silurian, Devonian, and Mississippian formations at locations where these layers outcrop or are near the surface beneath shallow glacial deposits. Much of the limestone is used in the manufacture of Portland cement. Additionally, limestone and dolostone are used extensively as soil amendments in agriculture. Michigan's crushed stone industry relies heavily on limestone and dolostone for industrial products from cement aggregate and pharmaceutical additives to large blocks for controlling shoreline erosion. Most of the quarries are located near the Great Lakes shoreline because of proximity to the outcrop and for ease of shipping.

Sand and Gravel Mining

Because of the thick deposits of Pleistocene glacial sediments that cover much of the surface of Michigan, these unconsolidated layers of sand, gravel, and clay are widely mined as a local resource. Much of the mined material is used for industrial and construction purposes. Many local concrete plants are sited at or near these gravel pits. Material for construction fill and landscape design also often comes from the quarries. The quality and particle size of the gravel varies considerably. Some of the aggregate is locally derived, as the glaciers excavated much of the local bedrock and incorporated it into the deposits. This local material is from the outcropping sedimentary rocks throughout the basin. Sandstone, limestone, dolomite, and shale fragments are frequently incorporated into these deposits and may be useful in tracking the travel paths of some glacial lobes. Heavy mineral grains in the sand-sized fraction of the sediment have also been used as indicators of the source terranes from which these glacial lobes collected sediments. There is also a significant component of crystalline igneous and metamorphic rock that was derived from Precambrian basement rocks exposed in the Canadian Shield and the western Upper Peninsula.

Michigan.7
Oil, Gas, and Coal Resources

More than 50,000 oil and/or natural gas wells have been drilled in Michigan since 1925 (Figure Michigan.41). Michigan ranks sixteenth in the nation for oil and gas production, having produced a cumulative 1.248 billion **barrels of oil** and 6.591 trillion cubic feet of natural gas (Figure Michigan.42), and also provides the largest natural gas storage capacity of any state. More than 8,000 Michigan residents are employed in the oil and gas industry, and as of 2004, this industry was responsible for about 2 billion dollars of yearly economic activity.

Early Discoveries: Oil Springs

Figure Michigan.41 shows the locations of important early oil fields discussed in the following section. Oil was first discovered in the Michigan Basin 20 miles (32 kilometers) east of Port Huron, Michigan, across the U.S.-Canada border, in what is today Oil Springs, Ontario. Here, in 1851, Charles and Henry Tripp began digging in the “gum beds,” where the Devonian Dundee Formation crops out at the surface and the hydrocarbons within the unit have **biodegraded** to gooey asphalt. They were the first to commercially sell petroleum, all before Col. Edwin Drake drilled “the first oil well” at Titusville, Pennsylvania, in 1859.

Discovery of oil at Oil Springs, Ontario, pointed the way, and between 1886 and 1898, small quantities of oil and gas were discovered in the Port Huron, Michigan, area. The Port Huron Field had 21 wells each producing less than 10 barrels of oil a day by 1910. The field was eventually abandoned in 1921.

Often, companies drilling for brine (for salt production) noted small flows of oil and gas as they drilled through various formations. These companies were only interested in brine, so oil and gas was a curse rather than a blessing, amounting to little more than a drilling and brine production problem.

Saginaw Field: East Side of the Michigan Basin

Michigan’s first commercial natural gas well began production in 1911, but it was not until 1925 that truly commercial quantities of oil and gas would be found. James C. Graves, formerly a chemist with Dow Chemical Company, was one of the first to be successful in this venture. While drilling on Saginaw city-owned property known as Deindorfer Woods, on August 29, 1925, Graves’ new company struck oil. Although the well production rates were only 6–13 barrels of oil per day, they were enough to be commercial, and more importantly, attractive to many other out-of-state speculators. The oil business in Michigan took off.

Muskegon Field: West Side of the Michigan Basin

Numerous test wells were drilled between 1925 and 1927, with minimal results. Then, on December 8, 1927, the Reeths 1 well being drilled four miles north of Muskegon, in western Michigan, by Dixie Oil Company (a Standard Oil of Indiana subsidiary), encountered natural gas in the Traverse Formation at 1,640 feet (500 meters). The well was deepened to 1,700 feet (518 meters) where it started to flow oil, eventually reaching a rate of 330 barrels per day. Muskegon became an oil boomtown overnight, and the Michigan oil industry became a solid reality.

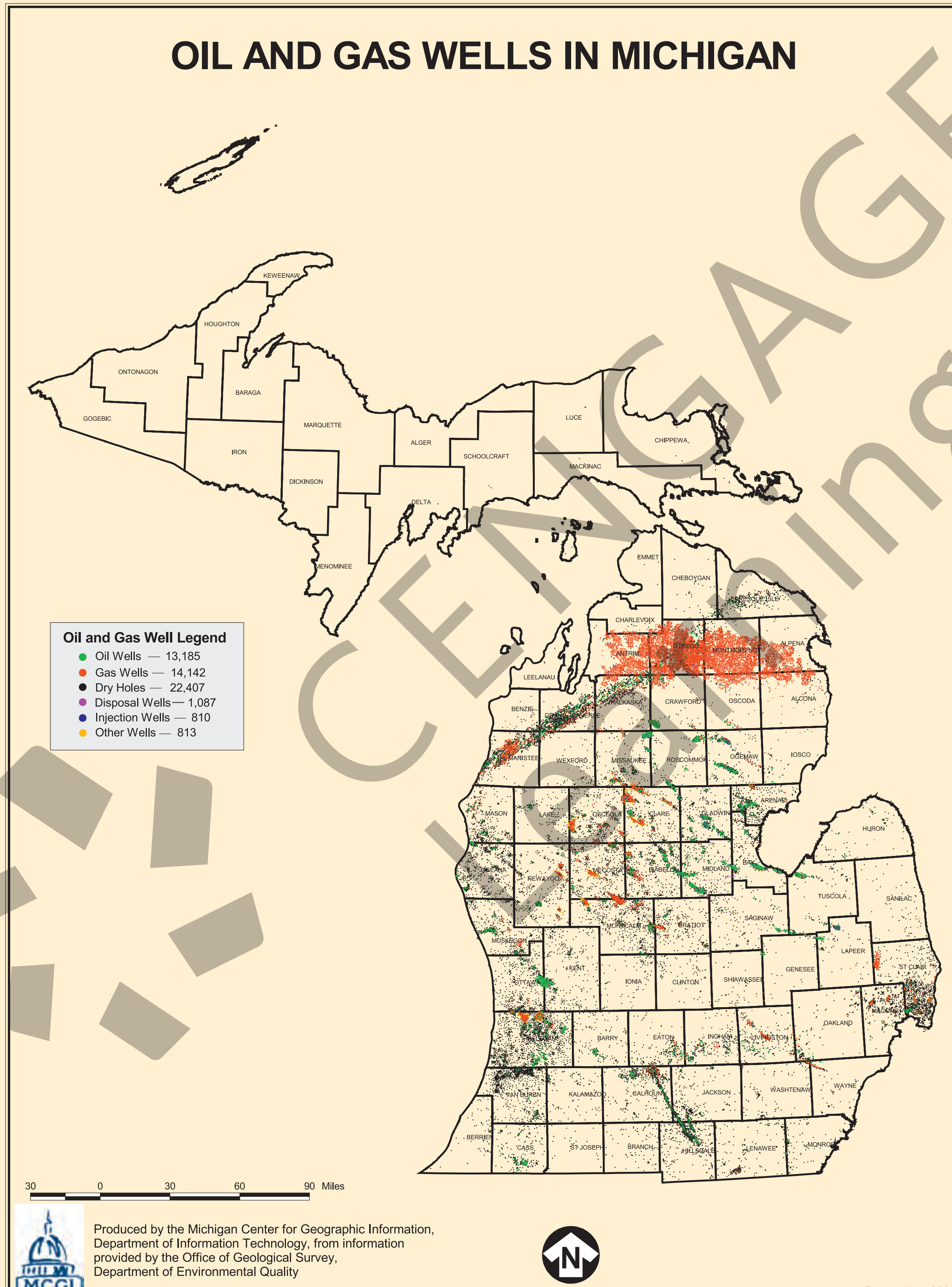
Mt. Pleasant Field: Center of the Michigan Basin

Besides the Saginaw and Muskegon Fields, nine more fields were discovered in Michigan during the 1920s. The most important of these was the Mt. Pleasant Field. Both the Saginaw and Muskegon Field discoveries are located along the flanks of the Michigan Basin. The Mt. Pleasant Field, located in the middle of the state, proved that oil was also present in the center of the Michigan Basin, and that oil and gas were prospective throughout the entire basin. The Pure Root #1 discovery well found 50–60 feet (15–18 meters) of oil sand at 3,554 feet (1,083 meters), making it the richest Michigan strike of the decade. The city of Mt. Pleasant rapidly expanded as the field grew, and oil field supply and service companies opened shop. Nearby refineries were constructed to handle the field’s output. Mt. Pleasant quickly became the predominant hub of the oil business in Michigan.

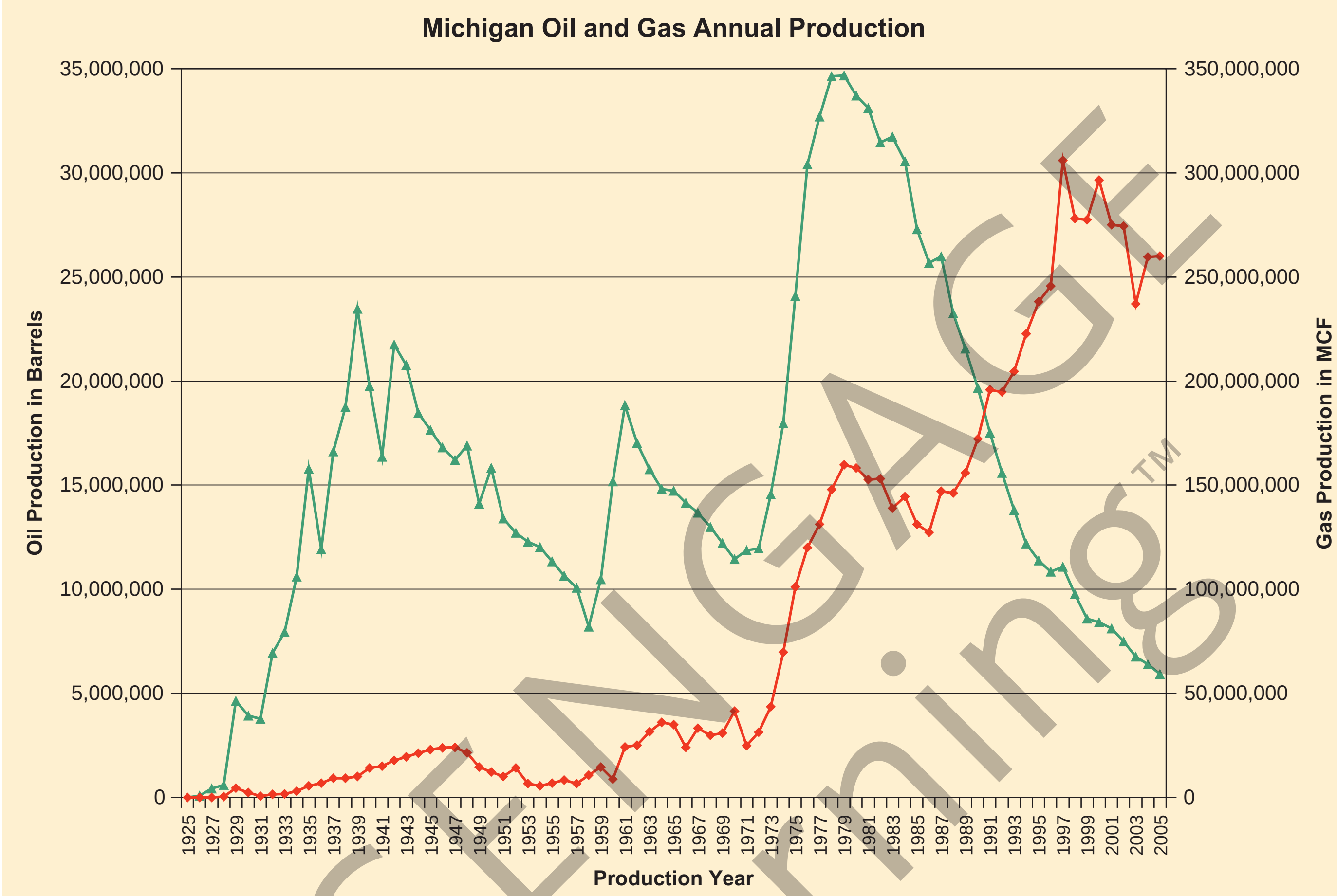
Bloomingdale Field

The sleepy village of Bloomingdale, in Van Buren County, 20 miles (32 kilometers) west of Kalamazoo, was originally a lumber center. That all changed during the last week of July, 1938, when the independent oil company Fischer-McCall brought in their Wiggins Estate #1 well from the Traverse limestone. Bloomingdale exploded as people rushed to buy leases and begin drilling. Eventually 437 wells would be drilled in the field. Wells were placed as close as possible to each other. One example shows 45 wells being located on only 80 acres of land, all in individuals’ backyards within the town limits. The field produced more than 10 million barrels of oil, but could have produced more if the reservoir had been managed properly by spacing out the drilling and limiting production. Development at Bloomingdale was so fierce and frantic, that for once, both state regulators and oilmen

▶ **Figure Michigan.41** Michigan Oil and Gas Fields.



▶ **Figure Michigan.42** Oil and Gas Annual Production (1928–2005) by Major Reservoir.



Compiled by W. B. Harrison, III.

alike agreed that legislation was needed to control drilling activity. This resulted in fundamental state legislation being enacted in 1939 that still regulates the Michigan oil industry to this day. Minimum well spacing rules and prorationing (limiting daily output to preserve reservoir dynamics) are the two most important legacies of Bloomingdale.

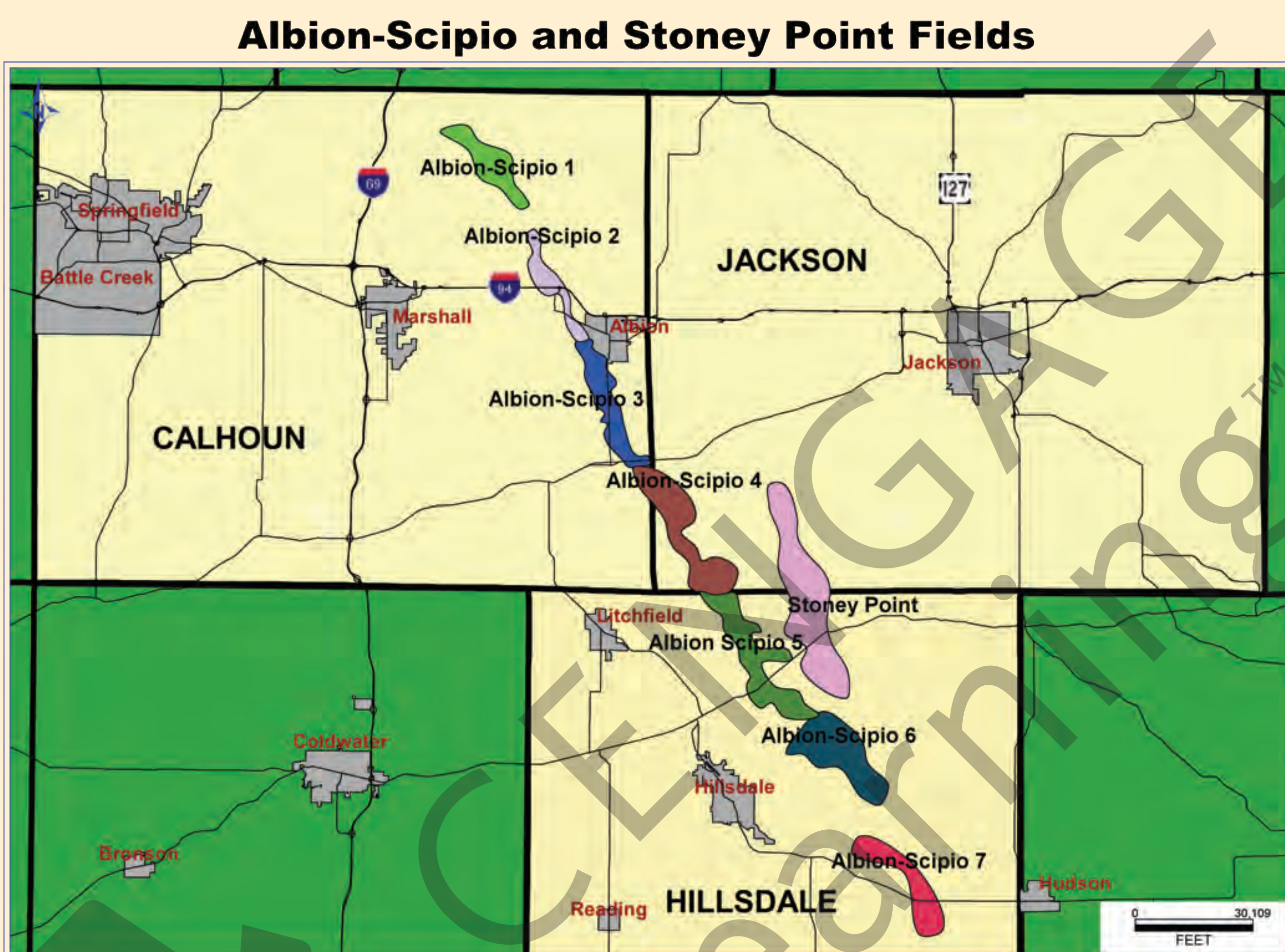
Albion-Pulaski-Scipio Trend

The Albion-Pulaski-Scipio Trend is Michigan's only "giant" oil field (>100 million barrels of oil). It is composed of a series of fields oriented northwest-southeast through south-central Michigan. The trend extends nearly 30 miles (48 kilometers) in length, being very long and linear, but extends only a mile to a mile and a half (1.6–2.4 kilometers), at most, in width (Figure Michigan.43). This linear shape is dictated by deep-seated basement **wrench faulting** and fracturing, which in turned has controlled the pattern of secondary **dolomitization** and reservoir development of the limestone bedrock. Both structural and stratigraphic influences control the distribution of hydrocarbons throughout the trend. Structurally, the field is characterized by a gentle syncline (up to 60 feet [18 meters] of sag) cutting through a region of nearly uniform north-northeast dipping rocks.

Ordovician-age Trenton and Black River limestones and dolomites form the hydrocarbon reservoir within the trend. The Trenton and Black River Formations are generally observed to be dense limestones throughout the region. However, within the trend, these limestones have been altered to secondary dolomite, primarily due to hydrothermal fluids circulating through fractured rocks along the wrench fault system. This secondary dolomitic alteration creates the porosity necessary to develop the reservoir (Figure Michigan.44). Unaltered regional limestone forms the lateral seal, with a combination of unaltered limestone, cap dolomite (20–30 feet [6–9 meters] thick), and overlying Utica Shale forming the vertical seal.

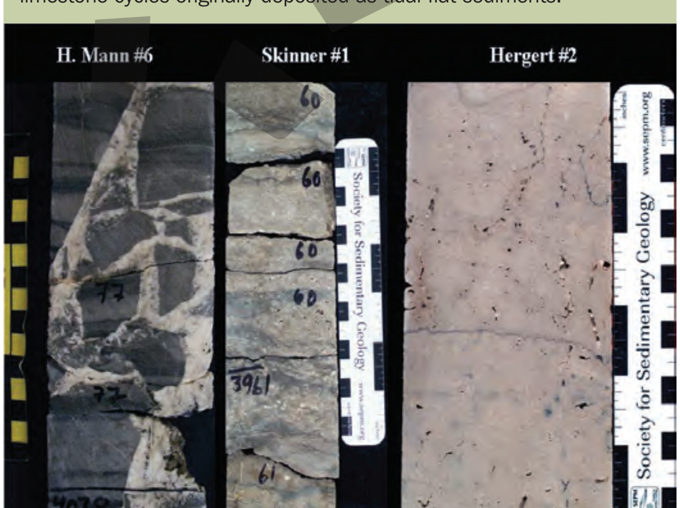
The Scipio Field, the southern portion of the trend, was discovered first, largely through the determination of Ferne Houseknecht, on whose farm in Scipio Township, Hillsdale County, Michigan, the discovery well is located. Based on information conveyed to her by a family friend and psychic, "Ma" Zulah Larkin, Ferne hired a driller, C.A. "Cliff" Perry to drill a well on her property at the spot foretold by the fortune teller. Oil was struck at 3,776 feet (1,151 meters) in the Trenton Formation on January 7, 1957, at 4:00 p.m. The discovery well (Houseknecht #1) was deepened to 3,900 feet (1,189 meters) in the Black River Formation, and tested

▶ **Figure Michigan.43** Albion-Scipio Trend: Discovered 1957. There were 320 producing wells in the field by the early 1960s. The trend comprises more than 14,500 acres and is 35 miles long and 1 mile wide. Original oil at this location was calculated to be 290 million barrels. So far, the trend has produced 125 million barrels of oil and 230 billion cubic feet of gas. The locations of the Mann #6, Skinner #1, and Hergert #2 wells are noted. Core samples from these wells are shown in Figure Michigan.48.



Map by Amanda Wahr.

▶ **Figure Michigan.44** Albion-Scipio Trend: Lithological variation observed in cores. Left, Mann #6 (4,078 feet), dolomite filled fractures. Center, Skinner #1 (3,959.6–3,962.9 feet), stacked limestone cycles created by storm deposits. Right, Hergert #2 (3,970 feet), limestone cycles originally deposited as tidal flat sediments.



Photographs by Robb Gillespie.

150 barrels of oil per day with considerable gas, before finally being officially completed July 1, 1957.

The outline of the trend began to take shape between 1959 and 1960 as new discoveries occurred along a straight line between the original Albion and Scipio wells. It was becoming obvious that the Scipio Field was actually part of one long, interconnected trend of fields related to some type of linear fault system. The synclinal sag over the top of the trend was also recognized by workers early on, and due to the incredible drilling success, this became known as the "Golden Gulch."

Rapid development of the entire Albion-Pulaski-Scipio Trend continued throughout 1960. Approximately 320 wells were completed and producing by January 1961. Through 1986, there were 330 Trenton wells in Albion and 631 in Scipio (including **dry holes**). There were a total of 961 wells drilled in the trend by January 1986, 573 of which were producing. It would not be until 1982 that a "look-alike," the Stoney Point Field 5 miles (8 kilometers) to the east, would be discovered.

Silurian Niagaran Reef Trends

The 1970s began with Albion-Scipio drilling winding down. However, extension of the field to the northwest accidentally crossed the subsurface belt of Silurian reefs that nearly encircles the Basin. Several wells penetrated productive reefs on the way down to the Ordovician Trenton-Black River target in Calhoun County. These discoveries would suggest a broad fairway of potential reef targets across several counties in southern Michigan. Additional expansion of exploration for Niagaran reefs throughout southern Lower Michigan continued through the 1970s, 1980s, and 1990s westward into Oakland, Livingston, Ingham, Eaton, and Calhoun Counties. More than 330 individual reefs are now known from all the counties in southern Michigan. However, most are much smaller than the initial ones discovered in St. Clair County. Many of the newer fields are only one-well fields, but often produce hundreds of thousands of barrels of oil and associated gas per well. The Southern Niagaran Reef Trend covers eight counties from St. Clair to Calhoun. Cumulative production from the Southern Reef Trend exceeds 100 million barrels of oil and 400 billion cubic feet of gas.

A few discoveries of Silurian reefs in northern and western Lower Michigan in the early 1950s and again in 1969 confirmed that these reefs could also be found in other regions of the basin. Development of the northern part of the basin for Silurian reefs began in earnest in 1970 with several reef discoveries in Grand Traverse, Kalkaska, and Otsego Counties. Drilling in these counties, along with Manistee County discoveries in the mid-1970s, would dominate the Michigan exploration scene for the next 20 years. The northern and western portions of the Silurian reef trend would far surpass the southern part. It contains nearly 800 known reefs in parts of 13 counties from Presque Isle in the northwest to Ottawa on the west side of the Michigan Basin. Cumulative production from the Northern Reef Trend exceeds 325 million barrels of oil and nearly 2 trillion cubic feet of gas.

The 1970s saw the rapid expansion of drilling and field discovery in Northern Lower Michigan Silurian reefs, with nearly 500 new fields discovered during the decade. About 130 new fields were also discovered in the Southern Reef Trend in the 1970s. The decade of the 1970s produced around 225 million barrels of oil and almost 874 billion cubic feet of gas. Most of this production was from the Niagaran reefs. Niagaran reef exploration and development continued at a strong pace through the 1980s, with more than 360 additional fields discovered in the Northern and Southern Trends. The 1980s hold the record for total hydrocarbon production, with more than 238 million barrels of oil produced and an additional 1.4 trillion cubic feet of gas. In fact, the most oil and gas productive 10-year period in Michigan history was from 1975 to 1984. Each year during that time had over 24 million barrels of oil and averaged over 136 billion cubic feet of gas per year. Again most of the production was associated with Niagaran reef fields.

Although the 1970s and 1980s were dominated by the Niagaran reef play, several other noteworthy events occurred. The deepest hole ever drilled in Michigan **spudded** in North Star Township of Gratiot County in spring of 1974 and was not completed until October of 1975. It reached a total depth of 17,466 feet (5,327 meters) in a basalt dike that cut through a Precambrian section of red beds that were more than 5,000 feet (1,525 meters) thick. Although declared a dry hole as an oil and gas well, the McClure-Sparks, Eckelberger, Whightsil, et al. 1-8 well proved to be an important scientific test. Information derived from the well data and associated seismic, gravity, and magnetic surveys led to a much better understanding of central Michigan Basin deep structure. Analysis of this data demonstrated the existence of a failed crustal rift system in the late Precambrian that extended from the Upper Peninsula to southeastern Michigan (Fowler and Kuenzi 1978).

St. Peter Sandstone Play

Drilling deeper in the Michigan Basin gained a lot of additional momentum in 1980 with the completion of the Dart-Edwards 1-36 well in Reeder Township of Missaukee County as a discovery of natural gas in the Ordovician, St. Peter Sandstone. The St. Peter Sandstone (a.k.a. Prairie du Chien or PdC) is the geologically oldest and deepest zone of hydrocarbon production in Michigan. There are approximately 75 fields in the St. Peter Sandstone in Michigan that have produced over 800 billion cubic feet of gas.

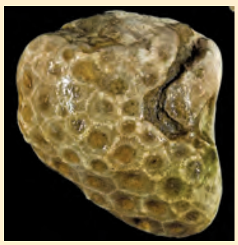
Antrim Shale Play

The late 1980s also saw dramatic growth in gas production from the shallow Devonian Antrim black shale. Although production from the Antrim Shale was known for decades, it was not considered a serious zone of commercial production. During the 1970s and 1980s, when thousands of wells were drilled in northern Lower Michigan for Niagaran reefs, each of these wells exhibited strong **gas shows** during drilling through the Antrim Shale. These shows were considered "nuisance shows" by most operators until the Niagaran reef production began significant declines and a few operators began novel completion and processing of the Antrim Shale gas reserves. Two major problems in Antrim gas production had kept most operators from trying this play. First, considerable amounts of formation water is produced initially with the gas. It was not uncommon to see a barrel of water produced for every thousand cubic feet of gas (1 MCF). Second, the maximum rate of gas production was often less than 100 MCF per day. Michigan operators were used to having gas wells that produced thousands or even tens of thousands of MCF of gas per day. The high cost of water disposal and low volume of gas production seemed to make the Antrim Shale a marginal or even uneconomic gas play.

A few operators decided on a different approach to producing the Antrim Shale gas. Instead of completing and producing individual wells as had previously been common practice, Antrim operators decided to drill multiple wells in an area and connect them to a central processing facility to process the gas. A single water disposal well was drilled to a

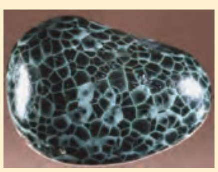
Figure Michigan.45 State Geological Symbols.

Michigan State Geological Symbols



State Stone

In 1965, the **PETOSKEY STONE** (*Hexagonaria pericarnata*) was adopted as the state stone. The Petoskey stone is fossilized coral that existed in the northern Lower Peninsula about 350 million years ago. (Photo by Linda Harrison)



State Gem

In 1972, **CHLORASTROLITE** (literally "green star stone") was adopted as the state gem. Known as the Isle Royale greenstone, Chlorastrolite ranges in color from yellow-green to almost black. It is primarily found in the Upper Peninsula. (Photo by John Jaszczak)

State Fossil

In 2002, the **MASTODON** (*Mammut americanum*) became the state fossil. Fossils of the prehistoric mammal have been found in more than 250 locations in the state. (http://www.copyrightexpired.com/earlyimage/bones/large/display_shubert_mastodon.htm)

State Soil

In 1990, **KALKASKA SAND** was chosen as the state soil. First identified as a soil type in 1927, Kalkaska sand ranges in color from black to yellowish brown. It is one of more than 500 soils found in the state. Unique to Michigan, Kalkaska sand covers nearly a million acres in 29 Upper and Lower Peninsula counties. (http://www.earthscape.org/t2/scr01/scr01db.html)

Compiled by W. B. Harrison, III.

deeper formation, often Traverse or Dundee, and the water from all the wells in that project was disposed in one well. Dozens of Antrim gas wells could now be handled by a single disposal well. The produced gas was then piped to another processing facility to remove CO_2 and other impurities present in the natural gas. Gas from hundreds, sometimes thousands, of wells was treated at the gas processing facilities that were owned by Michigan gas utilities that purchased the gas. This economy of scale proved profitable for the operators.

Throughout the 1990s and into the 2000s, the drilling and production of Antrim shale wells has dominated the Michigan oil and gas scene. Seventy-five to ninety percent of the wells drilled in Michigan during this most recent 15-year period have been Antrim wells. During this time of Antrim peak production, over 8,000 commercial wells have been drilled in 9 counties in northern Lower Michigan. The play area extending from Alpena to Manistee Counties has produced over 2.5 trillion cubic feet of gas, making it the most prolific gas zone in the Basin. The Antrim gas has been determined to be primarily the result of microbial (biogenic) activity with minor contribution of **thermogenic gas** from deeper in the basin (Martini et al. 1996, 1998).

Today, Michigan's oil and gas industry is still vibrant, active and contributing to the economy of the state. Table 1 highlights some of the fundamental statistics related to the current and historic production of oil and gas in Michigan.

In addition to geology impacting oil, gas, minerals and other geological materials that provide economic benefit to the State of Michigan, tourism, a huge economic industry, is also impacted by geology. The geology of various parks and recreation areas create much of the beauty and interest that attracts millions of people to the Michigan outdoors every year. Table 2 is a selected list of some of the parks and their geologic highlights

Table Michigan.1 Chart of Oil and Gas Statistics.

Michigan's Oil and Gas Industry Statistics	
Production from Counties	64 of 68 Lower Peninsula Counties
Cumulative Historic Production	Oil—1,258,641,000 barrels; Gas—7,063,692,000 MCF (2006)
2006 Annual Production	Oil—5,694,934 barrels; Gas—174,432,506 MCF (2006)
Total wells drilled (since 1925)	Oil—14,794; Gas—13,081; Dry holes—21,173 (2006)
Michigan's Rank among 33 Oil and Gas States	Population—10.1 million; Rank—8th (2006) Gross Domestic Product—$381 Billion; Rank—9th (2006) Market Value of Agricultural Products—$3.8 Billion; Rank—22nd (2002) Oil Production—5,350,000 barrels; Rank—18th (2006) Gas Production—257,404,000 MCF; Rank—12th (2005)
Estimated Oil and Gas Value	Oil—$345,892,066 (2006 data @$60.73/barrel); Gas—$1,306,815,891 (2006 data @$7.49/MCF)
Michigan State Taxes and Fees	Severance Tax—$78,238,469; Fees—$7,268,425 (2006)
Oil and Gas Consumption	Oil—197,383,000 barrels; 2.6% of U.S. total (2004) Gas—914,107,000 MCF; 4.1% of U.S. total (2005)
Consumption vs. Production	Oil—Michigan produces about 2.7% of Oil consumed Gas—Michigan produces about 28.2% of Gas consumed

MCF = thousand cubic feet of natural gas, a standard unit of measure.
A Barrel of Oil = 42 U.S. Gallons

The above information was compiled by William B. Harrison, III from:
1. Michigan State Energy Profile from U.S. Energy Information Administration http://tonto.eia.doe.gov/state/state_energy_profiles.cfm?sid=MI
2. Michigan Oil and Gas Association online http://www.michiganoilandgasassociation.org/News/ExplorationProduction.htm

Prepared by W. B. Harrison, III.

Table Michigan.2 Selected Michigan State and National Parks: Geologic Significance.

Geological Significance of Selected Michigan Area Parks

State Parks	County	Near-by Cities	Geological Significance
Upper Peninsula **www.michigandnr.com/parksandtrails**			
Porcupine Mountains Wilderness (Porkies)	Ontonagon	Ontonagon, Silver City	Designated Wilderness
Tahquamenon	Chippewa	Paradise	Large Falls, Wetlands and Peat Areas
Laughing Whitefish Falls Scenic Site	Alger	Sundell	Impressive Falls
Lower Peninsula **www.michigandnr.com/parksandtrails**			
Petoskey	Emmet	Petoskey	Petoskey Stones—State Stone
Onaway (Black Lake)	Presque Isle	Onaway	Cobble Beach, Rock Outcrops
Tawas Point	Iosco	East Tawas	Large, Complex Coastal Spit
Ludington	Mason	Ludington	Shoreline Evolution, Hamlin Lake
Muskegon	Muskegon	Muskegon	Lake Michigan Beach, Dunes
P.J. Hoffmaster	Muskegon	Muskegon	**Gillette Sand Dune Visitor Center**
Yankee Springs	Barry	Middleville	Glacial Outwash, Kettle Lakes
Fort Custer Recreation Area (Eagle Lake)	Kalamazoo	Battle Creek, Augusta	Moraines, Outwash, Kettle Lakes
Waterloo Recreation Area	Jackson	Chelsea	**Gerald E. Eddy Discovery Center**
National Sites **www.nps.gov**			
Sleeping Bear Dunes National Lakeshore	Leelanau	Glen Arbor, Empire	Moraines, Pearched Dunes, Beach
Pictured Rocks National Lakeshore	Schoolcraft	Munising, Grand Marais	Lake Superior Cliffs, Beaches, Dunes
Keweenaw National Historical Park	Houghton	Calumet, Hancock	Copper Mines (Quincy Mine)
Isle Royal National Park	Houghton	Houghton	Glacial Erosional Landscape

Compiled by Robb Gillespie.

Review Workbook

ESSENTIAL QUESTIONS SUMMARY

Michigan and Great Lakes.1 Introduction

■ *Why is the geology of Michigan important to students of physical geology and to all the inhabitants of the state today?*
Learning about the geology of Michigan helps students understand the principles of physical and historical geology. This understanding helps all residents appreciate the role the mineral wealth of Michigan has played in the state's economic and sociological development. Residents will be better equipped to interact with the landscape and utilize and manage resources in an ongoing, responsible manner.

Michigan and Great Lakes.2 Precambrian and Paleozoic Geology

■ *What is the structural pattern of the sedimentary rock layers of the Michigan Lower Peninsula that makes it a basin?*
All sedimentary rock layers dip toward the center of the Lower Peninsula from every direction. This creates a pattern similar to a series of stacked bowls representing each rock formation.

■ *What are the various regional structural or geologic elements that define the margins of the Michigan Basin?*
The Canadian Shield is the northern boundary, the Wisconsin/Kankakee Arch is to the southwest, and the Findlay Algonquin Arch is to the southeast.

■ *What are the ranges of ages for sedimentary rocks in Michigan's Lower Peninsula?*
Sedimentary rocks range in age from Cambrian to Jurassic.

■ *Describe the main geologic differences in rock in Michigan's Eastern and Western Upper Peninsula.*
Eastern Upper Peninsula rocks are part of the sedimentary rocks of the Michigan Basin, ranging in age from Cambrian to Lower Devonian. Rocks of the Western Upper Peninsula are Precambrian-age igneous, metamorphic, and metasedimentary.

Michigan and Great Lakes.3 Quaternary Geology

■ *What were the main controlling factors during formation of the Great Lakes basins?*
Glacial erosion was the main agent that created the Great Lakes basins. Bedrock type and outcrop pattern were also important factors. Glacial deposition created much of the landscape in Michigan's Lower Peninsula.

■ *When was the last glacial (Wisconsinan) event?*
The Wisconsinan glacial event began approximately 65–79 ka. Retreat began about 18 ka, and the last of the Great Lakes basins was ice-free by 9 ka.

■ *Where did erosional and depositional glacial landscapes develop in the Great Lakes watershed?*
Erosional landscapes include the Upper Peninsula of Michigan and the Canadian Shield to the north. The Lower Peninsula of Michigan is typified by glacial depositional landscapes.

■ *What types of depositional landforms are found throughout Michigan?*
Kames, kame terraces, eskers, and ice-channel fillings are indicative of ice-contact, outwash deposition. Outwash plains and valley trains, pitted outwash plains, kettles, and kettle lakes are indicative of deposition near the ice, but farther removed from the immediate ice front.

■ *What types of modern-day coastal features are currently evolving along Michigan's shorelines?*
Shoreline features are in a constant state of evolution. Beaches, sand dunes, beach ridges, hooked spits, and mid-bay and bay mouth bars are the main features found along Michigan's current shorelines.

■ *How did the inland lakes in Michigan form?*
Most of the numerous inland lakes in Michigan formed as glacial kettle lakes associated with pitted outwash plains. Some of the more northern lakes in the state (e.g., Burt and Mullet Lakes) were scoured out by glacial erosion. A few lakes along the present-day shoreline formed as hooked spits and bay mouth bars isolated estuaries along the coastline.

Michigan and Great Lakes.4 Modern-Day Geologic Processes

■ *What are the two main types of shoreline found around the Great Lakes in Michigan?*
Erosional and depositional shorelines.

■ *Name three processes that reshape the Michigan shoreline and a depositional feature produced by each process.*
Dropping lake levels produce beach ridges, wind produces sand dunes, and longshore currents produce hooked spits and bay mouth bars.

Michigan and Great Lakes.5 Geology of Water Resources

■ *What are the two types of geologic materials that contain groundwater in Michigan?*
Potable groundwater is contained in unconsolidated glacial deposits and consolidated sedimentary bedrock.

Michigan and Great Lakes.6 Mineral Resources

■ *What is "banded iron formation" (BIF)?*
BIFs are alternating layers of chert and iron oxide. They are a primary source of iron ore.

■ *What are the main types of copper ore?*
High-grade native copper ore forms as either amygdaloidal, conglomeritic, or vein copper. These were the principle types of ore mined up until the 1950s. Chalcocite (copper sulphide) is a low-grade copper ore that is mined today.

■ *Name some of the other non-metallic mineral resources produced in Michigan.*
Limestone, dolostone, gypsum, salt, magnesium, bromine, and sand and gravel.

Michigan and Great Lakes.7 Oil, Gas, and Coal Resources

■ *When and where was oil first discovered in the Michigan Basin?*
Oil was first discovered in the Michigan Basin at Oil Springs, Ontario, in 1851, eight years before Drake discovered oil in Pennsylvania.

■ *What was the significance of discovering oil at the Saginaw, Muskegon, and Mt. Pleasant Fields?*
The Saginaw discovery proved oil was present along the eastern flank of the Michigan Basin. The Muskegon discovery proved oil was present along the western flank. The discovery of oil at Mt. Pleasant, located in the center of the basin, proved the entire Michigan Basin was oil prospective.

■ *What geologic factors controlled the ultimate shape and size of the Albion-Scipio Field?*
Deep-seated basement wrench-faulting fractured the overlying Paleozoic limestones. Hydrothermal fluids followed these fractures and altered the adjacent rocks into porous dolomites that could then contain oil. The size and shape of the field primarily developed in response to the fault pattern, and secondarily to the development of porous dolomites.

■ *What oil and gas exploration and development plays were important in Michigan in the 1970s and 1980s? In the 1990s and 2000s?*
The Silurian Niagaran Reefs and the St. Peter Sandstone were important in the 1970s and 1980s. The Antrim Shale was important from the 1990s to the present day.

ESSENTIAL TERMS TO KNOW

Amygdaloidal A rock containing amygdules. Amygdules are gas cavities or vesicles in an igneous rock, which are filled with such secondary minerals as calcite, quartz, chalcedony, or a zeolite.

Banded iron formation (BIF) Sedimentary rocks made up of thin alternating bans of silica (chert) and iron minerals (mostly hematite and magnetite).

Barrels of oil Used in the petroleum industry, a volumetric unit of measurement equivalent to 42 U.S. gallons (158.76 liters).

Beach ridge A low, essentially continuous mound of beach or beach-and-dune material (sand, gravel, shingle) heaped up by the action of waves and currents on the backshore of the beach beyond the present limit of storm waves or the reach of ordinary tides, and occurring singly or as one series of approximately parallel deposits. The ridges are roughly parallel to the shoreline and represent successive positions of an advancing shoreline.

Biodegrade Subject to decomposition by microorganisms.

Conjugate joints A joint system, the sets of which are related in deformational origin, usually compression.

Core A relatively undisturbed, vertical section of rock or soil collected in a core barrel or tube.

Diamicton A general term for the nonlithified equivalent of a glacial till.

Dry hole The universal term in the petroleum industry for an unsuccessful well (i.e., one that does not produce oil or gas in commercial quantities).

Escarpment A long, more or less continuous cliff or relatively steep slope facing in one general direction, breaking the continuity of the land by separating two level or gently sloping surfaces, and produced by erosion or by faulting.

Euxinic Pertaining to an environment of restricted circulation and stagnant or anaerobic bottom conditions, such as a fjord or a nearly isolated or silled basin with toxic bottom waters. Also pertaining to the material (such as black organic sediments and hydrogen-sulfide muds) deposited in such an environment or basin, and to the process of deposition of such material.

Foredune A coastal dune or dune ridge oriented parallel to the shoreline, occurring at the landward margin of the beach, along the shoreward face of a beach ridge, or at the landward limit of the highest tide, and more or less completely stabilized by vegetation.

Gas show A term used in the oil and gas industry to indicate when natural gas is encountered by drilling and appears in the drilling fluids.

Glacial drift A collective term for all sediment deposited directly by glacial ice (till) and by meltwater streams (outwash).

Glacial tunnel valley Glacially modified and buried bedrock valleys, as well as subglacial channel networks, formed at the base of continental ice sheets.

Intergranular The space between individual grains in a sedimentary rock. Often used to describe the pore space that exists between the grains (intergranular porosity).

Interstade A warmer substage of a glacial stage, marked by a temporary retreat of the ice, a climatic episode within a glaciation during which a secondary recession or a still-stand of glaciers took place.

Intracratonic Said to be "on top of" a craton area.

Kame Conical hill of stratified drift originally deposited in a depression on a glacier's surface.

Kame terrace A terrace-like ridge consisting of stratified sand and gravel formed as a glaciofluvial of glaciomarine deposit between a melting glacier or a stagnant ice lobe and a higher valley wall or lateral moraine, and left standing after the disappearance of the ice. A kame terrace terminates a short distance downstream from the terminal moraine; it is commonly pitted with kettles and has an irregular ice-contact slope.

Kettle (kettle hole), kettle lake A steep-sided, usually basin- or bowl-shaped hole or depression, commonly without surface drainage, in glacial-drift deposits (especially outwash and kame fields), often containing a lake or swamp; formed by the melting of a large, detached block of stagnant ice (left behind by a retreating glacier) that had been wholly or partly buried in the glacial drift. Kettles range in depth from about a meter to tens of meters, and in diameter to as much as 13 kilometers.

Laurentide ice sheet A major continental glacier that at its maximum, completely covered North America east of the Rockies from the Arctic Ocean to a line passing through the vicinity of New York, Cincinnati, St. Louis, Kansas City, and the Dakotas.

Lineaments A linear topographic feature of regional extent that is believed to reflect crustal structure. Examples are fault lines, aligned volcanoes, and straight stream courses.

Lithologies, lithostratigraphic unit A body of rock, such as a formation, defined solely by its physical attributes.

Longshore current A current resulting from wave refraction found between the breaker zone and a beach that flows parallel to the shoreline.

Megabreccia A coarse breccia that contains individual blocks as long as 400 meters that developed downslope from large thrusts or collapses that accumulate from gravitational sliding.

Metasediments Sediment or a sedimentary rock that shows evidence of being subjected to metamorphism.

Metavolcanic Volcanic rocks that show evidence of being subjected to metamorphism.

Palynological A branch of science that is concerned with the study of pollen of seed plants and spores of other ebryophytic plants, living or fossil, including their dispersal and applications in stratigraphy and paleoecology.

Petroliferous Bearing crude oil or natural gas.

Pinchout To taper or narrow progressively to termination; thin out.

Pitted outwash plain An outwash plain marked by several irregular depressions such as kettles, shallow pits, and potholes.

Porous (porosity) The percentage of a material's total volume that is pore space.

Siliciclastic Clastic, non-carbonate rocks.

Smelting The process by which a metal is obtained from its ore, usually by heating beyond the melting point and ordinarily in the presence of reducing agents (e.g., coke) or oxidizing agents such as air.

Solution mining In-place dissolution of water-soluble mineral components of an ore deposit by permitting a leaching solution, usually aqueous, to trickle downward through the fractured ore to collection galleries at depth.

Spudded To break ground with a drilling rig at the start of well-drilling operations.

Stadial Formed during a stade, which is a substage of a glacial stage marked by glacial re-advancement.

Subaerial Conditions and processes, such as erosion, that operate in the open air on or adjacent to the land surface or materials situated on the land surface.

Subcrop An area within which a formation occurs directly beneath an unconformity.

Terrane A block of rock with characteristics different from those of the surrounding rocks. Terranes probably represent seamounts, oceanic rises, and other seafloor features that accreted to continents during orogenies.

Terrestrial red bed deposits Sedimentary rocks, mostly sandstones and shales, with red color due to the presence of iron oxides.

Thermogenic gas Natural gas that is formed by the thermal maturation of sedimentary organic matter and which occurs at relatively deep depths.

Transgressive The spread or extension of the sea over land areas.

Valley train A long, narrow deposit of stratified drift confined within a glacial valley.

Wireline log A graphic record of the measured or computed physical characteristics of the rock section encountered in a well, plotted as a continuous function of depth.

Wrench faulting A lateral fault in which the fault surface is more or less vertical.

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REFERENCES AND ADDITIONAL READING

Catacosinos, P. A., P. A. Daniels, Jr., and W. B. Harrison, III. 1991. Structure, stratigraphy and petroleum geology of the Michigan Basin. In Interior cratonic basins, edited by M. W. Leighton, D. R. Kolata, D. F. Oltz, and J. J. Eidel. AAPG Memoir 51:561–602.

Catacosinos, P. A., W. B. Harrison, III, R. F. Reynolds, D. B. Westjohn, and M. S. Wollensack. 2001. Stratigraphic lexicon for Michigan. Michigan Geological Survey Bulletin 8, Department of Environmental Quality and Michigan Basin Geological Society, 56 pp.

Catacosinos, P. A., W. B. Harrison, III, R. F. Reynolds, D. B. Westjohn, and M. S. Wollensack. 2000. Stratigraphic nomenclature for Michigan. Michigan Department of Environmental Quality, Geological Survey Division, 1 sheet. <http://www.deq.state.mi.us/documents/deq-gsd-info-geology-Stratigraphic.pdf> Accessed April 16, 2007.

Cross, A. T. 1998. The Ionia Formation: New designation for the Mid-Jurassic age “red beds” of the Michigan Basin [abstract]. AAPG Bulletin 82:1766.

Dorr, J. A., and Eschman, D. F. 1970. *Geology of Michigan.* Ann Arbor, MI: University of Michigan Press, 476 pp.

Fisher, J. H., M. W. Barratt, J. B. Droste, and R. H. Shaver. 1988. Michigan Basin. In Sedimentary cover—North American craton, U.S., The Geology of North America, v. D-2, edited by L. L. Sloss. Boulder, Colorado: Geological Society of America, pp. 361–82.

Fowler, J. H. and W. D. Kuenzi. 1978. Keweenawan turbidites in Michigan (deep borehole red beds): A foundered basin sequence developed during evolution of a proto-oceanic rift system. *Journal of Geophysical Research* 83, no. 12:5833–43.

Kozlowski, A. L., A. E. Kehew, and B. C. Bird. 2005. Outburst flood origin of the Central Kalamazoo River Valley, Michigan, USA. *Quaternary Science Reviews* 24:2354–74.

Larson, G. J., Lowell, T. V., and Ostrom N. E., 1994. Evidence for the Two Creeks interstade in the Lake Huron basin: Canadian Journal of Earth Sciences, V. 31, pp. 793–797

Larson, G. and R. Schaetzl. 2001. Review—Origin and evolution of the Great Lakes. *Journal for Great Lakes Research* 27, no. 4:518–46.

Marshak, S. 2005. *Earth, portrait of a planet*, 2nd. ed. W. W. Norton and Co., Inc., Castle House, 75/76 Wells St., London W1T 3QT, Figure 22.39, p. 710.

Martini, A. M., J. M. Budai, L. M. Walter, and M. Schoell. 1996. Microbial generation of economic accumulations of methane within a shallow organic-rich shale. *Nature* 383:155–58.

Martini, A. M., L. M. Walter, J. M. Budai, T. C. W. Ku, C. Kaiser, and M. Schoell. 1998. Genetic and temporal relations between formation waters and biogenic methane: Upper Devonian Antrim Shale, Michigan Basin, USA. *Geochimica et Cosmochimica Acta* 62, n. 10:1699–720.

Monroe, J. S., R. Wicander, and R. Hazlett. 2007. *Physical geology—Exploring the earth*, 6th ed. Thomson Brooks/Cole—Thomson Higher Education, 10 Davis Dr., Belmont, CA 94002-03098, Figure 17–23 a–d, p. 556.

Sloss, L. L., 1963. Sequences in the Cratonic Interior of North America: Geological Society of America Bulletin, v. 74, pp. 93–114.

Westbrook, Jack R. 2005. A history of Michigan oil and gas—Exploration and production. Clarke Historical Library, Central Michigan University, Mt. Pleasant, Michigan, 84 p.