MESTA Summer Field Trip 2022

The Michigan Basin in the Eastern Upper Peninsula

August 1st – 4th

Field trip led by Peter Voice PhD

The Bluffs at Fayette State Historic Park

MICHIGAN EARTH SCIENCE TEACHERS ASSOCIATION

Contents

Introduction

The Michigan Basin and the Paleozoic Earth

The Following discussion is summarized from Gillespie et al. (2008) and LoDuca (2009).

The Michigan Basin is an intracratonic basin. A basin is a topographic low on the crust where sediment can be deposited. Intracratonic means that the basin is in the interior of the craton, where the craton is the old, stable portion of the continent. In terms of areal extent (Figure 1), the Michigan Basin underlies the entirety of the Lower Peninsula as well as portions of the eastern Upper Peninsula, eastern Wisconsin, northeastern Illinois, northern Indiana, northern Ohio, and the western side of Peninsular Ontario. It also then underlies Lakes Michigan, Lake Huron, and the western portion of Lake Erie.

Figure 1: Map of the Michigan Basin. Refer to the key in the upper left for the ages of the sediments. From Gillespie et al. (2008).

Our best estimate is that the Michigan Basin became a basin sometime in the later part of the Ordovician Period as a far-field effect of the stresses caused by the collision of the Taconic Island Arc during the Taconic Orogeny. Prior to the Taconic Orogeny, Michigan likely had two major depo-centers – one in the eastern Upper Peninsula and a second in the Lower Peninsula. These depo-centers were separated by a ridge which was the remnants of the Northern Michigan Highlands, a mountain range that had formed during the Precambrian because of a series of Orogenies. By the Middle Ordovician, these mountains had worn down by weathering and erosion. During the collision of the Taconic Island Arc, stresses propagated through the crust causing gentle warping of the crust into lows and highs. Adjacent to the collisional zone, a low developed forming the trough of the Appalachian Basin. The

Appalachian Basin is separated from the Michigan Basin by crustal highs, the Cincinnati and Algonquin Arches (Figure 1). The Algonquin Arch today forms the spine of Peninsular Ontario – to the northwest sediments of the Michigan Basin onlap it, while to the southeast sediments of the Appalachian basin onlap it. On the south side of the Michigan Basin is the Kankakee Arch in northern Indiana and northeastern Illinois. The western margin is composed of the Wisconsin Arch. These arches separate the Michigan Basin from the Illinois Basin (to the south) and the Forest City Basin (to the west underlying Iowa).

Each subsequent orogenic event on the east coast of North America propagated compressional stresses through the crust deepening the Michigan Basin each time. In addition, the weight of the sediments deposited in the basin acted as loading agents also causing subsidence as the topographic low was slowly filled in during the intervals between orogenies. The Devonian Acadian Orogeny was caused by the collision of small microplates (Avalonia and the Carolina Slate Belt) on the eastern margin of North America. A third orogeny, the Alleghanian Orogeny, occurred during the Carboniferous and included the collision of the African margin of the supercontinent Gondwanaland colliding with the eastern margin. All three orogenies resulted in the uplift of the Appalachian Mountains – which then served as the source of enormous amounts of clastic sediments from weathering and erosion. We see pulses of clay and silt come into the Michigan Basin over the arches as these orogenies proceeded.

North America (or Laurentia as the geologists call the continent during the Early Paleozoic) was positioned near the equator during the time interval that we are interested in. This influenced the climatic conditions that North America experienced this time – and the climatic conditions controlled the types of sediment that were laid down in the Michigan Basin. We will look at a brief history of North America in the next few paragraphs during the Early Paleozoic.

In the late Precambrian, Laurentia rifted from the supercontinent Rodinia. Rodinia was a long-lasting supercontinent that was assembled approximately 1.1-1.0 billion years ago. It started to break up between 800 and 700 million years ago. At the start of the Cambrian, 540 million years ago, Laurentia was tectonically quiet, and the continent's margins were all passive margins. In Michigan, there were two distinct depocenters – one in the eastern Upper Peninsula and the other in the Lower Peninsula. Both depocenters were sites of accumulation of clastic sediments, mostly sand. These deposits accumulated in a set of environments that included alluvial fans along the highlands, braided streams systems, sand dunes, and shallow marine shelves. In the terrestrial environments, the dominant life were microbes. In the shallow marine shelves, paleontologists have found early trilobites, inarticulate and articulate brachiopods, and the eel-like conodonts. They also observe burrows in the marine deposits, showing that some animals were digging into the seafloor for food resources or shelter.

During the Late Precambrian, the world experienced a series of severe glaciations. These glaciations ended at roughly 600 million years ago, and as the world warmed up the ice sheets melted back and sea level rose. This sea level rise continued through the Middle Ordovician, covering much of Laurentia with shallow seas. The tropical setting combined with the shallow seas led to the formation of tropical marine environments like mud banks, reefs, and tidal flats where carbonate sediments (now limestone or dolostone) could accumulate. The oceans had a diverse faunal assemblage dominated by animals like brachiopods, trilobites, crinoids (sea lilies), and tabulate and rugose corals. Some of the earliest fish were also present. The dominant predators included cephalopods (nautiloids) and sea scorpions (eurypterids).

The global climate started to cool off during the Late Ordovician as the world entered into another glaciation. This glaciation was not as drastic as the Late Precambrian glaciations, with ice sheets building to significant size in Gondwanaland which was positioned over the southern pole. In Laurentia, the glaciation's primary influence was on sea level. During glaciations, colder phases are characterized by larger volumes of water stored on land as glacial ice causing sea level to drop, while warmer phases are characterized by melting back of the glaciers and the release of meltwater back to oceans causing sea level rise. This sequence of regressions and transgressions due to climatic swings influenced the deposition of sediments. During transgressions, we see deeper water deposits in the Michigan Basin, while during regressions we see either shallower water deposits or even unconformities. This change in climate was also coincident with the Taconic Orogeny. The collision of the Taconic Island Arc with the eastern margin of North America crumpled the margin into the Taconic Mountains (the first phase of construction of the Appalachian Mountains). The position of the Taconic Mountains influenced the local climatic conditions in Laurentia, likely developing a monsoon system similar to the modern Himalayas. The intense amounts of rainfall led to weathering and erosion of the Taconic Mountains which shed sediment into the adjacent Appalachian Basin. The sheer volume of fine-grained sediment generated led to pulses of sediment that overtopped the Algonquin and Cincinnati Arches and were then deposited in the adjacent Michigan and Illinois Basins as well! The Late Ordovician in the Michigan Basin is characterized by thick deposits of shale, argillaceous limestone, and limey shale. The combination of cooling climate and locally the abundant fine-grained sediments impact the organisms living in the region. Many of the prominent organisms that lived during the Paleozoic were filter feeders – filter feeding becomes a much less feasible feeding strategy when seawater is filled with sediment. The Late Ordovician, called the Hirnantian Stage, is one of the major mass extinction events recorded in our planet's history.

The Taconic Orogeny extends into the Silurian, with pulses of clastic sediments being shed into the Michigan Basin intermittently during the period. Between clastic pulses, the sediments laid down were dominantly carbonate during the Early Silurian. These limestones and dolostones were laid down in shallow marine settings including the open shelf, mudbanks, reefs, and tidal flats. The environment was likely quite amenable to life, as this interval is when the gigantic pinnacle reefs were accumulating in the Lower Peninsula – pinnacle reefs cover a couple acres but have heights up to 700 ft tall! The animals living in these environments include many of the major Paleozoic invertebrate groups such as brachiopods, bryozoans, mollusks (snails and bivalves), rugose and tabulate corals, stromatoporoids (massive sponges with a calcified internal skeleton), trilobites, and nautiloids.

During the Silurian, North America slowly shifted north into the arid tropical belt. This will have a major influence on the Michigan Basin. In the arid tropical belt, evaporation removes water from the basin. The water left behind becomes saltier and saltier over time. If we take modern seawater and evaporate it, it will produce a sequence of mineral precipitants that include:

> Calcite ($CaCO_3$) – seawater can produce this without evaporation
>
> Gypsum ($CaSO_4{\cdot}nH_2O$) – after about 40% of seawater has been evaporated, the remaining brine is concentrated enough to produce gypsum
>
> Halite (NaCl) – after 90% of the seawater is evaporated, halite (or rock salt) is precipitated

Bittern Salts – continued evaporation will produce a variety of minerals including chlorides (sylvite, KCl), bromides, magnesium salts, etc. depending on the chemistry of the brine

By the Late Silurian, the Michigan Basin was quite arid and thick deposits of dolostone, rock gypsum, and rock salt had accumulated – in some parts of the basin up to 3000 ft thick! In the central Lower Peninsula, the evaporation proceeded to the point where economic deposits of sylvite accumulated.

During the Early Devonian, the Michigan Basin experienced climatic swings that led to alternation between more humid deposits of carbonates followed by more arid deposits of rock salt. During at least one of these more humid spans, water infiltrated into the Silurian evaporite deposits in the northern basin causing dissolution and the creation of cave networks. Continued dissolution widened out the caverns until they could not be supported, and the caverns collapsed forming a significant deposit of collapse breccia in the Straits of Mackinac region.

In the eastern Upper Peninsula, our depositional history ends in the Early Devonian. In other parts of the Michigan Basin, deposition continued through the Devonian and Carboniferous Periods, followed by an interval of erosion creating an unconformity. Overlying this unconformity are deposits in the central Lower Peninsula of Jurassic sandstones (the Ionia Formation), which represents the last phase of deposition in the Michigan Basin. Post-Jurassic, the Michigan area experienced a second major phase of erosion leading to the formation of a second big unconformity. The next interval of deposition was during the Pleistocene Epoch, when the Laurentide ice sheet covered Michigan – the melting of the glacial ice deposited thick deposits of sediment (till and outwash) across the region.

The Topography of the Eastern Upper Peninsula

The underlying bedrock has a strong influence on the topography of the eastern Upper Peninsula. We will see two sets of rock units that have proven to be resistant to weathering – the Cambrian Escarpment and the Niagara Escarpment. The Cambrian Escarpment is best observed in the Pictured Rocks National Lakeshore – the cliffs along the shoreline of Lake Superior. These cliffs are composed of sandstones and a capping sandy dolomite of the Munising and Au Train Formations. The Niagara Escarpment is present along the Lake Michigan shoreline from the Garden Peninsula across to Drummond Island. The Niagara Escarpment is a significant topographic feature that not only is present in the Upper Peninsula but also includes:

1) The Door Peninsula of Wisconsin and much of the shoreline along eastern Wisconsin
2) The bedrock beneath Chicago, as well as northeastern Illinois, northern Indiana, and northern Ohio
3) The spine of Manitoulin Island and the Bruce Peninsula – which partially close off Georgian Bay in Ontario
4) The bedrock at Niagara Falls over which the Niagara River flows over (though technically, this portion of the escarpment is part of the Appalachian Basin system instead of the Michigan Basin – the rocks are similar thought)

Let’s look at the Cambrian Escarpment first. The Cambrian Escarpment is technically a cuesta. Cuestas are hills formed from dipping layers of rock. They are characterized by a gentle slope which parallels the dip of the layers and a steep slope that cuts across the layering. In the eastern Upper Peninsula, rivers that drain to Lake Superior flow across the Cambrian escarpment – because they are then flowing over a cuesta, these rivers are characterized by waterfalls. The Upper Falls of the Tahquamenon River, Munising Falls, Miners Falls, Wagner Falls, Laughing Whitefish Falls, etc. are all examples of waterfalls where the river flows over the steep portion of the cuesta. The Lower Falls of the Tahquamenon River and Au Train Falls are examples where the escarpment is further inland from the Lake Superior shore and the river flows over smaller drops. The smaller drops are controlled by a combination of bedding planes and fractures that yield a step-like pattern to the falls. The rivers draining to Lake Superior tend to be relatively faster moving, higher gradient, shorter rivers.

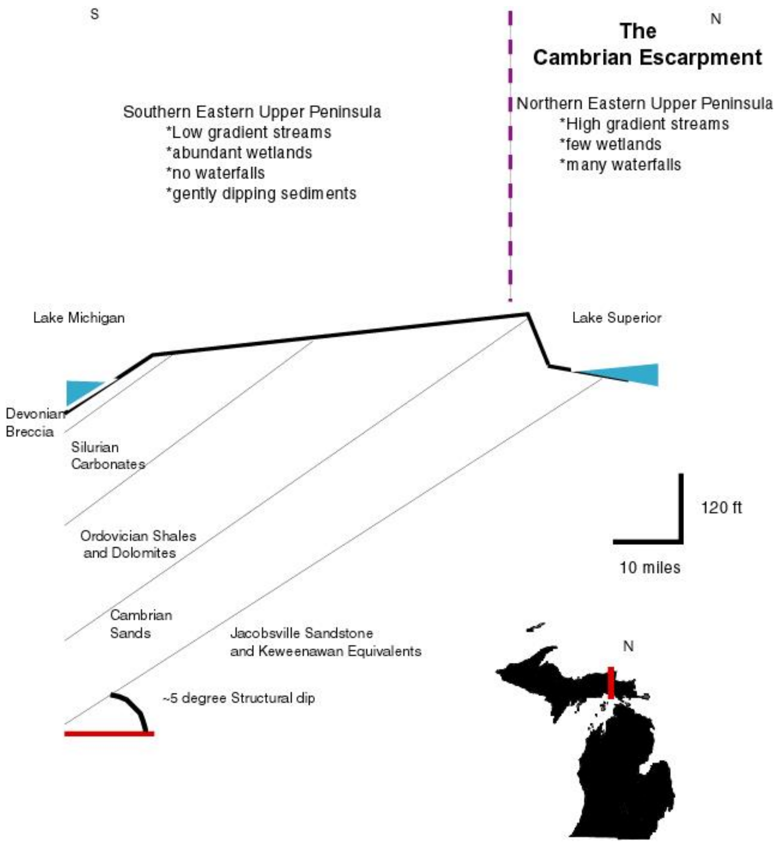


Figure 2: Diagrammatic cross section of the eastern Upper Peninsula showing the dipping layers of the basin sediments to the south and the Cambrian Escarpment on the southern shore of Lake Superior (from Voice and Harrison, 2014).

The rivers that flow south to Lakes Michigan and Huron tend to be slower, lower gradient rivers usually without waterfalls (a perusal of waterfall guidebooks to the Upper Peninsula will show that Mackinaw and Chippewa counties in the southeastern Upper Peninsula have a paucity of waterfalls!). You will also notice as you drive through this interval the large swathes of boggy terrain – much of this terrain overlies the Ordovician shales and hence the drainage is very poor over these rocks.

The Niagara Escarpment is not as prominent over much of the eastern Upper Peninsula, though when we are on the Garden Peninsula, you will see the prominent bluffs on the western side of the Peninsula at Fayette.

Superimposed on these bedrock features, are topographic features left behind by the glaciers. There are a series of glacial moraines that were left behind by the retreating glaciers 8000 to 7000 years ago.

There are also inland sand dunes that were deposited during higher lake level periods. In addition to these depositional features, the glaciers carved the landscape creating embayments between more resistant rock (figure 3). The soft shales of the upper Trenton Formation (Haymeadow Falls Member) and the Bills Creek Shale were preferentially eroded by the glaciers to form Little Bay de Noc between the resistant lower Trenton Formation along the shore by Escanaba and the more resistant mixed carbonates and shales of the Stonington Formation along the western edge of the Stonington Peninsula. Big Bay de Noc had a similar origin, as the softer shales of the Cataract Group were preferentially eroded away between the Stonington Peninsula and the Garden Peninsula.

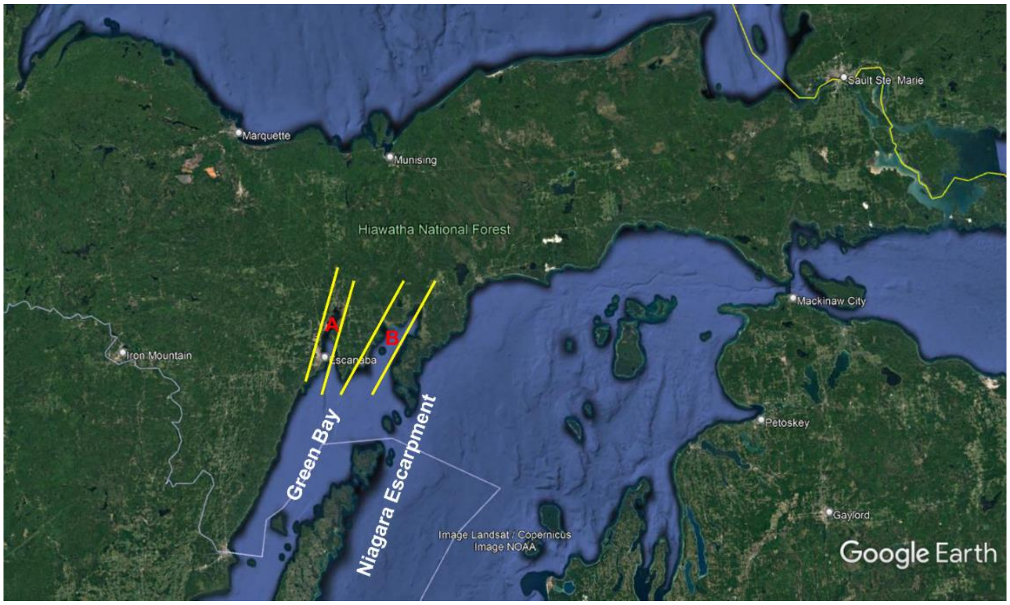


Figure 3: Satellite imagery of the Upper Peninsula showing Little Bay de Noc (labeled A) and Big Bay de Noc (labeled B). Both bays were carved by the glaciers by preferentially eroding of the softer Ordovician and Silurian shales. The peninsulas in between the bays are made up of more resistant bedrock (including the Niagara Escarpment along the Garden and Door Peninsulas). Green Bay was also formed from the preferential erosion of softer rocks.

One last element of the topography that we will explore are coastal erosional features. We will see two flavors of coastal erosion during our trip. At Pictured Rocks National Lakeshore, modern wave erosion is slowly eroding down the headlands of the Cambrian Escarpment. Waves coming into shore will wrap around headlands, directing their energy on the sides of the headlands. Any sediment carried by the water can then act like sandpaper to slowly grind down the headlands. This forms a sequence of landforms as erosion continues – sea caves, sea arches, and sea stacks (Figure 4). In front of the headland, the waves can erode a wave-cut platform and at the very base of the cliff can cut a wave-cut notch at lake level. The modern Pictured Rocks National Lakeshore has headlands that have reached the sea cave and sea arch stages in this evolution. We also will see evidence of earlier coastal erosion events during higher lake stands – one such higher lake stand event was the Nipissing event approximately 6000 to 3500 years ago. During this event, beach terraces and wave-cut platforms were carved into bedrock around the margins of the Great Lakes and headland erosion occurred along Lakes Huron and Superior. This headland erosion proceeded to the sea stack phase – several of these features are preserved elevated above the current shoreline by isostatic rebound (a rise in the ground surface as a response to the removal of the large mass of glacial ice that had artificially depressed the land surface).

On Mackinac Island, you can visit Arch rock, a beautiful sea arch. Around St. Ignace, there are several sea stacks, including Castle Rock and St. Anthony's Rock.

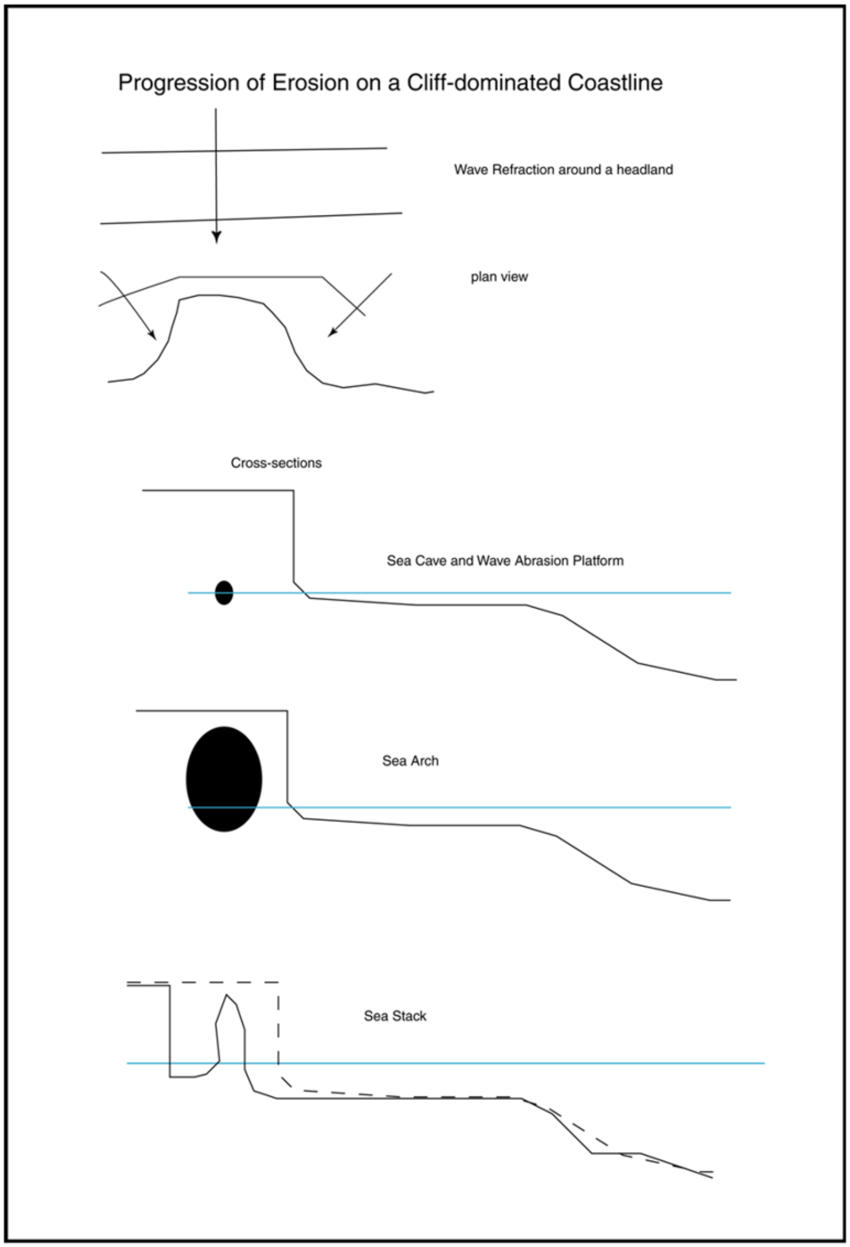


Figure 4: When waves come into shore near a headland, wave refraction wraps those waves around the sides of the headlands directing the wave energy onto the sides. Sediment carried by the waves erodes the rock of the headland forming initially a sea cave. Eventually the cave will go through the entire headland – then erosion will widen out the sides and ceiling of the cave to form a sea arch. Finally, after erosion has removed much of the support for the ceiling, it will collapse and leave an isolated pillar of rock away from the headland called a sea stack.

A Primer on Lithostratigraphy and Stratigraphic Nomenclature

Geologists use several distinct basic units when describing the Earth's geology and natural history. These units were developed by early geologists like William Smith when they were figuring out how to make sense of the rock record. William Smith and the Baron Georges Cuvier independently developed two methods to break the rock record up into manageable parts: lithostratigraphy and biostratigraphy.

Lithostratigraphy – the identification of rock units, their description, and their correlation to other rock units. Lithostratigraphy relies entirely on the physical characteristics of the rocks such as composition, grain texture (size, roundness, sorting), sedimentary structures and layering, and other features of the rock to identify unique rock strata. William Smith and others proposed that these unique strata if mappable across a region should be classified into rock units. The basic unit for mapping is the "formation". [Note you will see the word formation used in cave systems for distinctive structures usually formed from precipitation from fluids migrating through the caves like stalactites and stalagmites – this use of the word is different from the lithostratigraphic term]. A formation is a rock unit with distinctive character that can be mapped at a reasonable scale (somewhat arbitrary) across the Earth's surface and into the subsurface. There are other lithostratigraphic units – and the formation is part of a hierarchical set of rock units:

- Supergroup
  - Group
    - Formation
      - Member
        - Bed

Formations deposited under similar environmental conditions are linked together as groups. The formations in a group may have been deposited in different parts of a larger depositional environment, for example in river settings one formation may represent the finer-grained deposits of the floodplain while another formation may represent the cross-bedded, coarser deposits of the river channels. In this case, the two formations are coeval. In other cases, a group represents a cycle of sea level change – where sea level rises (or falls) sediments of one formation grade into sediments of another formation, representing a gradual change in environmental conditions in a region.

Groups can then be linked together into supergroups. A supergroup usually recognizes that the lithostratigraphic units were deposited under similar tectonic conditions. For example, in the western Upper Peninsula, the rock units filling in the midcontinent rift are composed of the Portage Lake Volcanics (a series of mostly basaltic lava flows) and the Oronto Group sediments – these two units together are part of the Keweenawan Supergroup.

At the finer scale, a formation can be divided into Members. Members represent intervals within a formation characterized by similar conditions but at a scale that is not as feasible for mapping (again this is somewhat arbitrary – as it depends on the scale to which the geologist is mapping the area). We can also discuss individual layers within a formation (or within a member of a formation) called beds – this is generally the smallest scale we would work at, usually within a single outcrop. In some cases, beds have been tracked over 100s of square miles – these beds are usually marker beds. Marker beds are layers that we can assume are the same age everywhere we see them – because they formed under very specific conditions. Types of marker beds include:

1) Volcanic ash deposits – deposits from a single eruption that took days to months to accumulate, usually downwind of the volcano.
2) Storm deposits – major hurricanes can leave behind a record of their migration through a region in the form of shell beds made up of abraded and disarticulated skeletal material. Deposited during the waning period of the storm and likely representing only a few days of sedimentation.
3) Tsunami deposits – regional deposits along the margin of a basin after a tsunami wave passes through.
4) Asteroid and meteorite ejecta layers – the fallout from an impact with the Earth can deposit significant amounts of debris (microspherules – melted crustal materials now glass; microtektites – fragments of the asteroid, etc.) across much of the Earth's surface. Sometimes these layers have significant chemical fingerprints (such as the Iridium spike in the K-T boundary deposits at the end of the Cretaceous).

Each of these lithostratigraphic units is formally named – usually using a name from a town or location in the area where the unit was first identified and described. For example, we will look at the Manistique Group, which outcrops along the Lake Michigan shoreline at the town of Manistique, hence the name of the group. Beds are usually not named unless they are well-recognized marker beds – for example there is an Ordovician ash deposit called the Deicke Bentonite which is found across a wide area of the eastern North America.

One other style of rock unit is the facies. Facies are not formally named. They are objective descriptions of the rock – a formation can be made up of 1 or more facies. A facies description includes:

1) Composition – what minerals are present
2) Grain Texture – grain size, grain rounding, grain sorting
3) Type(s) of cement and degree of cementation
4) Sedimentary structures
5) Fossils present
6) Nature of Layering – layer thickness, nature of contacts between layers (sharp, gradational, erosional)
7) Rock type (i.e., sandstone, limestone, conglomerate, etc.)
8) Nature of contact or geometric relationships with other facies

Once we have a facies description of the rock, we can use the various characteristics to infer the depositional environment of that rock.

The Baron Cuvier and William Smith also suggested that fossils could be used to infer age relationships of different rock units. The basic idea is that if these units have the same fossil species then they are the same age – relying on the idea that each fossil species has a specific temporal range. Species originate from speciation, then persist for some amount of time on the Earth before becoming extinct. Both Cuvier and Smith recognized that there was a trajectory to the fossil record – that species did not come back at some later period in time after going extinct (with the caveat that we may see an extension of the temporal range of a species as we look at slightly younger rocks more carefully). Their work led to the field of biostratigraphy – using the fossil record to constrain the age of the rock units as well as to correlate rock units from one location to another.

You will also see time units used in this guidebook. Time units were another set of geologic units developed by the early geologists as they used relative dating, lithostratigraphy and biostratigraphy to understand the Earth's rock record. Time units are the formal units used in the Geologic Time Scale (see Appendix 2). Geologic time units are hierarchical just like the units of time we use in our daily lives.

Human history time units:

- Second
  - Minute (60 seconds = 1 minute)
    - Hour (60 minutes = 1 hour)
      - Day (24 hours = 1 day)
        - Year (365.25 days = 1 year)
          - Century (100 years = 1 century)

You should note that the time units we use in our daily lives and in our discussion of Humanity's history are both hierarchical and represent very precise fractions of time. Geological time units are hierarchical but less precise:

- Supereons (billions of years)
  - Eons (hundreds of million years to a billion years)
    - Eras (hundreds of million years)
      - Periods (10s to 100s million years)
        - Epochs (1 to 10s million years)
          - Age (1000s of years to millions of years)

For example, we are currently living in the Phanerozoic Eon. The Phanerozoic Eon is made up of the Paleozoic, Mesozoic, and Cenozoic Eras – and we are currently living during the Cenozoic Era. The Cenozoic Era is made up of the Paleogene, Neogene, and Quaternary Periods. We are living during the Quaternary Period. The Quaternary period is split into the Pleistocene and Holocene epochs (though there is a push to split off part of the Holocene as the proposed Anthropocene Epoch). The modern world is called by most geologists the Holocene, while a growing minority favor splitting of the interval when humanity have been agent of geological activity (think mining, dredging harbors, mixing faunal communities, developing fires (and nuclear bombs), etc.). The lack of agreement is currently a function of when to put the lower boundary of the Anthropocene – contenders include the first use of fire (when exactly was that?), the first use of agriculture (another good question as to when this really started), 1492 AD, 1950 AD, etc. Later geologists used radiometric dating to constrain the timing of the periods and other units on the modern Geologic Time Scale.

You may also see chronostratigraphic terminology used in this guidebook. Chronostratigraphic or time-rock units were another early type of geologic unit. These units recognize that rock material represents geologic time – it took time for the sediment to accumulate or the lava to cool. Time-rock units explicitly recognize this tie – so for example, the Silurian System represents all rock units that were deposited during the Silurian Period. The main place where you will see these is when we discuss the rock records of the periods at the epoch level. A pair of examples will show how this works:

Isotelus, a genus of trilobite, has been found in the Middle and Upper Ordovician System.

Isotelus, a genus of trilobite, lived during the Middle and Late Ordovician Period.

Lower, Middle and Upper refer to stratigraphic position within a rock package of known age (chronostratigraphy). Early, Middle, and Late refer to geologic age (geochronology).

Road Log

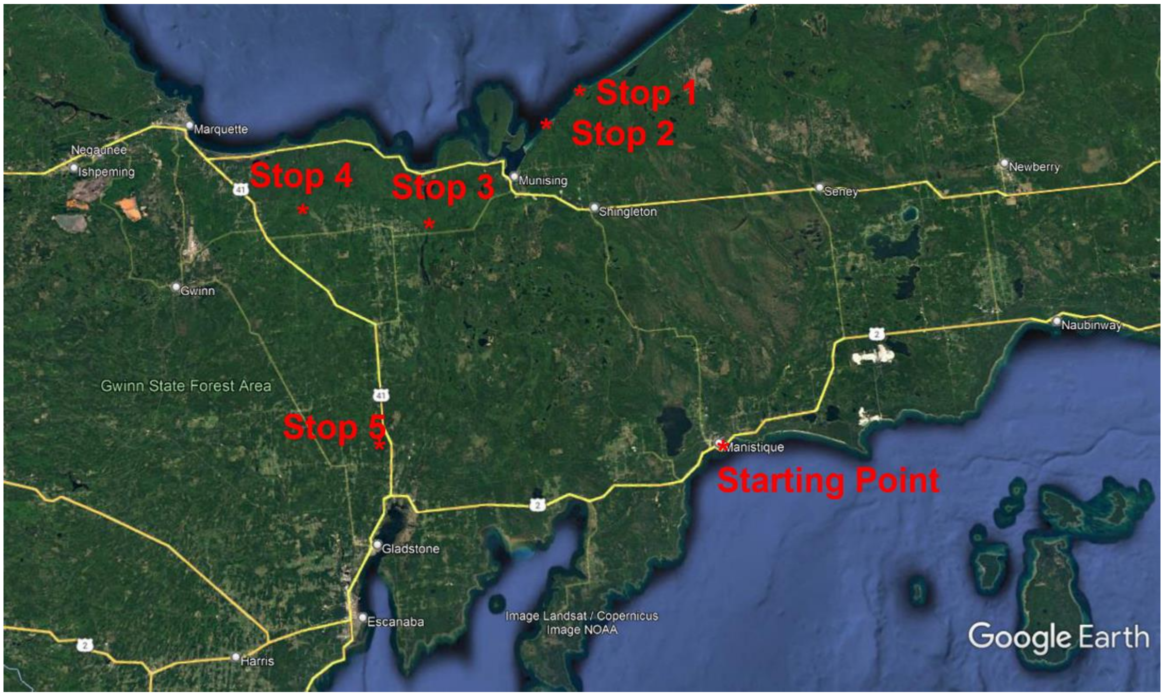
This road log will start each day from Jack's Fresh Market in Manistique. This location will serve as a good rendezvous point and a place for purchasing lunch supplies. Where possible, I have provided latitude and longitude for the stops. Stop descriptions are present later in the guidebook after the sections on the relevant bedrock geology.

August 1^{st} Log

Please note that today's stops are all in parks – please do not collect samples!

1. Turn right out of the driveway for the Jack's Fresh Market complex onto US-2.
2. Continue 0.75 miles, turn right onto Arbutus Ave/S. Maple St. at flashing light.
3. Continue 0.6 miles, turn left onto Elk St.
4. Continue 0.25 miles, veer right onto Deer St. Cross over the bridge and continue on Deer St.
5. Continue 0.9 miles, turn right onto 5^{th} St/M-94
6. Continue 33.6 miles to junction with M-28 at Shingleton. Go straight onto H-15.
7. Continue 4.9 miles to junction with H-58. Turn left.
8. Continue approximately 4 miles, turn right onto Miners Castle Rd/H-11
9. Continue 5.25 miles to **Miners Castle Visitor Center, Pictured Rocks National Lakeshore – Stop 1**. (N46°29.301', W8633.064')
10. Backtrack to H-58. Turn right.
11. Take H-58 4miles. Turn right onto Washington St.
12. Continue 0.5 miles to Munising Falls Visitor Center – turn right into Parking Lot. **Munising Falls – Stop 2**. (N46°25.424', W86°37.466')
13. Backtrack to H-58, turn right. Continue 1.25 miles to roundabout. At roundabout, continue on E. Munising/M-28 (will continue along lakeshore west, do not take M-28 to the southeast).
1. Continue 11.4 miles on M-28. Turn left onto Arbutus St/Au Train Forest Lake Road.
2. Continue 7.6 miles and turn right onto Power Dam Road/CR-533 – take to end – **Au Train Falls – Stop 3**. (N46°20.266', W86°51.183') [note Power Dam Road is the last road on the left before the junction with M-94 – so if you miss it, turn around at the junction and back track ~0.1 miles – the falls are much better marked from the south]
3. Return to Au Train Forest Lake Rd. Turn left and continue to M-94.
14. Turn right onto M-94. Continue 12.25 miles (follow M-94 signs through Chatham where the road takes two 90° turns.
15. Turn right onto 327/Sundell Rd. Continue 2.75 miles to the Laughing Whitefish Falls trailhead. – **Laughing Whitefish Falls – Stop 4**. [Note the trail is approximately 1 mile round trip to the falls. At the Falls, there is a staircase to a platform at the bottom of the Falls – 155 steps].
16. Backtrack 2.75 miles to M-94. Turn right.
17. Continue 6.4 miles to US-41. Turn left.
18. Continue 27.9 miles. Turn right onto S-15.
19. Continue 0.4 miles. Turn left into **Rapid River Falls – Stop 5**. (N46°0.1348', W86°58.936')
20. Backtrack to US-41. Turn right.
21. Continue 6.7 miles to junction with US-2. Turn left (eastbound) onto US-2.

22. Continue 39.6 miles on US-2. Turn left into Jacks Fresh Market. End of Day 1.



Map 1 – Locations of August 1st stops.

August 2nd Log

1. Turn right out of Jacks Fresh Market drive onto US-2.
2. Continue 36.4 miles west on US-2. Turn left onto C.R. 513 (note Papa Jim's Pizza is just after the intersection).
3. Continue 11 miles south on C.R. 513. Look for Lakewood Cemetery Sign on right side of road. Outcrop will be on the left. **Stonington Formation – Stop 6.** (N45°45.811', W86°58.569')
4. Continue south on C.R. 513 2.8 miles (note will pass junction with C.R. 511 after ~0.8 miles).
5. Turn right onto Swede 13 Road. Continue 0.25 miles, veering to the right into boat landing parking lot. **Stonington Formation – Stop 7**. [Note, author may give additional directions to a third Stonington outcrop if lake levels permit access and sufficient time available to visit it]
6. Return to C.R. 513. Turn left. Continue 2 miles to junction with C.R. 511.
7. Turn right onto C.R. 511. Continue 7.5 miles (note that C.R. 511 will have a right-angle turn to the north). Stop along road along hill. **Big Hill Dolomite - Stop 8**. (N45°47.007', W86°51.797')
8. Continue north on C.R. 511 5.5 miles – turn left at T-junction continuing on C.R. 511.
9. Continue 0.7 miles to junction with Township Hall X-5. Turn right on Township hall.
10. Continue 2.5 miles north to U.S. 2.
11. Turn right onto U.S. 2.
12. Continue 8.2 miles east. Turn left onto National Forest FH-13.
13. Continue 3.3 miles north. Turn right onto 28/2231.
14. Continue 2.6 miles east – **stop 9 – Cabot Head Shale**. (N45°56.682', W86°39.770')
15. Turn around and backtrack to FH-13, then to U.S. 2 (11.5 miles).
16. Turn left onto U.S. 2. Continue east 23.9 miles. Turn left onto Chippewa Ave (just before BP Station on west side of Manistique).

17. Continue 1.0 mile. Turn left onto Deer St.
18. Continue 0.4 miles. Turn right onto 5th Ave/M-94.
19. Continue 4.7 miles. Pull onto margin of road carefully beside outcrops. **<u>Stop 10 – Burnt Bluff Group at Sawheidle Quarry and roadside outcrops</u>**.
20. Carefully turn around. Backtrack 4.7 miles to junction with Deer St. [Note for groups camping at Indian Lake State Campground – instead of continuing to Jack's Fresh Market – you can turn right at the junction with Deer St. and take C.R. 442 3.7 miles to the Campground entrance on right]
21. Turn left onto Deer St.
22. Continue 0.9 miles, crossing bridge over Manistique River. Turn left onto Elk St.
23. Continue 0.2 miles. Turn right onto Maple St.
24. Continue 0.6 miles. Turn left onto US-2.
25. Continue 0.75 miles. Turn left into Jack's Fresh Market. End of Day 2.

August 3rd Log

1. Turn right out of Jack's Fresh Market onto US-2.
2. Continue 16.8 miles west on US-2. Turn left onto M-183.
3. Continue 16.4 miles south on M-183. Turn right into State Park. – stop at Visitor Center and explore **<u>Fayette State Historical Park – Stop 11</u>**. (N45°43.045', W86°40.055') <u>No collecting in Park</u>.

Map 2 – Approximate locations of August 2nd stops. Note Stop 10 is to the north of Manistique on M-94.

4. Return to Park entrance. Turn left onto M-183. Pull over at outcrops of the Byron Formation approximately 0.1 miles after Park Drive. **<u>Stop 12</u>**. ((N45°43.407', W86°38.626').
5. Continue north on M-183 3.4 miles. Pull over on side of road carefully. **<u>Outcrops of the Hendricks Formation – Stop 13</u>**. (N45°44.187', W86°37.009')

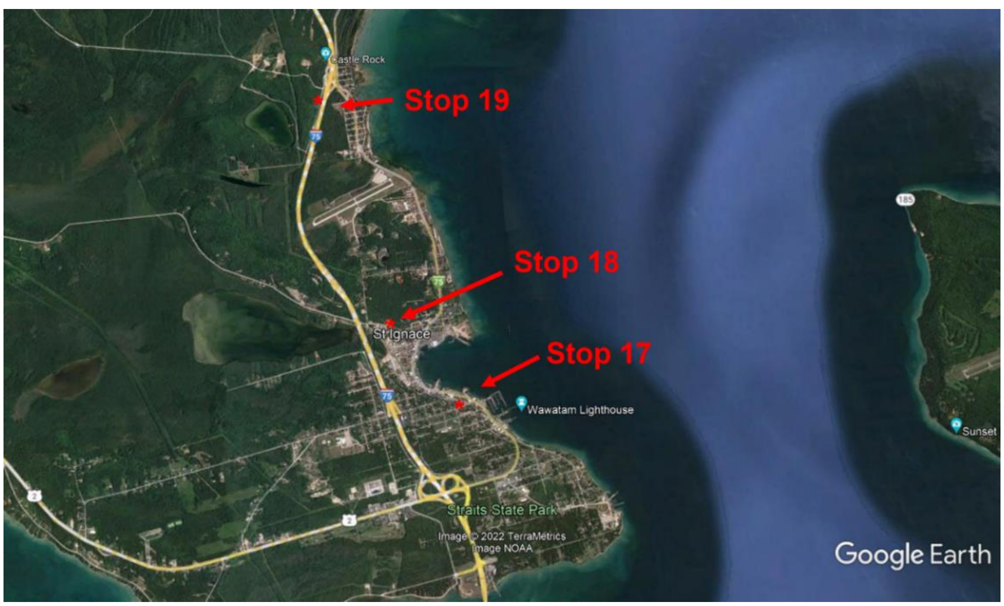
6. Continue north on M-183 12.9 miles to US-2. Approximately 0.2 miles before junction with US-2 turn left into Ozzie Hazen Park for lunch. After lunch continue to US-2 and turn right.
4. Continue 28.8 miles east on US-2 into Gulliver, MI. Turn right onto Port Inland Road/432.
5. Continue 4.25 to junction with Seul Choix Point Rd/431.
6. Turn right onto Seul Choix Point Rd/431
7. Continue 4.1 miles to Seul Choix Lighthouse – **Stop 14 Engadine Outcrops**.(N45°55.291', W85°54.784') <u>No collecting in Park.</u>
8. Return to junction with 432 (4.1 miles), turn left and continue to US-2 (4.25 miles).
9. Turn right onto US-2.
7. Continue 38.8 miles. Turn left onto Borgstrom Rd. (note if you see Garlyn Zoo, you have gone past Borgstrom Rd)
8. Continue north on Borgstrom Rd. 4.75 miles.
9. Turn right onto Hiawatha Trail. Continue 6.6 miles east.
10. Turn left onto Trout Lake Rd. Continue 1.75 miles.
11. Turn left onto Fiborn Quarry Road. Continue 2.5 miles to 2^{nd} gate and park. <u>**Fiborn Karst Preserve – Stop 15**</u>.
12. Return to Trout Lake Rd. Turn left and continue east on Trout Lake Rd.
13. Continue 7.8 miles into Trout Lake. Turn right on M-123/Trout Lake Road.
14. Continue 1.0 mile. Turn left onto Trout Lake Rd.
15. Continue approximately 8.4 miles. Turn right onto Quarry Road. Continue approximately 0.5 miles on dirt track. Park at base of hill and walk up to quarry. <u>**Scott's Quarry – Stop 16**</u>. (46°10.827'N, 84°50.154'W).
16. Return to Trout Lake Rd. Turn left.
17. Continue 8.4 miles. Turn right onto M-123/Trout Lake Rd.
18. Continue 1.0 Miles. Turn left onto Trout Lake Rd.
19. Continue 9.6 miles. Turn left onto Hiawatha Trail.
20. Continue 4.75 miles on Hiawatha Trail to Borgstrom Rd. Turn left onto Borstrom Rd.
21. Turn right onto US-2 heading west. Continue 50.6 miles
22. Turn right into Jacks Fresh Market. End of Day 3.

August 4^{th} Log

1. Turn left out of Jack's Fresh Market onto US-2.
2. Continue 87.5 miles east into downtown St. Ignace (US-2 will merge with Bus-75 – do not get onto I-75, instead stay on Bus-75 which goes into downtown St. Ignace).
10. Turn left onto Truckey Rd St (just after Thunderbird Motel).
11. Less than 0.1 mile – turn right onto Underhill St. – follow loop around parking lot (1-way) to lower level in front of St. Anthony's Rock. <u>**Stop 17 – St. Anthony's Rock**</u>. (N45°52.064', W84°43.554')
12. Return to E. Truckey Ave. following 1-way route. At E. Truckey turn left onto N. State St./Bus-I-75.
13. Continue 0.8 miles. Turn left onto Reagan St. (Sheplers' ferry will be on right).
14. Continue 0.1 miles. Turn right onto Lemotte St.
15. Continue 0.25 – pull over to right (across from Mackinaw County Animal Shelter)– **Stop 18 – Point Aux Chenes Outcrop**. (N45°52.544', W84°44.049')
16. Turn around, backtrack to N State St/Bus-I-75. Turn left.

17. Continue 2.7 miles. Turn left – note that the road splits into the on-ramp for I-75 S and W Lant Rd – veer right to stay on W. Lant.
18. Continue 0.5 miles. Find spot to turn vehicles around. Park across from outcrop **– Stop 19 – Mackinac Breccia outcrop**. (N45°54.069', W84°44.641')
19. End of Trip – can return to I-75 and continue home.

Map 3 – Approximate locations of the stops for August 3rd.



Map 4 – Approximate locations in St. Ignace for the August 4th stops.

Section 1 – Cambrian to Middle Ordovician Stratigraphy of the Michigan Basin

In the Upper Peninsula the Cambrian to Middle Ordovician Stratigraphy consists of four formations – the Munising, Au Train, and Black River-Trenton Formations. Traditionally, the Munising Formation has been assigned to the Cambrian Period, while the Au Train Formation is thought to be Middle Ordovician in age. The Au Train Dolomite is a sandy dolomite with some intervals being very rich in the mineral glauconite (a green clay). The best exposures of the Munising Formation are in the Pictured Rocks National Lake Shore and around the town of Munising. Just west of Munising, the Munising Formation bends to the southwest – and isolated outcrops are found at Felch and Quinnesec. It also outcrops in central Wisconsin with notable outcrops in the Dells and the Baraboo regions. The Au Train Dolomite outcrops along the Au Train River. It too bends to the southwest, with outcrops between Iron Mountain and Escanaba in the Hermansville area – where the Au Train Dolomite is called the Hermansville Dolomite. The Black River-Trenton Formations are an interesting set of carbonate units (limestones, dolostones, and calcareous shales) that are at times difficult to differentiate, so many workers lump them together as one unit. The Black River Formation does not outcrop well – there are small river cuts near the town of Trenary and at the Bony Falls Dam west of Escanaba. The lower Trenton Formation is usually a cleaner (and more resistant) carbonate, so more outcrops have been identified – significant outcrops include Groos Quarry in Escanaba and the Rapid River Falls north of Rapid River. The upper Trenton Formation consists of calcareous shales and muddy limestones, with the best exposure at Haymeadow Falls. Unfortunately, the author visited Haymeadow Falls during the preparation of this guidebook and found that path was not easily accessible due to the washout of a pedestrian bridge. We will look at these units in more detail below.

Munising Formation

The Munising Formation and the underlying Jacobsville Sandstone were for a long time lumped together as the “Lake Superior Sandstone” even considering the distinctly different lithologic natures of the two sandstones and the presence of a significant unconformity between the two sandstones (Hamblin, 1958). The Jacobsville Sandstone is a Precambrian aged unit, whose contact with the overlying Munising Formation can be observed at Grand Island north of Munising. Lane and Seaman (1909) proposed the Jacobsville Sandstone for the exposures in the quarries at Jacobsville, where this unit was historically mined for dimension stone. The Jacobsville Sandstone is a maroon, medium- to coarse-grained sandstone with reduction spots (giving the unit a mottled appearance – as these spots are locations where no hematite was precipitated as cement by the groundwater in low oxygen conditions after the sands were deposited) and trough cross-bedding. The age of the Jacobsville Sandstone is still debated (see Malone et al. 2016 and 2018, and Bornhorst, 2018 for conflicting views on the age). This unit was likely deposited in an environment dominated by alluvial fans and braided streams.

At the contact between the Jacobsville Sandstone and Munising Formation is a unconformity that Hamblin (1958) notes the following features that suggest the Munising Formation is younger than the Jacobsville Sandstone:

1) The Jacobsville Sandstone has a gentle dip to the north, while the Munising Formation dips to the south – making this unconformity an angular unconformity. (Cross-cutting relationships)
2) Sandstone dikes in the Jacobsville Sandstone truncate at the contact with the Munising Formation (Cross-cutting Relationships)

3) Well-rounded, pebbles and cobbles of lithified Jacobsville Sandstone are found in the basal Munising Formation (Principle of Inclusions)

The Munising Formation was also named by Lane and Seaman (1909) for the upper portion of the "Lake Superior Sandstone" exposed in the cliffs east of Munising. Hamblin (1958) did the first modern description of the Munising Formation and subdivided it into three members: Basal Conglomerate Member, Chapel Rock Sandstone, and Miners Castle Sandstone.

Basal Conglomerate Member

Haddox and Dott (1990) and Hamblin (1958) provide descriptions of the Basal Conglomerate which is summarized here. The Basal Conglomerate Member is a pebble to cobble conglomerate up to 15 feet thick overlying the Jacobsville Sandstone. The pebbles and cobbles are mostly made up of clasts of the Jacobsville Sandstone, but also includes a variety of pre-Jacobsville quartzite and chert clasts derived from the crystalline metamorphic rocks of the Marquette Range Supergroup. Clasts are well-rounded. The conglomerate is matrix-supported, meaning that the clasts float in a matrix of finer-grained sand and pebbles. Sand-dominated horizons within the conglomerate are characterized by high-angle, planar cross-bedding in sets up to 1 meter thick.

Hamblin (1958) used the cross-bedding to determine the paleocurrent directions of the braided stream system that deposited the Basal Conglomerate. The flow directions he interpreted from the cross-bedding suggest a northward flow of the rivers.

Chapel Rock Sandstone

Hamblin (1958) and Haddox and Dott (1990) described the Chapel Rock Member as a buff to white, well-sorted, medium-grained, quartz sandstone with large scale cross-stratification (Figure 5a). The Chapel Rock Member is poorly to moderately well cemented with silica and a small amount of hematite. The sand is dominated by quartz, chert, or quartzite grains. The contact between the Basal Conglomerate and the Chapel Rock Sandstone ranges from sharp to gradational.

Haddox and Dott (1990) describe four facies in the Chapel Rock Sandstone:

1) Cross-bedded sandstone – 10 to 20 m thick and is composed of well-rounded, medium- to coarse-grained, somewhat pebbly, quartz sandstone with large-scale trough cross-bedding (Figure 5B).
2) Horizontally stratified sandstone – medium-grained, quartz sands with horizontal to slightly dipping beds. Interbedded with thin shales – sands from overlying sandstone beds fill in burrow structures of *Rusophycus* and *Cruziana*. Minor cross-laminae can be present as well as both asymmetrical and symmetrical ripple marks.
3) Channelized conglomerate and intraclast breccia – volumetrically minor facies. These are lag deposits of angular to rounded pebbles and cobbles filling river channels. Clasts include both pre-Munising clasts and locally derived Munising clasts.
4) Laminated mudstones – dark gray mudstones are present as thin (up to 10 cm thick) lenses that extend up to 30 meters. Sedimentary structures present include planar and ripple cross laminations in interbedded sandstones, soft-sediment deformation structures, mud intraclasts, and mud-cracks. Trace fossils include *Planolites*, *Rusophycus*, and *Cruziana*.

Haddox and Dott (1990) inferred a depositional environment of a sandy tidal inlet or sandy delta. The majority of the paleocurrent indicators to the north and northwest – which makes a tidal inlet a less feasible interpretation (tidal inlets should show bimodal currents). A Delta consists of several parts, and I have put Haddox and Dott's (1990) facies next to the ones they match up to:

1) A river intersects the shoreline – the channel breaks up into distributary channels to form a delta (facies 2 – horizontally stratified sandstone and facies 3 – channelized conglomerates)
2) Between distributary channels are interdistributary areas – which may have been partly inundated at high tide. These areas are the equivalent of the floodplain further inland – and are generally dominated by finer-grained sediment then along the channels (facies 4 – laminated mudstones)
3) Offshore, deltas build out into the basin forming a gentle slope. This environment tends to show a mix of inputs from both the terrestrial and marine realms (facies 1 – cross-bedded sandstones)

Note that one of the best places to see the Chapel Rock Sandstone is at the Lower Tahquamenon Falls (Figure 5a). At the falls, you can walk out onto bedding planes in the rock and see the ripple marks on these surfaces.

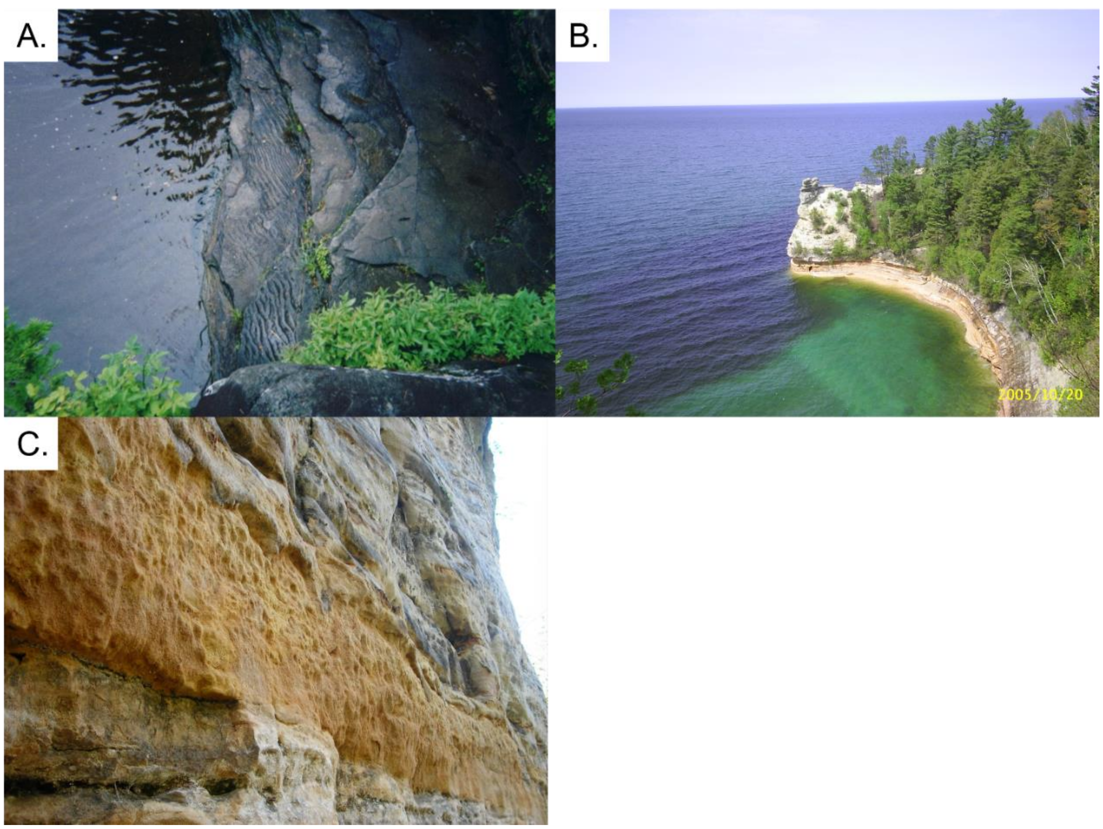


Figure 5. A.) Ripple marks in the Chapel Rock Sandstone, Lower Tahquamenon Falls. B) the Munising Group at Miners Castle. Note the orangish-colored layers at lake-level – these layers are the Chapel Rock Sandstone. The remainder of the headland (lighter-colored) is made up of the Miners Castle Sandstone. C) Bioturbated (heavily burrowed) sandstone layer in the Miners Castle Sandstone at Munising Falls. Modified from Voice and Harrison (2014).

Miners Castle Sandstone

The Miners Castle Sandstone exhibits a gradational change from fine- to medium-grained, cross-bedded quartz sandstone in the lower portion of the formation to an intensely bioturbated sandstone (Figure 5c) at the top (Haddox and Dott, 1990). Cross-bedding paleocurrent directions are to the west (Hamblin, 1958). Haddox and Dott (1990) and Stumm (1956) report a fauna consisting of trilobites, cephalopods, and brachiopods.

Haddox and Dott (1990) interpret the Miners Castle Member to be the open marine shelf deposits in the pro-delta position.

The age of the Miners Castle Sandstone is in flux. The fossil fauna reported by Haddox and Dott (1990) and Stumm (1956) suggested a Cambrian age for the unit. More recent work by Miller et al. (2006) has extracted conodonts from the Miners Castle Sandstone of the Munising Formation. These conodonts suggest that at least the upper Miners Castle Sandstone may actually be early Ordovician in age.

Evidence for the Timing of Michigan Basin Initiation

Hamblin (1958, 1961) used the paleocurrent orientations of the Cambro-Ordovician rocks to infer the timing of Michigan Basin initiation. As a quick summary:

1) The Precambrian Jacobsville Sandstone has paleocurrent flows directions to the North.
2) The Basal Conglomerate of the Munising Formation has paleocurrent flow directions to the North.
3) The Chapel Rock Sandstone has paleocurrent flow directions to the north and northwest.
4) The Miners Castle Sandstone has paleocurrent flow directions to the west.
5) The Au Train Dolomite has paleocurrent flow directions to the south.

Hamblin (1961) and Ells (1967) inferred that the Munising Formation was separated from the Cambrian sandstones in the Lower Peninsula (the Mt. Simon Sandstone and the Munising Group) by a mountain belt they called the Northern Michigan Highlands. These mountains were the remnants of the Penokean Orogeny (1.8 billion years ago) and the uplift of the rift valley walls of the Mid-Continent Rift system (1.1 billion years ago) and these mountains had been slowly eroding and shedding sediment ever since. They had two main lines of evidence for this mountain range:

1) In the Upper Peninsula, the Munising Formation thins to the south.
2) The Jacobsville Sandstone and Munising Formation have paleocurrent flow directions to the north, northwest or west (Figure 6).

If the Munising Formation was deposited in the Michigan Basin, the flow directions of paleocurrent indicators should be *<u>to the south</u>* towards the basin center. Instead, we do not observe southward flow until the Au Train Formation was deposited – suggesting that the Michigan Basin had formed by this time!

One interesting quirk, structurally the Munising Formation has the same orientation as the overlying Paleozoic sediments (Au Train Dolomite and younger units) – so it has a structural dip that dips towards the Michigan Basin (see Figure 2). Hamblin (1961) and Ells (1967) infer that the weight of the overlying sediments has deformed the Munising Sandstone such that it dips in the same direction as these overlying sediments.

Au Train Dolomite

Grabau (1906) defined and named the “Aux Trains” series for the outcrops along the Au Train River west of Munising. This interval includes the lower third of the formation, which has only been described completely from subsurface core samples. Unfortunately, at most locations, only the very lowest portion of this formation outcrops – usually forming the capping bedrock on the Cambrian Escarpment where waterfalls occur. Later, the formation name was changed to the Au Train Dolomite (Catacosinos et al. 2001).

At the Au Train River locality, Grabau (1906) defined two informal members – a lower glauconitic dolomitic sandstone and an upper glauconite-free dolomitic sandstone. Glauconite is an iron potassium clay that forms from alteration of fecal pellets over time. Lukens (1971) described the Au Train Dolomite from thin sections cut from subsurface core samples, while Blake (1962) described thin sections from samples taken at Au Train Falls (Figure 7a). Their studies observed:

1) Heavy minerals in the Au Train Dolomite are dominated by pyrite (+ glauconite) followed by garnet
2) Clastic sediments range from coarse silt to medium-grained sand
3) Dolomite is present as cement that totally encases the clastic sediment
4) Glauconite is present as isolated pellets and pellet-rich layers (Figure 7b)
5) Non-clastic grains include ooids and skeletal grains
    a. Several oolitic zones are present in the upper Au Train Dolomite
    b. Skeletal grains are generally highly abraded and broken up and are unidentifiable
    c. Some oncolitic grains were also observed (like ooids but formed from layered calcified algae – i.e., essentially free moving stromatolites washed by the currents)
6) Algal-laminated intraclasts and stomatolitic horizons were found by Lukens (1971) in the upper Au Train

Several workers have found fossils in the Au Train Dolomite. Blake (1962) found cephalopods, gastropods, bivalves, and brachiopods at the Van Meer Quarry east of Munising. Guldenzopf (1967) and Miller et al. (2006) extracted conodonts from the Au Train Formation – Miller et al. report an age of early Ordovician for the Au Train Dolomite.

The observations from the various workers provide us constraints on the possible depositional environment of the Au Train Dolomite. The presence of glauconite and pyrite suggests that the water chemistry was poorly oxygenated and the sedimentation rate was low. Garnets are likely derived from the same basement rocks that provided the quartz sands of this sandy dolomite. The environment was likely a clastic-dominated environment with the dolomite coming in much later during lithification (where dolomite was then precipitated as cement). The abraded skeletal grains, ooids and oncolites suggest that a portion of the depositional system was in high energy, shallow water environments (modern ooids for example form in 1-2 meters water depth in areas with a lot of wave energy). The stromatolitic horizons likely formed in low energy environments – which then experienced the occasional storms that ripped up intraclasts and transported them elsewhere in the environment. The fossils found are open marine organisms. Altogether, the Au Train Dolomite was laid down on a shallow open-marine shelf with low sedimentation rates and pulses of clastic sediment coming in periodically, while at the same time an active carbonate factory was present generating algal, oolitic and skeletal carbonates.

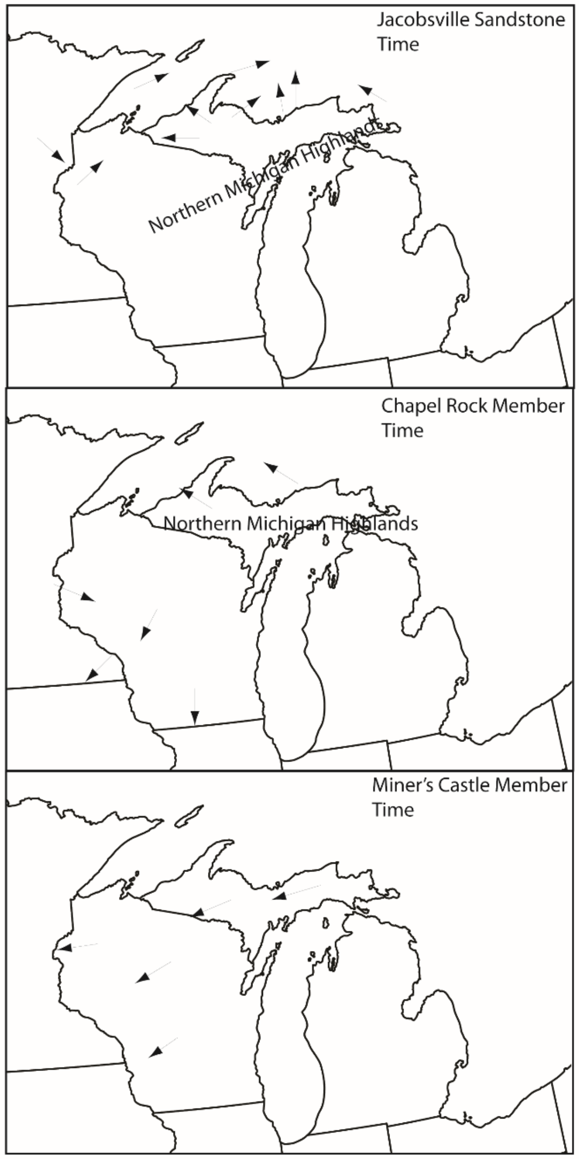


Figure 6: Paleocurrent maps for the Jacobsville, Chapel Rock and Miners Castle Members redrawn from Hamblin (1958). Note that in all three units, the paleocurrents do not reflect flow directions into the Michigan Basin. Image from Voice and Harrison (2014).

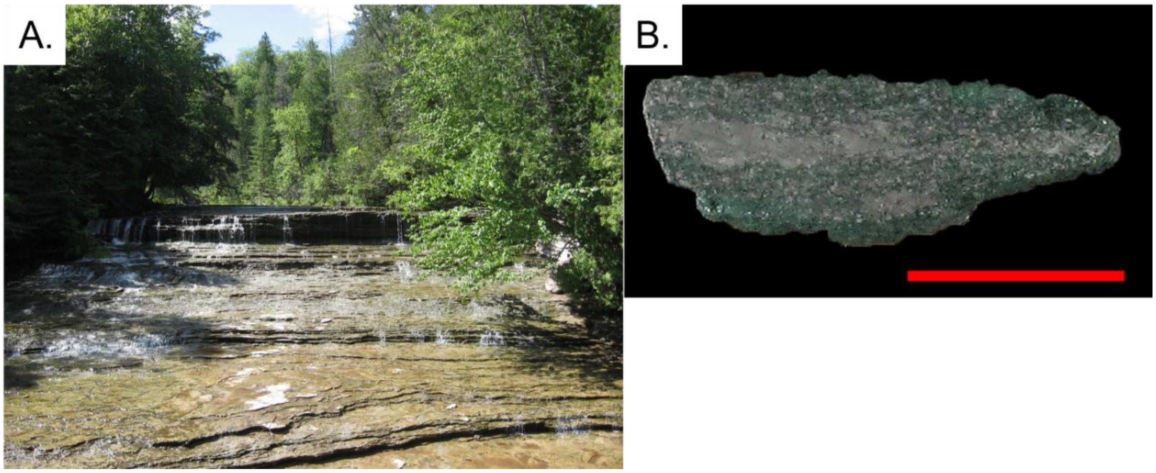


Figure 7. A) a view of a portion of Au Train Falls at Au Train, Mi. B) Slab of glauconitic, sandy dolostone. The scale bar is 3 cm. Modified from Voice and Harrison (2014).

Black River – Trenton Formations

The Black River and Trenton Formations are often lumped together by geologists working in the Michigan Basin. Both formations have similar rock characteristics – both are made up of a mix of argillaceous carbonates, limestones, dolostones, and calcareous shales. The contact between the two units is also gradational in many locations. The Black River-Trenton interval was deposited as part of a larger swath of tropical carbonate deposition across much of North America during the Middle Ordovician – which is recognized as "The Great American Carbonate Bank" (Harrison and Grammer, 2012). We will focus on the Trenton Formation during our visit to the central Upper Peninsula.

Black River Formation

The Black River Formation was proposed by Vanuxem (1842) for limestones outcropping along the Black River in north-central New York. This stratigraphic name was then propagated west by early geological mappers who correlated the Black River Formation to other carbonate packages in the Michigan and Illinois Basins. Hussey (1936) provides the first modern survey of the Black River Formation in the Upper Peninsula. He describes the unit as ranging from limestone to argillaceous limestone with an open marine fauna. Faunal elements include brachiopods, bryozoans, ostracods, nautiloids, stromatoporoids, and algae. More recent work at the Bony Falls Dam site has used the ostracods to infer a Middle Ordovician age for the unit (Kesling et al. 1960, Kesling, 1960a, Kesling, 1960b, and Kesling et al. 1962). Hussey (1952) formally proposed a member in the Black River Formation – the Bony Falls Member.

The Black River Formation outcrops along the west branch of the Whitefish River at US-41 south of Trenary (figure 8a). Unfortunately, the riverbanks are very steep and it is difficult to get to a good vantage point to look at the outcrop. This unit also outcrops at the Boney Falls Dam on the Escanaba River – unfortunately, this site is a bit far afield from our route.

Trenton Formation

Like the Black River Formation, the Trenton Formation is a stratigraphic term propagated from New York to the Michigan and Illinois Basins. Vanuxem (1838) defined the Trenton Limestone from rocks exposed at Trenton Falls in Oneida, New York and later redescribed these rocks in his 1842 publication. Smith (1915) described the Trenton of the Michigan Basin as a blue to buff and brown, argillaceous, lowmagnesian to high-magnesian limestone. Hussey (1936, 1950, and 1952) also examined the Trenton Formation and subdivided several members in the unit. Hussey (1952) defines the base of the Trenton Formation as the Chandler Falls Member from rocks exposed at Chandler Falls (unfortunately, now submerged after the construction of a hydroelectric dam) north of Escanaba. The Chandler Falls Member consists of:

1) Argillaceous limestones and shales with a prominent zone enriched in bryozoans that Hussey calls the *Prasopora* horizon.
2) A conglomerate
3) Limestones, argillaceous limestones, and shale with minor interbedded volcanic ash beds. Increasing number of the gastropod *Maclurites* up section.

Hussey noted that the Chandler Falls Member had a diverse fauna including rugose corals, brachiopods, gastropods, bivalves, bryozoans, and trilobites.

Above the Chandler Falls Member is the Groos Quarry Member which Hussey (1952) defined using the section exposed in the Groos Quarry to the west of Escanaba. The Groos Quarry Member is characterized by a higher amount of clay – with argillaceous limestones and black shales interbedded with limestone. An important marker fossil near the top of the section is the bivalve *Whitella eardleyi*. Fossils are more irregularly distributed through the Groos Quarry Member with a less diverse fauna of graptolites, brachiopods, conularids, bivalves, snails, ammonoids and trilobites.

At Haymeadow Falls on Haymeadow Creek (Figure 8c), Hussey (1952) described a dark brown, fine-grained shale (though the current author notes that this material fizzes very nicely during an acid test – and a lime mudstone is a better term to describe this unit [figure 8d]). Hussey referred this material to the Collingwood Shale but used the new name of the Haymeadow Falls Member. The Collingwood is a fine-grained interval at the top of the Trenton Formation – in the Lower Peninsula it is an organic-rich, lime mudstone (Hiatt, 1985) that has been of interest to the local Oil and Gas Industry as a possible unconventional reservoir. The Haymeadow Falls Member has a low diversity fauna dominated by deep water organisms such as graptolites. Hussey (1952) also observed several brachiopod species, a conularid, an ostracod, and several trilobite species.

Stop 1 – Miners Castle, Pictured Rocks National Lakeshore

At this stop, we will see two members of the Munising Formation (the Chapel Rock Sandstone and the Miners Castle Sandstone) as well as the Au Train Dolomite (Figure 5b).

Stop 2 – Munising Falls, Munising, MI

At Munising Falls, we will have the opportunity to see the Miners Castle Member of the Munising Formation more closely in the walls of the canyon bordering the Munising Falls Creek. The Au Train Dolomite is the cap rock at the top of the cliff.

Stop 3 – Au Train Falls, Au Train, MI

At Au Train Falls, we will examine the Au Train Dolomite and see a very scenic waterfall (Figure 7a)!

Stop 4 – Laughing Whitefish Falls, Onota Township, MI

At Laughing Whitefish Falls, we will see another scenic waterfall. In the rocks that the water is flowing over, we will see the Munising Formation and Au Train Dolomite.

Figure 8. A) Outcrop of the Black River Formation at Trenary. B) Rapid River Falls, Rapid River, Mi. The water flows over bedding planes of the Trenton Formation. The falls have a step-like pattern from weathering of the rock along bedding planes and joints. Picture courtesy of Linda Harrison. C) Haymeadow Falls, Rapid River, Mi. This waterfall has a similar geometry to the Rapid River Falls – with flow over bedding planes in a step-like pattern from weathering along joints and bedding planes. Picture courtesy of Linda Harrison. D) Sample of the Haymeadow Falls Member of the Trenton Formation from Haymeadow Falls. The rock is a fine-grained, muddy limestone. The small black linear patches on the rock are carbon films of a planktonic organism called a graptolite. Modified from Voice and Harrison (2014).

Stop 5 – Rapid River Falls, North of Rapid River, MI

At this small set of falls, we will see the Trenton Limestone (Figure 8b). With a careful look at the bedding planes at this site, you will see a variety of fossils – mostly as skeletal fragments.

Section 2 – Upper Ordovician Stratigraphy of the Michigan Basin

The Upper Ordovician stratigraphy consists of the Richmond Group. The Richmond Group is subdivided into the Bills Creek Shale, Stonington Formation and the Big Hill Dolomite. The Bills Creek Shale poorly outcrops and is an argillaceous shale. The Stonington Formation is further subdivided into two formal members, the Bay de Noc and Ogontz Members. The Stonington Formation consist of calcareous shales, shales, argillaceous limestones, and limestones. The Stonington Formation was deposited in open marine conditions likely in deeper water below normal wave base but above storm wave base. This interpretation of the water depth is based on the fine-grained nature of the rock and the interbedded more skeletal-rich horizons that are likely storm deposits. It is incredibly fossiliferous. The Stonington Formation outcrops along the eastern shore of Big Bay de Noc – though many of these outcrops are only accessible via boat. The Big Hill Dolomite is a fine-grained dolostone – with the best occurrences present in a pair of quarries on the eastern side of the Stonington Peninsula. The recent discovery of a fossil lagerstätte in the National Forest Service Quarry has made access to these sites much more difficult.

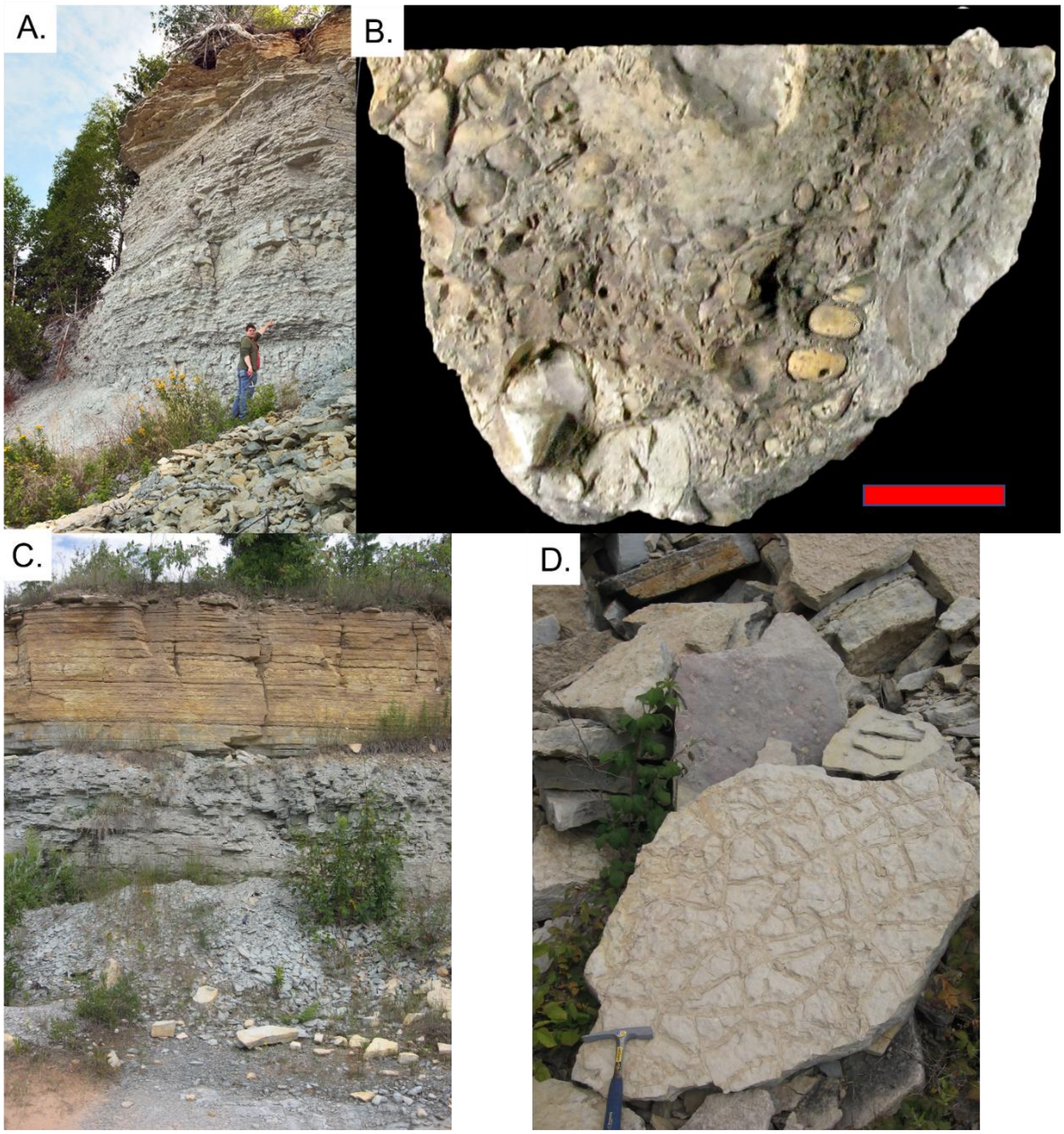


Figure 9. A) Outcrop of the Stonington Formation showing the Bay de Noc and Ogontz Members along the Lake Michigan shoreline. The upper 4-5 feet are in the Ogontz Member. The author for scale and the picture is courtesy of Linda Harrison. B) Internal molds of snails and brachiopods in the Ogontz Member. Scale bar is 2 cm. C) View of the National Forest Service Quarry showing a portion of the Big Hill Dolomite. D) Burrowed dolostone in the Big Hill Dolomite. Modified from Voice and Harrison (2014).

Richmond Group

Hussey in a series of papers (1926, 1950, 1952) defined/formalized the stratigraphic nomenclature for the Richmond Group, described the units, and provided significant lists of the faunal elements of each unit. The Richmond Group from base to top includes the Bills Creek Shale, the Stonington Formation, and the Big Hill Dolomite. The Stonington Formation was formally split into two members (the Bay de Noc and Ogontz Members) by Foerste in 1917.

Bills Creek Shale

Hussey (1926) defined the Bills Creek Shale for outcrops along Bills Creek to the northeast of Rapid River. He described the Bills Creek Shale as a thinly bedded, soft shale that ranges from gray to dark chocolate brown in color and weathers to a bluish color. The composition of the unit ranges from argillaceous shale to thin, interbedded fossiliferous limestones.

The contact between the Bills Creek Shale and the overlying Stonington Formation is a disconformity marked by an intraclastic lag deposit at the base of the Stonington Formation (Hussey, 1950, 1952). The intraclastic deposit also includes fragments of *Isotelus sp.*, a large Ordovician trilobite.

Votaw (1980), Goldman and Bergström (1997), Wicander and Playford (1999) and LaRowe (2000) have examined the Bills Creek Shale carefully for microfossils that can be used for biostratigraphic age assignment. Votaw (1980) and LaRowe (2000) dissolved samples of the Bills Creek Shale to extract conodont elements (tiny, phosphatic, teeth-like structures of an eel-shaped animal closely related to stem-vertebrates). Both studies isolated conodont elements from the Richmondian stage. LaRowe (2000) further suggested based on the assemblage of conodont species that the Bills Creek Shale was deposited in deeper marine waters. Goldman and Bergström (1997) isolated and described graptolites (planktonic, colonial animals [phylum hemichordata] now extinct that are preserved as carbon films) which also confirms a Richmondian Stage timing. Wicander and Palyford (1999, 2008) isolated a diverse assemblage of organic-walled microfossils (acritarchs), scolecodont elements (jaw “bones” of annelid worms), chitinizoans (another group of organic-walled fossils likely related to ameobas), and graptolites. They suggest a shallower water environment for the deposition of the Bills Creek Shale then other workers had suggested.

Unfortunately, outcrops of the Bills Creek Shale are difficult to get to and we will not be able to look at this unit during this trip.

Stonington Formation

Foerste had examined the Richmond Group in southern Ohio, before examining similar rocks in the central Upper Peninsula on the Stonington Formation. In his 1917 paper, he recognized a fauna of brachiopods, bryozoans, mollusks (gastropods and bivalves), and rugose corals similar to the fauna observed in the region around Cincinnati. Foerste (1917) defined the Stonington Formation and recognized two informal members: the Argillaceous Richmond and the Cherty Richmond. Hussey (1926) revisited the outcrops and formally defined the Bay de Noc Member (=Argillaceous Richmond) and the Ogontz Member (=Cherty Richmond). The Bay de Noc Member consists of gray-blue, argillaceous limestone interbedded with more indurated limestone layers and is incredibly fossiliferous (Foerste, 1917, Hussey, 1926). Hussey (1926) describes the Ogontz Member as ranging from soft, argillaceous to hard, cherty, fossiliferous limestone. Hussey (1926) used the clay content of these members to infer a depositional environment for the unit consisting of a shallow marine environment with periodic influxes of argillaceous sediment, suggesting a deltaic environment. The Ogontz Member being characterized by much lower clay contents were then interpreted as being deposited in clear, offshore waters. Danita Brandt and her students in a series of abstracts suggested a very different interpretation of the Bay de Noc Member – they noted the open-marine fauna and interpreted skeletal-rich beds as tempestites deposited under open shelf conditions above storm wave base (Brandt et al. 1987, 1988 and Larcinese et al. 1987). The Ogontz Member is characterized by a fauna rich in bivalves and the lithology is more pure limestone and Brandt and students suggest that this was a shallower water and higher energy environment where clays could not be deposited due to the current activity.

Like the Bills Creek Shale, several studies have used index fossils to assign an age to the Stonington Formation. Wicander and Playford (1999, 2008) isolated a diverse and abundant organic-walled microfossils (acritarchs). They interpreted the diversity of species to mean that the Stonington Formation had been deposited in offshore, shelf environment. LaRowe (2000) extracted conodonts from both members of the Stonington Formation finding a similar assemblage to the one he had observed in the Bills Creek Shale. These index fossils suggest a Richmondian age (near the end of the Ordovician). Appendix 1 has a set of plates from Foerste (1917) that show some of the basic fossil species found in the Stonington Formation for reference.

We will see the Stonington Formation at stops 6 and 7 (and depending on time and conditions, we may try to stop at a third optional stop).

Big Hill Dolomite

Hussey (1926) defined the Big Hill Dolomite for rocks outcropping in the eastern Stonington Peninsula. Unfortunately, he was unable to find the contact between the Big Hill Dolomite and the underlying Stonington Formation. Both Votaw (1980) and Hussey (1926) described the outcrops along C.R. 511, where they observed hard, argillaceous limestones and soft, to moderately hard limestone with a diverse assemblage of animals including tabulate and rugose corals, bryozoans, brachiopods, and cephalopods. Ehlers et al. (1967) described a core from the town of Cooks that drilled from the surface bedrock (Byron Formation) down to the Black River Formation. They did not note an unconformity between the Big Hill Dolomite and the underlying Stonington Formation. They describe a very fossiliferous dolostone with a wide variety of rugose and tabulate corals and bryozoans.

In the National Forest Service Quarry, Votaw (1980) observed a mix of limestone, shaly limestone to calcareous shale, and dolostones. For the 2014 Michigan Basin Geological Society Field Trip, the author was able to enter the National Forest Service Quarry and described the following lithologies from the quarry wall (Voice and Harrison, 2014):

1) Non-fossiliferous, bioturbated limestones with ripple marks and large burrows.
2) Thinly bedded, non-fossiliferous limestones
3) Shaly limestone to calcareous shale
4) Massively bedded, dolomitic limestones

Samples of the dolomitic limestone exhibited horizons enriched in snails

LaRowe (2000) extracted conodonts from the National Forest Service Quarry. The species present suggested a Richmondian age – and one species, *Rhipidognathus symmetricus* was used by LaRowe to infer a shallow water environment. The mix of open marine fauna including a diverse assemblage of corals suggest an open marine environment for the bulk of the Big Hill Dolomite. At the National Forest Service Quarry, the lack of fossil material, the ripple marks, and burrows suggest a more restricted environment near fairweather wave base. The presence of intact macroalgae fossils (LoDuca, 2019 and Lamsdell et al. 2017) suggest that the deposits were within the photic zone and that the algae had not been transported far implying low energy conditions.

et al. (2017 and 2019) describe the lagerstätte with an emphasis on the arthropods found at the site. If you are interested in the Big Hill Lagerstätte, several videos have been posted on YouTube that provide an overview of the site and the many impressive fossils collected there:

A brief documentary about the site:

https://www.youtube.com/watch?v=xakfqiwX1Fc

A presentation by Dr. James Lamsdell (West Virginia University):

https://www.youtube.com/watch?v=WqdsEg2WlKs

Stops 6 and 7 – Stonington Formation Outcrops, near Stonington, MI

Stops 6 and 7 allow us to examine both members of the Stonington Formation. Both locations will also allow you to collect a variety of fossils. Stop 6 is a road outcrop across the street from the Lakewood Cemetery. The outcrop is in the Bay de Noc Member of the Stonington Formation. Stop 7 is at a boat landing south of the town of Stonington on Swede 13 Road. This location is likely in the lower Ogontz Member as the author has found a variety of bivalve fossils at this location.

The optional stop is of CK-17 between stops 6 and 7 (Figures 9a and 9b). It will involve a significant walk down the Lake Michigan shoreline to the bluffs. In past years, lake level has been high enough that these outcrops were not accessible (no beach). The author will check this site out prior to the trip to see if it is feasible – if it is feasible, then it allows us another look at both members of the Stonington Formation.

Stop 8 – Big Hill Dolomite, eastern Stonington Peninsula

This will be a brief visit to the Big Hill Dolomite. We will look at small outcrops near the base of the "Big Hill" that gives the unit its name. At the top of the hill are two quarries – a National Forest Service Quarry (Figure 9c and 9d) on the left (west) and a private dimension stone quarry on the right (east) of C.R. 511. We do not have permission to access either quarry. The National Forest Service Quarry has recently stopped providing permission to access the site due to the discovery of a fossil lagerstätte that has a variety of soft-bodied fossils (jellyfish, algae) and very well-preserved hard-bodied fossils (a mix of invertebrates notably including eurypterids).

Section 3 – Lower Silurian Stratigraphy of the Michigan Basin

The Lower Silurian consists of four major stratigraphic groups – the Cataract, Burnt Bluff, Manistique, and Engadine Groups. The Cataract Group consists of the Manitoulin Dolomite and the Cabot Head Shale. The Manitoulin Dolomite does not outcrop well in the Upper Peninsula – it consists of fine-grained dolostones interbedded with minor red and green shales. The overlying Cabot Head Shale consists of red and green shales with interbedded dolostones and rock gypsum. Above the Cabot Head Shale, is the Burnt Bluff Group which consists of the Lime Island, Byron, and Hendricks Formations. Like the Manitoulin Dolomite, the Lime Island Formation does not outcrop very well – with the type locality on Lime Island in the St. Mary's River on the far eastern side of the Upper Peninsula. The Lime Island Formation is made up of limestone and dolomite with incredibly abundant pentameride brachiopods. Above the Lime Island is a sequence of fine-grained dolostones deposited in shallow water lagoons and tidal flats – this interval is called the Byron Formation. The Byron Formation is overlain by the Hendricks Formation which includes open-marine limestones and dolomites characterized by a fauna of pentameride brachiopods and tabulate corals. Overlying the Hendricks Formation is the Manistique Group. The Manistique Group is subdivided into the Schoolcraft and Cordell Formations. These units are cherty dolomites with an open-marine (but deeper water) fauna of brachiopods and tabulate corals. The final group in the Lower Silurian is the Engadine Group. The Engadine Group consists of fossiliferous dolomites with a diverse fauna of stromatoporoids, tabulate corals, brachiopods, nautiloids, and gastropods (snails). We will spend quite a bit of time looking at these units.

Cataract Group

The Cataract Group was named by Schuchert in 1913 in an abstract published in the Geological Society of America's Bulletin. He included strata found downstream from Niagara Falls in his definition of the Cataract Group – and the name of the Group refers to the cataract of Niagara Falls. In Michigan, the Cataract Group is split into the Manitoulin Dolomite and the Cabot Head Shale.

The Manitoulin Dolomite was proposed by Williams (1913) for outcrops on Manitoulin Island. Ehlers and Kesling (1957) describe the unit as gray to buff gray, thin, uneven-bedded dolostone with a fossil assemblage including a variety of brachiopods, corals, and fenestellid bryozoans. Recent work by Bergström et al. (2009 and 2011) and Al-Musawi et al. (in press) have shown based on carbon isotope chemostratigraphy that the Manitoulin Dolomite is likely Late Ordovician in age.

Grabau (1913) proposed the Cabots Head Shale for outcrops at Cabot's Head Point on the Bruce Peninsula of Ontario (note that the author is mystified as to the timing of the dropping of the s on Cabots – as the formal stratigraphy in Michigan uses the Cabot Head Shale). Grabau (1913) described a series of interbedded red and green shales and red, marly sandstones underlying a unit he called the *Pentamerus* beds (now referred to the Dryer Bay Formation or Lime Island Formation). Voice et al. (2018) based on subsurface cores in northern Michigan and outcrops in the Upper Peninsula observed greater lithologic diversity in the Cabot Head Shale including:

1) Red and green, argillaceous shales
2) Fine-grained, fenestral, algal-laminated dolostones interbedded with burrowed dolostones.
3) Intraclastic dolostones with rip-up clasts of algal-laminated dolostones
4) Nodular gypsum interbedded with laminated dolostones
5) Gray, laminated muddy limestones with some pentameride brachiopods

In addition, the wells and outcrops from the Upper Peninsula record secondary gypsum lining fractures running through the unit – these gypsums are of a type called satin-spar gypsum (Figure 10a) and are very fibrous. Voice et al. (2018) interprets this package of sediments to have been deposited in a shallow marine environment under semi-arid conditions. The red and green shales represent pulses of clastic sediments brought into the Michigan Basin during the Taconic Orogeny from weathering of the rising Taconic Mountains and likely were deposited in the middle shelf under normal wave base but above storm wave base where clay can readily settle out of suspension. In the shallow water portion of this shelf, fine-grained carbonate sediments accumulated – likely sourced from calcareous algae. These dolostones include lagoonal deposits (burrowed dolostones and pentameride-rich limestones) and tidal flat deposits (fenestral, algal-laminated dolostones and nodular gypsum). Intraclastic zones (zones rich in angular clasts of local sediments) likely formed on a beach where storms stacked up ripped up material from the adjacent environments.

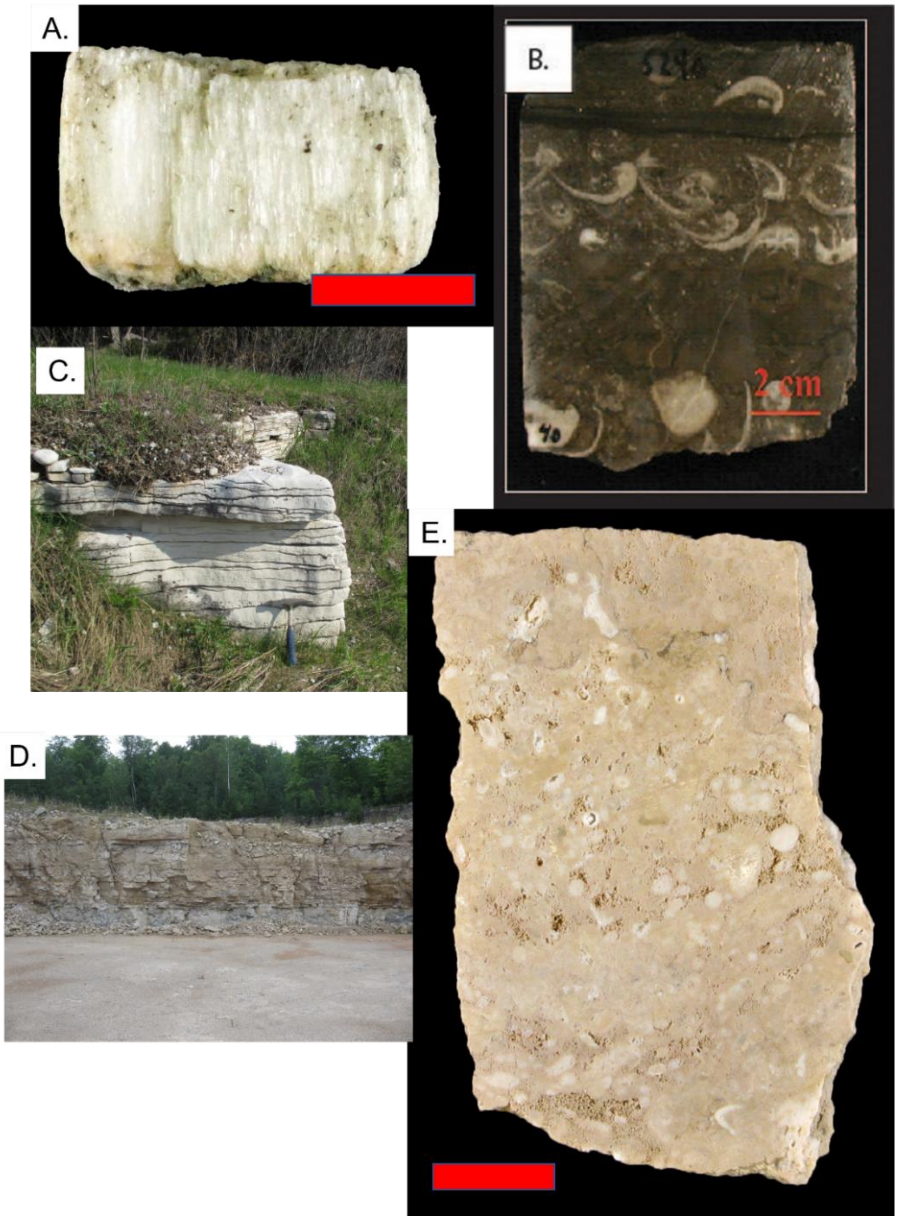


Figure 10. A) Sample of Satin Spar from the Cabot Head Shale at Mormon Creek Trail Quarry. Scale bar is 2 cm. B) Core photograph of the Lime Island Formation from the northern Lower Peninsula (Alpena County). Note the layers of skeletal grains – the concave grains are disarticulated brachiopod shells. C) Outcrop photograph of the Byron Formation from outside the entrance of Fayette State Historical Park. The Byron Formation consists of wavy-bedded to laminated dolostone with fenestral porosity and symmetrical ripple marks. D) View of the Sawheidle Quarry with interbedded Byron and Hendricks facies. E) Sample of the Hendricks Formation from the Sawheidle Quarry showing a rugose coral and bryozoan boundstone. Scale bar is 2.5 cm. Modified from Voice and Harrison (2014) and Voice et al. (2018).

Al-Musawi et al. (in press) have identified a negative carbon isotope excursion in the upper Cabot Head Shale and used both published and new conodont biostratigraphy to confirm the age of the Cabot Head Shale. They propose that the Cabot Head Shale is the oldest Silurian unit in the Michigan Basin.

We will see the Cabot Head Shale at stop 9.

Burnt Bluff Group

The Burnt Bluff Group is a unit that the author has spent a lot of time on – even having published articles on the unit (Voice and Harrison, 2016, Voice et al., 2018, and Al-Musawi et al. (in press)). The Burnt Bluff Group is named for Burnt Bluff on the Garden Peninsula (Ehlers, 1921) – unfortunately, the type locality is inaccessible, though in this case it is to preserve Native American pictographs. Ehlers in a series of publications defined several units in the Burnt Bluff Group including the Lime Island, Byron, and Hendricks Formations (Ehlers, 1921, 1930, 1973, and Ehlers and Kesling, 1957, 1962). Harrison (1985) also proposed an informal unit in the central Lower Peninsula that he called the Undifferentiated Burnt Bluff Group, recognizing that these rocks were in the stratigraphic position of the Burnt Bluff Group in this region, but were lithologically different from the traditionally defined units in the northern Lower Peninsula and eastern Upper Peninsula.

Lime Island Formation

Ehlers (1921) defined the Lime Island Formation for outcrops on Lime Island in the St. Mary's River between Lakes Superior and Lake Huron. Prior to his work, this unit had been referred to as the *Pentamerus* beds due to the sheer abundance of Pentameride brachiopod fossils in this unit. The Lime Island Formation is made up of muddy limestones and dolostones with an open-marine fauna dominated by pentameride brachiopods with minor faunal elements including stromatoporoids and tabulate corals. Most of the brachiopods are disarticulated (their two valves broken apart) and abraded suggesting some degree of transport from where they lived (figure 10b) – most workers interpret these shell beds as tempestites (storm deposits).

Unfortunately, the Lime Island Formation does not outcrop in the part of the Upper Peninsula that we will be visiting, so we will not see this unit. Even at the type locality on Lime Island, the formation is the subcrop – with only boulders of the material present at the surface (Harrison, personal communication).

Byron Formation

The Byron Formation is named for the town of Byron, Wisconsin on the Door Peninsula, where T.C. Chamberlin (1877) described the type locality for the unit. This is the rare stratigraphic nomenclature brought from the west into the Michigan Basin (as we have already seen several names brought over from New York to the east). He described a light colored, dolostone with thin bedding, mud-cracks, and ripple marks.

The underlying Lime Island Formation has a gradational contact with the Byron Formation. The diversity and abundance of fossils decrease and eventually disappear (Voice et al., 2018). Voice et al. (2018) described the following facies in the Byron Formation:

1) Black, laminated muddy limestones. Fossils are rare, generally fragmented and abraded and include brachiopods and ostracods.
2) Tan, burrow-mottled, muddy dolostones. Some skeletal grains present, including ostracods, gastropods, and brachiopods.

3) Tan, algal-laminated, muddy dolostones – stromatolites dominate this facies, with the majority being horizontally-laminated but crinkly textured stromatolites (figure 10c).
4) Tan, intraclastic dolostones – intraclasts are sub-angular to subrounded and consist of algal-laminated dolostones or black, laminated mudstones. The intraclasts are imbricated – meaning that the clasts are stacked with their long axes parallel to each other.
5) Gray, wispy-laminated, skeletal limestones – this unit is near the top of the Byron Formation and represents the transition to the overlying Hendricks Formation

These facies are interpreted as the deposits of a lagoon-tidal flat complex. Facies 1, 2 and 5 were deposited in the lagoonal system – which appears to have been restricted due to the low abundance and diversity of fossils. Facies 1 being black in color suggests that the water chemistry was reducing – and the darkness is likely from organic matter (± finely disseminated pyrite) which is preserved under these conditions. The algal-laminated dolostones (facies 3) have abundant mud-cracks suggesting that this facies was deposited in shallow water that was likely exposed at low tide. The intraclastic zones (facies 4) are likely storm deposits in the littoral setting – storm currents ripped up pieces of the sea floor and transported them inland a short distance. Facies 5 is interpreted as being deposits of the initial transgression that flooded the Byron lagoon-tidal flat complex with the open marine waters that would deposit the Hendricks Formation.

Hendricks Formation

The Hendricks Formation was named by Ehlers (1921) for the rocks observed in Hendricks Quarry in the eastern Upper Peninsula. The Hendricks Quarry was one of several quarries in the Rexton-Trout Lake Area which historically mined the upper Hendricks Formation (an interval called the Fiborn Limestone or Fiborn Member). Today, the Hendricks Quarry is part of the area that Graymont is mining around the town of Rexton.

The Hendricks Formation consists of gray, muddy limestones and dolostones with a diverse and abundant fauna of brachiopods (especially Pentameride brachiopods), tabulate corals, rugose corals, and stromatoporoids. Voice et al. (2018) describe from both outcrop and subsurface core samples five facies:

1) Gray, wispy, nodular, brachiopod muddy limestones. These are intensely bioturbated rocks – which generates a nodular texture.
2) Coral, stromatoporoid, mud-lean limestones and dolostones – these are characterized by skeletal debris, with the corals and stromatoporoids being abraded and being positioned in non-living orientations.
3) Crinoid, brachiopod, mud-rich limestones and dolostones with 2 variants:
    a. characterized by abundant skeletal grains floating in mud matrix – thin sections show that the matrix actually consists of pellets (likely fecal pellets).
    b. Or characterized by a greater amount of skeletal sand between larger clasts, more diverse fauna including more stromatoporoids and corals.
4) Stromatoporoid boundstone – a boundstone is a type of limestone where the skeletal grains are in their growth or living positions, usually from reef settings. In other parts of the basin, the reef-building creatures include bryozoans and rugose corals (figure 10e) or tabulate corals.

Voice et al. (2018) interpret these facies as open marine deposits on a shallow shelf. Facies 4 is interpreted as the deposits of a patch reef. Facies 2 and 3b were likely deposited near the patch reefs – as the abundance of coral and stromatoporoid material are likely derived from the reefs and were transported by storms or high tides into the adjacent shelf. Facies 1 and 3a are open marine deposits where the sea floor was an active environment where burrowers dug into it and likely left their fecal pellets behind as traces.

Burnt Bluff Group Depositional Model

Harrison (1985), Voice et al. (2018) and Al-Musawi et al. (in press) model the Burnt Bluff Group as a carbonate shelf deposited in a shallow tropical sea in the Michigan Basin. This shelf had a ramp-like morphology, with tidal flats and lagoonal deposits of the Byron Formation and open marine deposits of the Hendricks and Lime Island Formations (Figure 11). Outboard from the shallower open shelf deposits are the Undifferentiated Burnt Bluff Group rocks (Harrison, 1985) or clastic shales of the Cabot Head Shale (Voice et al. 2018 and Al-Musawi et al. (in press)). Each of these formations then represents a specific depositional environment, which when acted upon by changing sea level would have shifted position laterally along the ramp. Al-Musawi et al. (in press) provide constraints on the timing of each unit using a combination of carbon isotope excursions, conodont index fossils, ash bed U-Pb age dates, and Strontium isotopes.

Manistique Group

The Manistique Group was named by Smith in 1915. He defined the Manistique Series as a thick succession of dolomite between the Fiborn Limestone and the Engadine Group. Ehlers (1973) later raised the Manistique Series to the rank of a Formation and defined the Schoolcraft Dolomite and Cordell Dolomite. Catacosinos et al. (2001) has elevated the Manistique Formation to a group and the two members to formations.

A brief description of each of the formations (Figure 12) can be summarized from Ehlers (1973):

The Schoolcraft Formation ranges from massive, coarsely crystalline, brown dolostones and thin-bedded, finely crystalline, blueish-gray dolostones. The fossil fauna of the unit is dominated by pentameride brachiopods.

The Cordell Formation consists of thin, wavey-bedded dolomites with interbedded layers of chert nodules, isolated chert nodules, and silicified fossils. The fauna is more diverse with a mix of tabulate and rugose corals.

These units outcrop along US-2 in the town of Gulliver – unfortunately, the median is narrow and with the increased speed limit, this outcrop has become dangerous to stop at. Outcrops are also present along the shoreline at Manistique (Figure 12b). We will see the Manistique Group at Scott's Quarry, where the upper Schoolcraft Formation and the majority of the Cordell Formation can be observed (see stop 16 below).

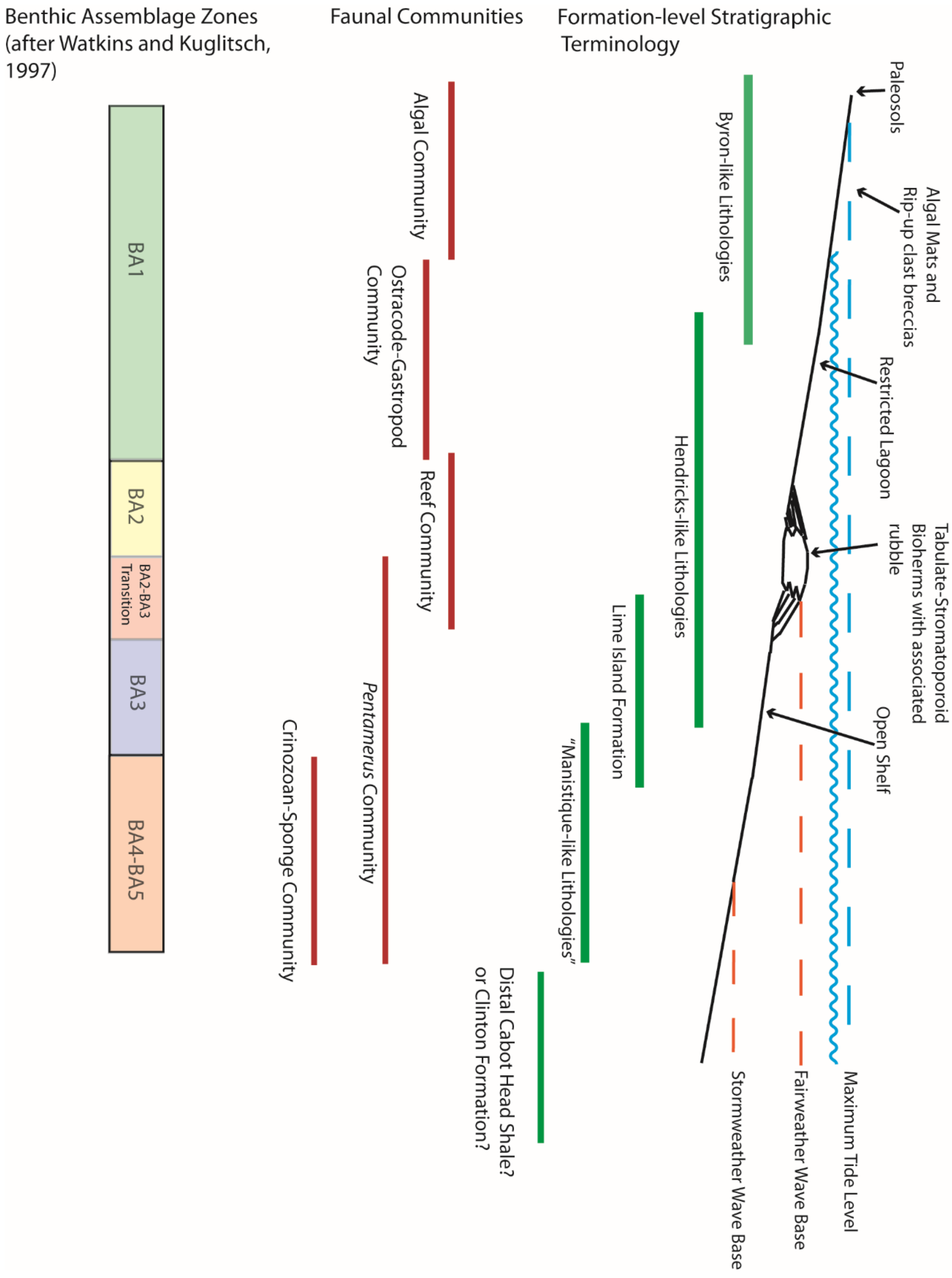


Figure 11: Depositional Model of the Burnt Bluff Group (from Voice et al. 2016).

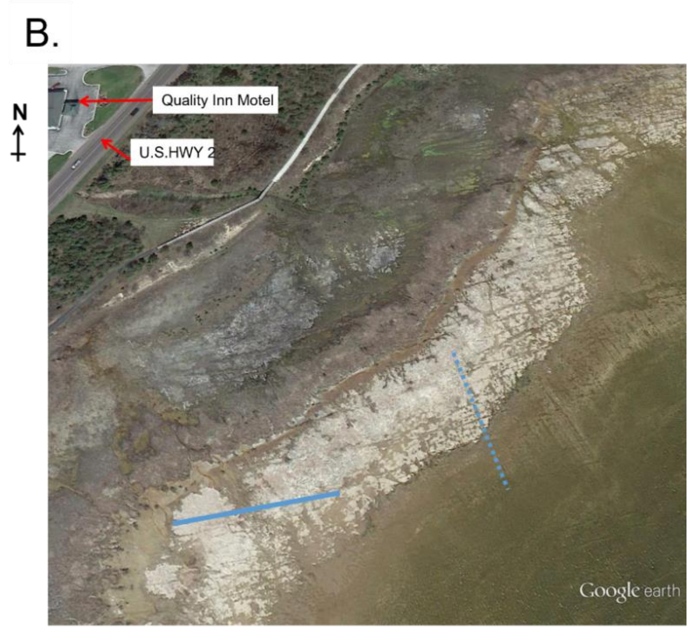


Figure 12: A) The Rock Hammer is positioned over the contact between the Schoolcraft and Cordell Formations at Gulliver. Note that the Schoolcraft is characterized by thicker, light gray dolostone, while the Cordell is thinner, less continuous beds of tan dolostone. B) Satellite image of the Manistique Group along the Lake Michigan coastline at Manistique. The two blue lines trace the dominant fracture orientations observable in this rock. Modified from Voice and Harrison (2014).

Engadine Group

The Engadine Dolomite was named by Smith (1915) for bluish-gray, massive, crystalline dolostone from the eastern Upper Peninsula in the area between Engadine and Trout Lake. Johnson et al. (1979) cite an abstract by Ehlers and Sorenson at the 1967 meeting of the Michigan Academy of Sciences, Arts, and Letters that elevated the Engadine Dolomite to a group (the author has not been able to find a copy of the abstract, but did find that the talk was given at the meeting [Karen Gross, Director of the Michigan Academy, personal communication, July, 2014]). Johnson et al. (1979) and Yokoyama (1981) provide detailed descriptions of the formations of the Engadine Group – which Ehlers and Sorenson had split into the Rockview Dolomite, the Rapson Creek Dolomite, and the Bush Bay Dolomite. The Bush Bay Dolomite is split into three members – the Prentiss Creek, Swede Road, and McKay Bay members. Their descriptions are summarized below:

1) The Rockview Dolomite consists of two interbedded facies. Facies 1a is a skeletal, crystalline dolostone with fine to coarse-grained skeletal debris in a matrix of equigranular dolomite. Skeletal grains include disarticulated crinoids, tabulate corals, bryozoans, and tabular stromatoporoids. Facies 1b is a dark gray, fine to medium crystalline dolomite with few fossils.
2) The Rapson Creek Dolostone is made up of three interbedded facies. Facies 2a is coarse-grained skeletal, muddy dolostone with scattered fossil grains of pentameride brachiopods, bryozoans, rugose and tabulate corals in a matrix of crystalline dolomite. Facies 2b is a gray, fine to medium, crystalline dolomite with rare fossils of brachiopods, gastropods, tabulate corals, and

stromatoporoids. Facies 2c is a skeletal boundstone dominated by tabulate corals (Halysitids and favositids) and tabular stromatoporoids in a matrix of light gray, medium to coarse crystalline dolomite. The corals and stromatoporoids are in their growth positions.

3) Bush Bay Dolomite
    a. Prentiss Creek Member consists of thin to medium bedded, gray to brown, fine- to medium-grained crystalline dolomite with a fauna dominated by pentameride brachiopods. Some silicified fossils.
    b. Swede Road Member – buff-brown, thinly bedded, poorly fossiliferous dolostone with a fauna of brachiopods, cephalopods (nautiloids), corals, and crinoids.
    c. McKay Bay Member – massive, gray, mottled, medium- to coarse-grained crystalline dolomite. Diverse fauna present (stromatoporoids, tabulate corals, brachiopods, gastropods, cephalopods, and bivalves)

The Rockview Dolomite and Rapson Creek Dolomite were interpreted by Johnson et al. (1979) and Yokoyama (1981) as open shelf deposits within the photic zone – and range from slightly restricted lagoon deposits to open-marine, turbulent waters with small patch reefs of tabulate corals and stromatoporoids. The Bush Bay Dolomite has a similar depositional environment with Johnson et al. (1979) interpreting the members as:

Prentiss Creek – open shelf in deeper water. Presence of silicified fossils likely represents deeper water conditions

Swede Road – Open shelf, between patch reefs – fossil debris derived by storms washing material from reefs into the adjacent shelf.

McKay Bay – patch reefs and adjacent open-shelf – some intervals with significant bioturbation (preserved as mottling)

Stop 9 – Cabot Head Shale, near Moss Lake

At this location, we will see a small quarry in the Cabot Head Shale on Mormon Creek Truck Trail off Forest Highway 13. This quarry was mined in the early 20th century for local plaster needs. Ehlers and Kesling (1957) described the section at this interval – they observed fine-grained buff to gray, argillaceous dolostones and gypsum. Some beds were enriched in the ostracod *Leperditia* sp.

For those interested in collecting samples, be sure to look for satin-spar gypsum (Figure 10a).

Stop 10 – Sawheidle Quarry roadside outcrops, Manistique, MI

At the outcrops along M-94 north of Manistique, we can look at the Burnt Bluff Group adjacent to Sawheidle Quarry (Figures 10d and 10e). These outcrops expose interbedded facies of both the Byron and Hendricks Formations.

Stop 11 – Fayette State Historical Park

At Fayette State Historical Park, we can see a historic mining district that was associated with the iron mining industry in Michigan – iron ore was shipped to Fayette for processing into pig iron. This process required smelting of the iron ore using the local hardwood forests and limestones from the Burnt Bluff Group. The limestones served as flux for the smelting process. The park preserves restored buildings on-site with a significant amount of the cultural history of the site on display. We can also walk over to the quarry site along the bluffs overlooking the harbor to see where the limestone was mined for flux. [Also, if the weather is hot, the park's visitor center and park store have ice cream for sale!]

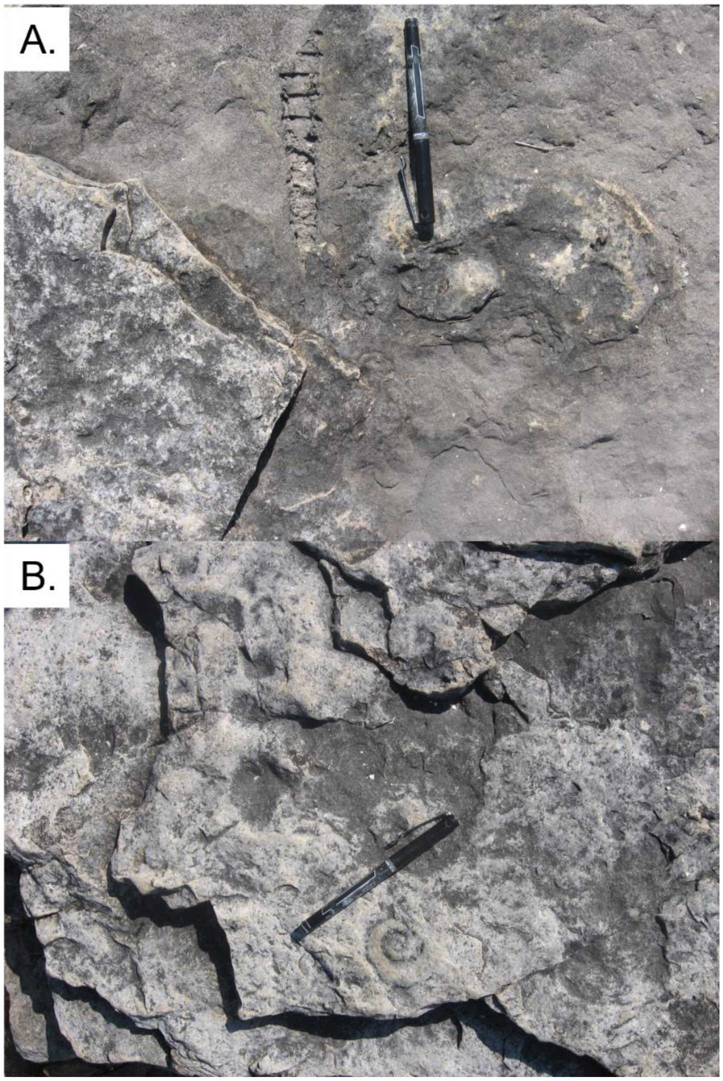


Figure 13: Examples of some of the fossils in the Engadine Group at Seul Choix Pointe. A) Nautiloid mold B) Internal mold of the large gastropod, Maclurites sp. Note the pen is approximately 6 inches long (15.25 cm). Modified from Voice and Harrison (2014).

Stops 12 and 13 – Outcrops along M-183

As we leave Fayette State Historic Park, we will visit some of the outcrops along M-183 to see both the Byron and Hendricks Formations. Just outside the park entrance are outcrops of the Byron Formation (Figure 10c). A few miles further north, we will stop at an outcrop of the Hendricks Formation.

Stop 14 – Seul Choix Pointe, Gulliver, MI

At Seul Choix Pointe, we will see a wonderful outcrop of the Engadine Group. Along the Lake Michigan shoreline, the Engadine Group is exposed and we will be able to walk on top of a bedding plane. On this bedding plane, you are essentially walking on the Silurian seafloor and scattered around on this seabed are a wide variety of fossils including pentameride brachiopods, tabulate corals (halysitids and favositids), and large gastropods (*Maclurites* sp.). Rare nautiloids are also present. Given time, you may also want to visit the Seul Choix Lighthouse – tours are $6 per adult and can be purchased at the gift shop.

Stop 15 – Fiborn Quarry

The Fiborn Quarry is part of the Fiborn Karst Preserve (https://caves.org/conservancy/mkc/index.html). We will take a short hike to visit zones 1 and 2 (see the separate handout for the Barbara Ann Patrie Memorial Trail), which will give us a look at both karst (limestone dissolution features) and the Fiborn Quarry. The Fiborn Member is the upper part of the Hendricks Formation – and is characterized by its high degree of limestone purity (Johnson and Sorenson, 1978) – the current mining at Rexton is mining this interval as it can be used in a wide variety of products including agricultural lime, flue gas desulfurization, various types of construction materials (mortar, plaster), flux for steel, etc. (More information can be found here: https://rextonproject.com).

Stop 16 – Scotts Quarry

Scotts Quarry is location where we can look at the Manistique Group. The lower quarry wall is made up of the Schoolcraft Member, while the remainder of the wall is made up of the Cordell Member. Please no climbing at this site.

Section 4 – Upper Silurian and Lower Devonian Stratigraphy of the Michigan Basin

The Upper Silurian in the Upper Peninsula is composed of the Pointe Aux Chênes Shale and the Bass Islands Group. The Pointe Aux Chênes Formation is a thick package of shales and dolomitic shales with minor intervals of rock gypsum. While the Bass Islands Group is split up into multiple formations in the subsurface of the Lower Peninsula, in the Upper Peninsula only 1 formation is defined – the St. Ignace Dolomite. The St. Ignace Dolomite does not outcrop – most of our information on this unit is from the borehole samples collected during the siting and construction of the Mackinaw Bridge or from clasts in the early Devonian Mackinac Breccia. The St. Ignace Dolomite consists of fine-grained dolomite deposited in shallow lagoons and tidal flats. Above the St. Ignace Dolomite is the early Devonian Bois Blanc Formation, which outcrops near Mackinaw City and on several of the islands in the Straits of Mackinac. At Mackinaw City, it is a very fossiliferous limestone. Clasts of the Bois Blanc Formation are also found in the Mackinac Breccia. The final unit in the region is the Mackinac Breccia which outcrops around St. Ignace and forms the bedrock under the northern side of the Straits of Mackinac. This breccia formed from the collapse of caverns in the Pointe Aux Chênes Formation and St. Ignace Dolomite. The breccia is made up of clasts of the St. Ignace Dolomite and Bois Blanc Formation lightly cemented together.

Pointe Aux Chênes Formation

The Pointe Aux Chênes Shale was defined by Landes et al. (1945) for dolomitic shales outcropping on the Pointe Aux Chênes headland northwest of St. Ignace along the Lake Michigan shoreline. Landes et al. (1945) correlates this unit to the Salina Group in the interior of the Michigan Basin which is a very thick succession dominated by rock salt and rock gypsum but also contains significant amounts of dolomite and shale. In the Upper Peninsula, the Pointe Aux Chênes tends not to outcrop well – only as low outcrops in ditches (Figure 14). Landes et al. (1945) describes this unit as an oolitic to fine-grained dolostone, rock gypsum, and red and green shales. Interestingly, there appears to have been sufficient rock gypsum that at least one attempt at mining the material was conducted in the 1850s near St. Ignace (Grimsley, 1903). Landes et al. (1945) observes a limited fauna of inarticulate brachiopods, articulate brachiopods, bivalves, graptolites, ostracods, and eurypterids. The limited fauna in the Pointe Aux Chênes Formation suggests that the environment was relatively harsh. We will see a small outcrop of this unit in St. Ignace.

Figure 14: Contact between the Pointe Aux Chênes Formation and the overlying Mackinac Breccia at Lemotte St. outcrop, St. Ignace.

Bass Island Group

Lane et al. (1908) defined the Bass Islands Group for outcrops on the islands in the western Lake Erie and used this terminology in southeastern Michigan and northeastern Ohio. In that portion of the Michigan Basin, the Bass Islands Group is subdivided into a series of units dominated by dolomite and rock gypsum and include the Greenfield, Tymochtee, Put-in-Bay, and Raisin River formations (Sparling, 1970). In the St. Ignace area, Landes et al. (1945) defines the St. Ignace Dolomite from subsurface core materials and clasts from the Mackinac Breccia – and recognizes that the Bass Islands Group is more homogenous in the Upper Peninsula. The St. Ignace Dolomite consists of fine-grained, algal-laminated dolostones, fenestral and laminated dolostones, and dolomudstones. Many of the clasts exhibit molds of lath-shaped crystals of gypsum. The sedimentary structures suggest that the St. Ignace Dolomite was deposited in shallow water environments in a semi-arid to arid climate.

Bois Blanc Formation

The Bois Blanc Formation outcrops along I-75 a mile south of Mackinaw City (Figure 15) – unfortunately, this outcrop is very dangerous to stop at, so we will not be able to visit it. This unit also outcrops on Bois

Blanc Island in Lake Huron. The Bois Blanc Formation was named by Landes et al. (1945). In this area, the Bois Blanc Formation is composed of cross-bedded, oolitic and skeletal limestones dominated by sand- and gravel-sized grains. The fossil grains are abraded and fragmented. This unit was likely deposited in a high energy shallow marine environment near fairweather wave base.

Figure 15: Slab of the Bois Blanc Formation from the I-75 Outcrop. Note the coarse-grained nature of this limestone – most of the fossils are heavily abraded and the larger clasts in this photograph include stromatoporoids and rugose corals.

Mackinac Breccia

Landes et al. (1945) redescribed the Mackinac Breccia – though interestingly enough Douglass Houghton actually named this unit (though in his field notes, he was not able to settle on one spelling for the unit – starting with Mackinac and then later using Mackinaw). The Mackinac Breccia is an intraclastic grainstone to rudstone (grainstone refers to sand-dominated material, while a rudstone is gravel-dominated) found in the St. Ignace area and Mackinac Island. Landes et al. (1945) also reports outcrops in Cheboygan, Emmet, and Presque Isle Counties. The clasts in the breccia are locally derived and can often be identified as clasts of the St. Ignace Dolomite (muddy dolostones) and Bois Blanc Formation (fossiliferous limestones). The clasts are angular and range in size from sand to boulders. The clasts are weakly cemented and the breccia has significant porosity.

Note that the Mackinac Breccia is an excellent example of the Principle of Inclusions – we know that the unit contains clasts of the St. Ignace Dolomite (Figure 16b) and Bois Blanc Formation, which means the Mackinac Breccia has to be younger than these formations.

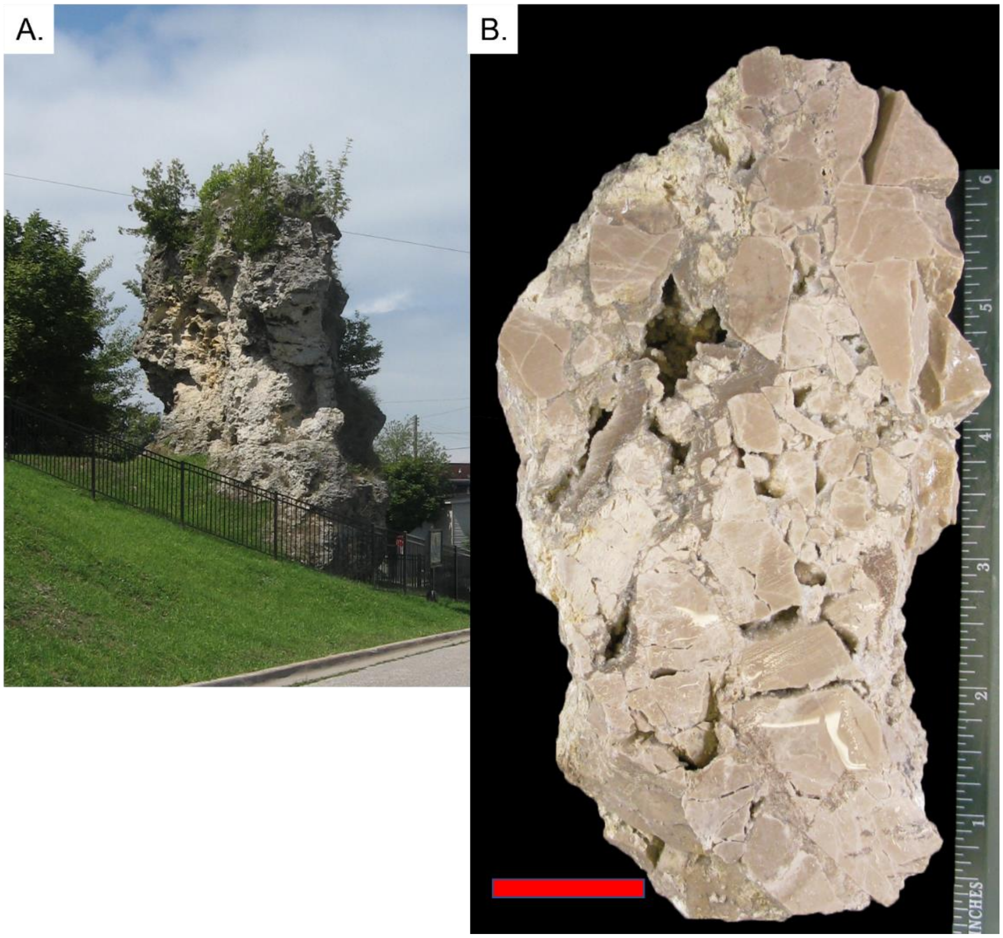


Figure 16. A) St. Anthony's Rock, a sea stack composed of Mackinac Breccia. B) Photograph of the Mackinac Breccia showing the angular nature of the clasts and the high degree of porosity between the clasts. In this example, the clasts are dominated by pieces of the St. Ignace Dolomite (Bass Islands Group). Scale bar is 2.5 cm. Modified from Voice and Harrison (2014).

Landes et al. (1945) interprets the Mackinac Breccia as a collapse deposit – suggesting that dissolution of evaporites in the underlying Pointe Aux Chênes Formation opened caverns that continued to open until the ceilings of the caverns were no longer supported. The ceiling material then collapsed into the caverns producing the chaotic mix of clasts that characterize this unit.

The Mackinac Breccia was a significant obstacle during the construction of the Mackinac Bridge. The high porosity (Figure 16b) meant that this unit soaked up the cement used to fix the pilings for the bridge in place!

Stop 17 – St. Anthony's Rock

In downtown St. Ignace, we will visit St. Anthony's rock (Figure 16a). St. Anthony's Rock was a sea stack created during headland erosion during the Nipissing high water event, 6000 to 3500 years ago. Subsequent isostatic rebound has lifted this wave-cut platform and sea stack above the modern lake level to its current position. St. Anthony's Rock is not the only sea stack in the area – if you drive to the north side of St. Ignace, you can visit Castle Rock which is a second stack (and tourist trap!).

St. Anthony's Rock is carved into the Mackinac Breccia. Take a look at the clasts – can you see any fossils? So which formation supplied the clasts to this portion of the Mackinac Breccia?

Stop 18 – Lemotte St. Pointe Aux Chênes Shale Outcrop

At Lemotte St. in St. Ignace, we will look at a road cut of the Pointe Aux Chênes Shale (Figure 14).

Stop 19 – West Lant Road Outcrop

This outcrop is a safe outcrop to stop at for collecting samples of the Mackinac Breccia (Figure 16b). Again, take a look at the clasts and try to identify which unit supplied the materials that were deposited at this location.

Concluding Statement

Thank you for attending the Michigan Earth Science Teachers Association Summer Field Trip for 2022. I hope that you enjoyed seeing the variety of rock units in the northern margin of the Michigan Basin.

A digital copy of this guidebook will be available at: https://mesta.wildapricot.org/page-18225.
Inquiries for further information can be directed to the author:

Peter.voice@wmich.edu

Peter Voice Department of Geological and Environmental Sciences, Western Michigan University, Kalamazoo. MI. 49008-5241.

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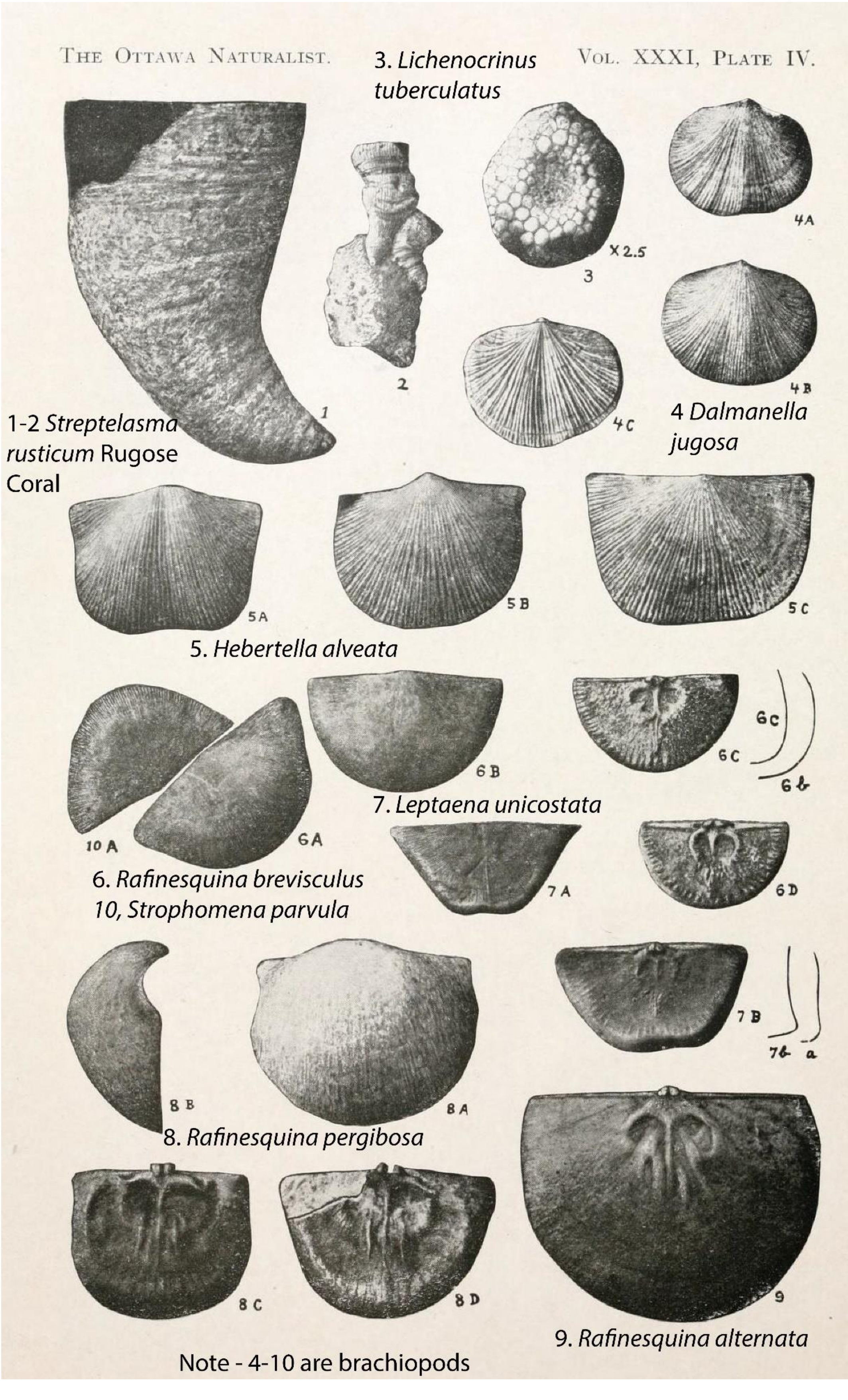
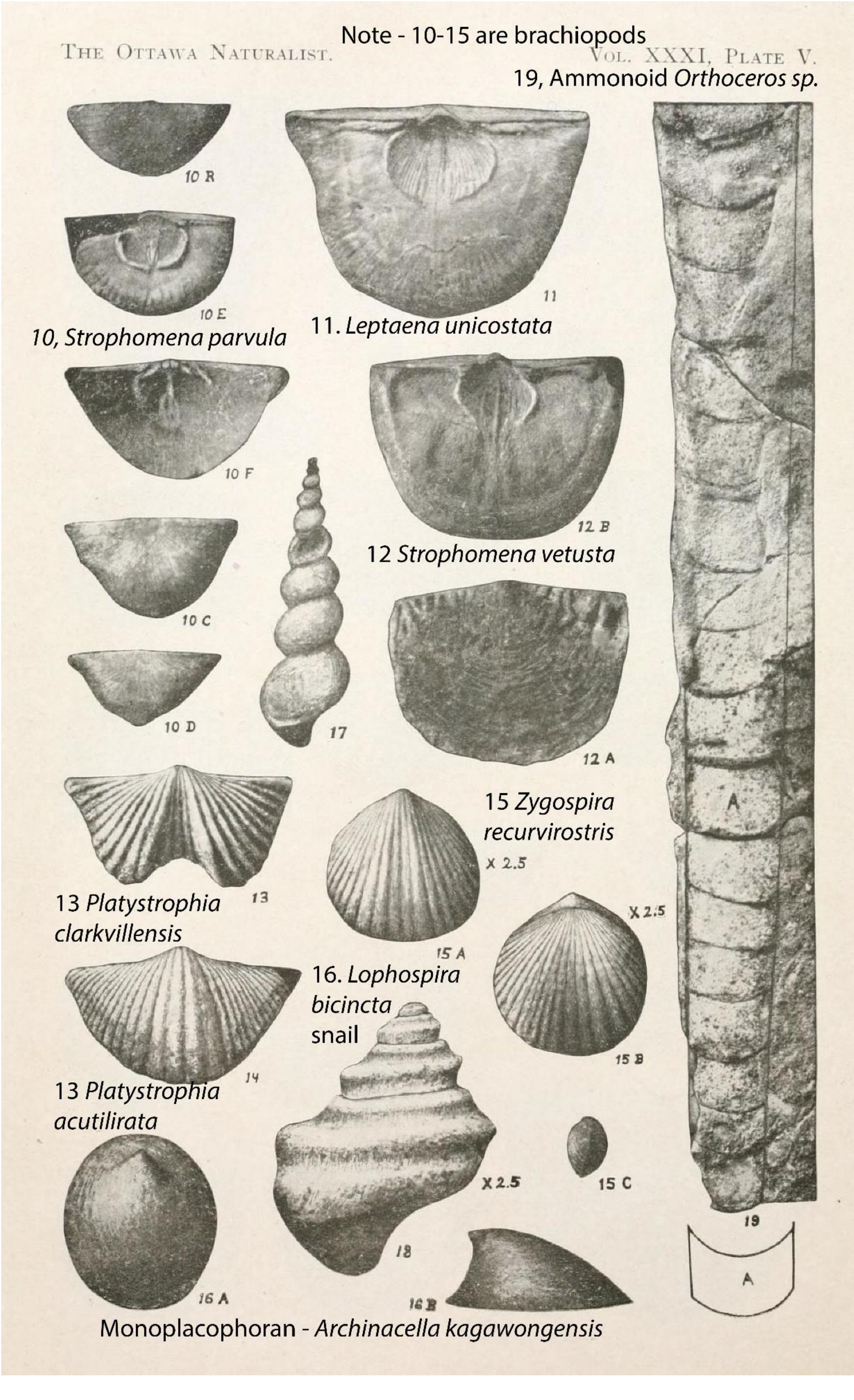
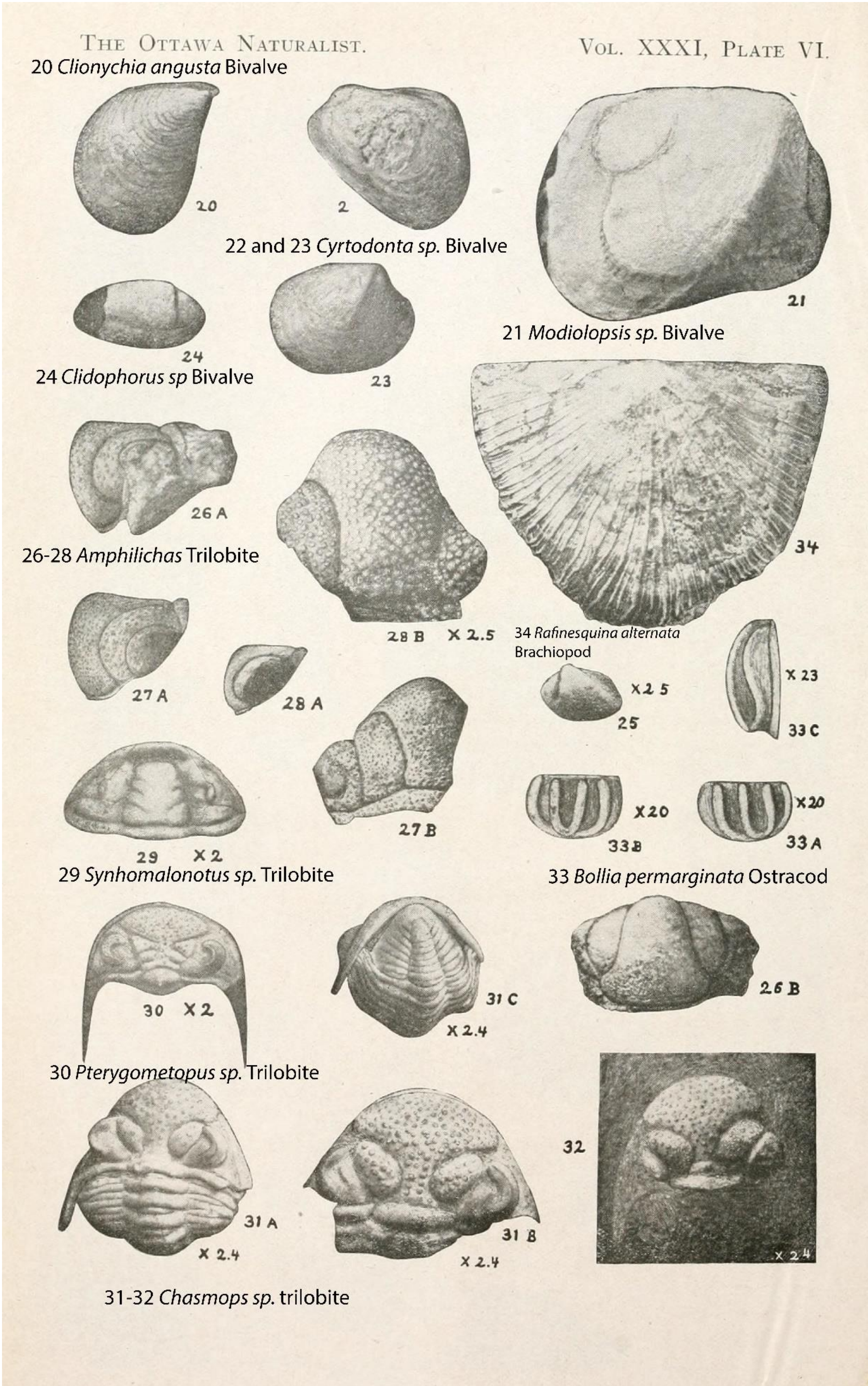
Appendix 1: Stonington Formation Fossils

On the proceeding pages are a series of scans of fossil plates from Foerste (1917) with labels of the different fossils. These will assist you in identifying the fossils you may find.


THE OTTAWA NATURALIST.
VOL. XXXI, PLATE IV.
3. *Lichenocrinus tuberculatus*
1-2 *Streptelasma rusticum* Rugose Coral
4 *Dalmanella jugosa*
5. *Hebertella alveata*
7. *Leptaena unicostata*
6. *Rafinesquina brevisculus*
10, *Strophomena parvula*
8. *Rafinesquina pergibosa*
9. *Rafinesquina alternata*
Note - 4-10 are brachiopods


THE OTTAWA NATURALIST.
Note - 10-15 are brachiopods
VOL. XXXI, PLATE V.
19, Ammonoid *Orthoceros sp.*
10 B
10 E
10, Strophomena parvula
11
11. *Leptaena unicostata*
10 F
12 B
12 *Strophomena vetusta*
10 C
10 D
17
12 A
15 *Zygospira recurvirostris*
X 2.5
A
13 *Platystrophia clarkvillensis*
13
15 A
X 2.5
16. *Lophospira bicincta* snail
15 B
14
13 *Platystrophia acutilirata*
X 2.5
15 C
19
18
A
16 A
16 B
Monoplacophoran - *Archinacella kagawongensis*

THE OTTAWA NATURALIST. VOL. XXXI, PLATE VI.



20 *Clionychia angusta* Bivalve

22 and 23 *Cyrtodonta sp.* Bivalve

21 *Modiolopsis sp.* Bivalve

24 *Clidophorus sp* Bivalve

26-28 *Amphilichas* Trilobite

34 *Rafinesquina alternata* Brachiopod

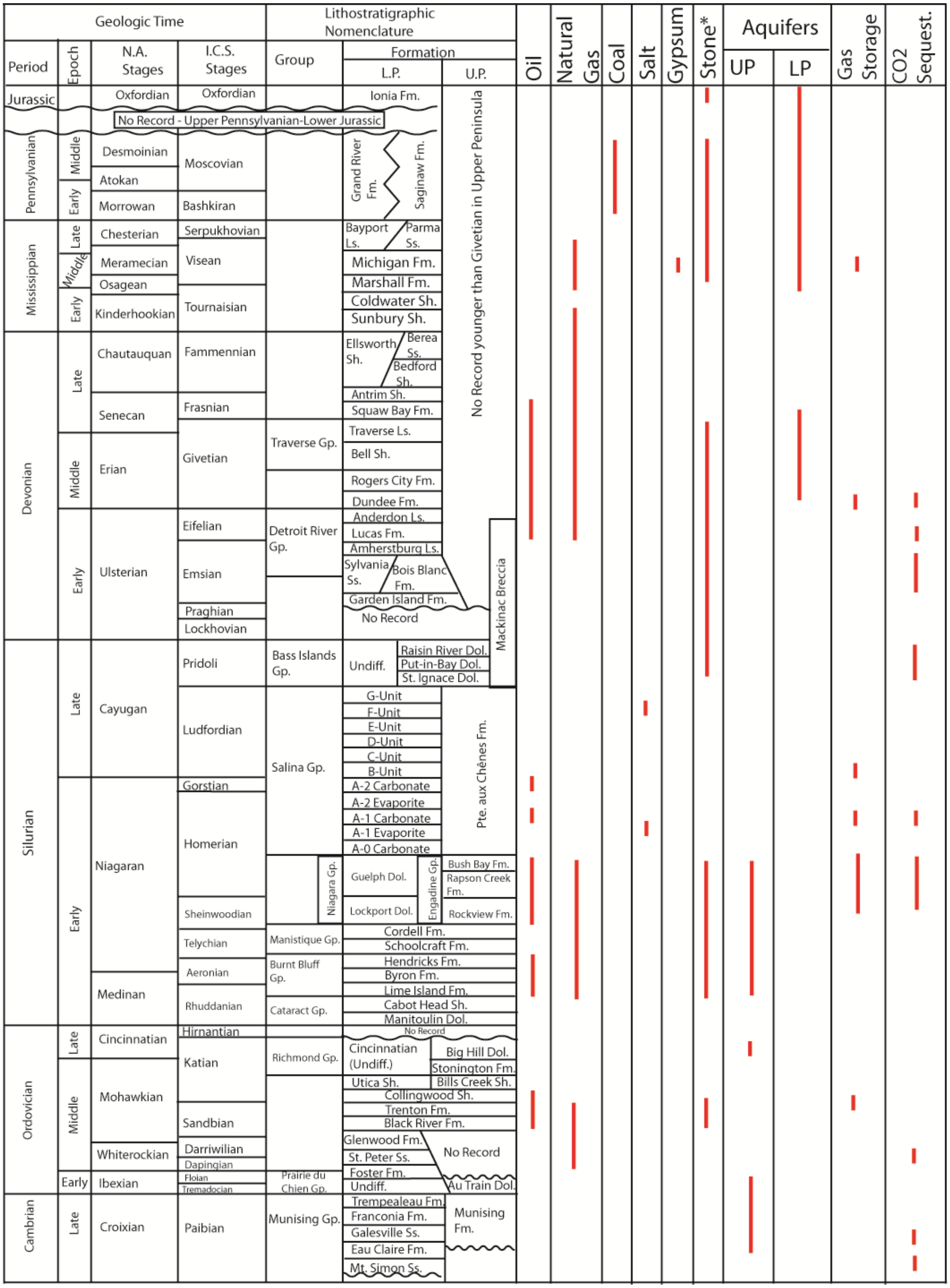
29 *Synhomalonotus sp.* Trilobite

33 *Bollia permarginata* Ostracod

30 *Pterygometopus sp.* Trilobite

31-32 *Chasmops sp.* trilobite

Appendix 2: Geologic Time Scale and Michigan Stratigraphy



From Grammer et al. (2018). Modified from Catacosinos et al. (2001).