STATE OF OHIO
DEPARTMENT OF NATURAL RESOURCES
DIVISION OF GEOLOGICAL SURVEY
Lawrence H. Wickstrom, Chief

Open-File Report 2012-1

GEOLOGY OF THE DAYTON REGION IN CORE AND OUTCROP—A WORKSHOP AND FIELD TRIP FOR CITIZENS, ENVIRONMENTAL INVESTIGATORS, GEOLOGISTS, AND EDUCATORS

By

Gregory A. Schumacher, Michael P. Angle, Brian E. Mott, and Douglas J. Aden

Prepared for the 2012 Geological Society of America
North-Central Section meeting in Dayton, Ohio

Columbus
2012

DISCLAIMER

Cover photo: Steam Boat Rock—Large slump block of Cedarville Dolomite resting in the bed of the Little Miami River at Clifton Gorge State Nature Preserve.

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AGENDA

MORNING WORKSHOP

9:00–10:00 A.M.	Welcome; Geology of the Dayton Region
10:00–11:00 A.M.	Utility of ODNR Division of Geological Survey map products
11:00–12:00 P.M.	Geology of the Dayton Region in core (hands-on exercises)

AFTERNOON FIELD TRIP

1:00 P.M.	Depart Dayton Convention Center
1:00–1:30 P.M.	Drive to Oakes Quarry Park
1:30–2:50 P.M.	**STOP 1: Oakes Quarry Park**
2:50–3:00 P.M.	Drive to Clifton Gorge State Nature Preserve
3:00–4:20 P.M.	**STOP 2: Clifton Gorge State Nature Preserve**
4:20–5:00 P.M.	Fill out evaluations; return to Dayton Convention Center

WORKSHOP AND FIELD TRIP LEADERS

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GEOLOGY OF THE DAYTON REGION IN CORE AND OUTCROP—A WORKSHOP AND FIELD TRIP FOR CITIZENS, ENVIRONMENTAL INVESTIGATORS, GEOLOGISTS, AND EDUCATORS

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INTRODUCTION

The goal of today's core workshop and field trip is to learn about the geology of the Dayton, Ohio, region using Ohio Department of Natural Resources (ODNR), Division of Geological Survey (Survey) mapping products and individual fact sheets for a future field guide entitled: *Ohio's Geology in Core and Outcrop—A Field Guide for Citizens and Environmental and Geotechnical Investigators.* For this guidebook, the Dayton region is defined as Montgomery and Greene Counties, Ohio.

Conducted between January 1, 2007, and December 31, 2009, a survey of nearly 500 Ohio citizens, students, faculty members, environmental scientists, geologists, and government decision makers revealed that when asked—"What is the geology beneath my feet?"—less than 10 percent could correctly identify the bedrock geologic unit they were standing on. These results are very surprising because most visitors to the ODNR Division of Geological Survey Horace R. Collins Laboratory or those attending a presentation about Ohio's geology have a better understanding of, or at least a higher level of interest in, Ohio's geology. Survey respondents were asked: "What can the Survey do to help educate Ohio's citizens on the geology of Ohio?" A common suggestion described the need for a concise field guide that combines existing geologic information available from the Survey and other sources with photographs of Ohio's geologic units in outcrop and core.

"What is the first bedrock unit beneath the Dayton Convention Center?" If your answer is the Late Ordovician-age Grant Lake Formation approximately 180 feet below, congratulations! If you are unsure, don't worry because when we complete this workshop and field trip, you will have a thorough understanding of the geology of the Dayton region. You will be introduced to the Survey's mapping products and how to use them. Hands-on exercises will allow you to answer the question—"What is the bedrock unit beneath my feet?"—at a number of locations in Montgomery and Greene Counties. Also, you will learn how to use a bedrock topography map, how to determine the thickness of the glacial drift and modern sediments, and how geologists map Ohio's glacial drift using stack mapping techniques. By the way, if you are wondering, approximately 180 feet of clay, silt, sand, gravel, and occasional cobbles and boulders have been deposited on top of the Grant Lake Formation that is deeply buried in the ancestral Great Miami River Valley directly beneath the Dayton Convention Center.

Once you have determined the mapped geologic units beneath your feet, you then can use the fact sheets (p. 18–58) to learn about the important characteristics and features that distinguish one geologic unit from the underlying and overlying units. For example, if you turn ahead to the Brassfield Formation fact sheet (p. 48), you will find an introductory paragraph describing: (1) the characteristic rock or rocks found in the Brassfield, (2) the environment present in the Dayton region when the Brassfield was deposited, (3) how the Brassfield was named, (4) the Brassfield's mapped distribution in the state of Ohio, and (5) unit thickness of the Brassfield. Also, the statewide distribution of the Brassfield is shown on a geologic map found in the upper left corner of the fact sheet, above the geologic time scale.

The body of the Brassfield fact sheet consists of twelve major categories providing information about: (1) diagnostic features, (2) general characteristics of the rocks comprising the unit, (3) how the rocks vary from one part of Ohio to another, (4) what fossils are present, (5) how this unit weathers when exposed, (6) the nature of the contacts with the overlying and underlying geologic units, (7) the overlying and underlying units and similarity of the Brassfield to other geologic units mapped in Ohio, (8) engineering properties, (9) hydrogeologic properties, (10) environmental hazards associated with the unit, (11) economic geology, and (12) scenic geology. The final components of the fact sheet are photographs of the Brassfield in both core and natural or man-made exposures and suggestions for further reading to learn more about the unit.

The future field guide will provide fact sheets for 85 surficial and bedrock geologic units mapped throughout Ohio. In some cases, figures or tables may be included for a particular unit to illustrate important geologic information.

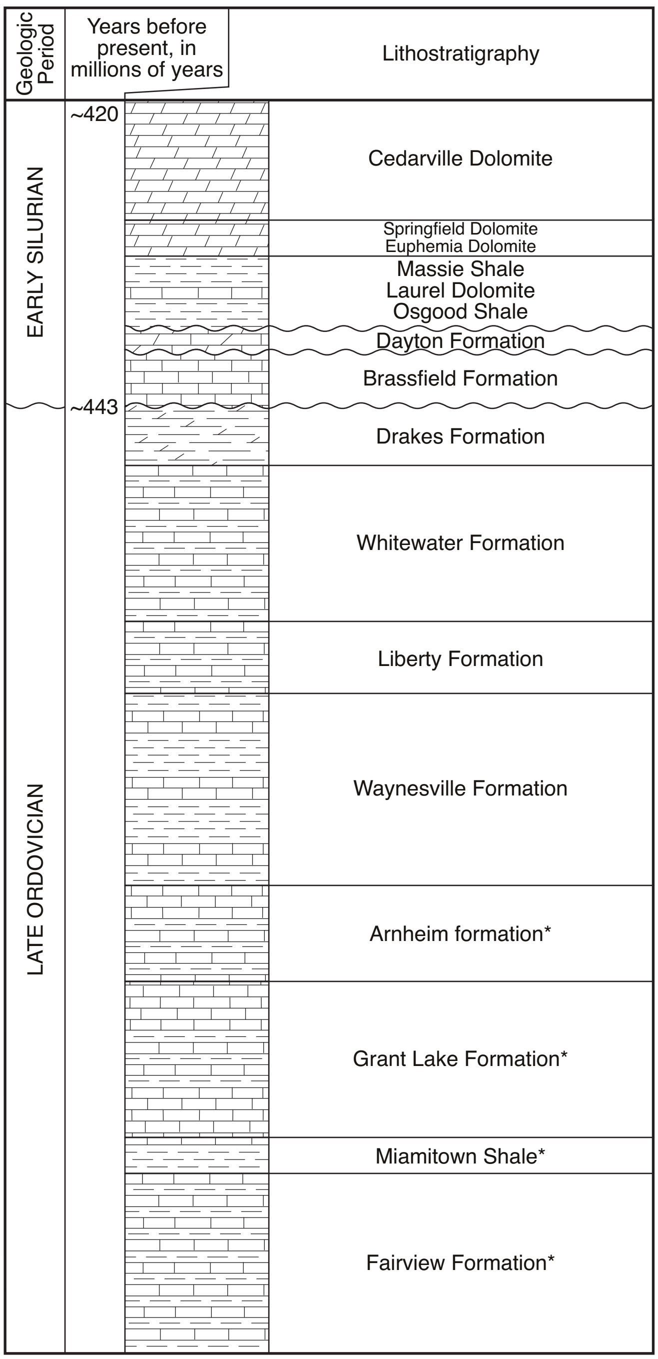
GEOLOGY OF THE DAYTON REGION

The surficial materials and near-surface bedrock of the Dayton region are defined as the earth materials that occur within a few hundred feet of the present-day land surface. These materials consist of soils, river deposits (alluvium), and glacial drift overlying bedrock, ranging in age from the Late Ordovician to the Late Silurian. Soils are defined as being the uppermost 5 to 6 feet of weathered material that overlay the uppermost parent material, which may be rock, alluvium, or glacial drift. The soils contain distinct layers or horizons that reflect the various weathering processes. Alluvium deposits are mainly gravel, sand, and silt and are associated with the active floodplain of streams and rivers. Glacial-drift sand-and-gravel deposits are located in outwash terraces and ice-contact features, such as kames that often occur adjacent to active floodplains. In 2010, over 608,000 tons of sand and gravel were mined in Montgomery County and 1,236,000 tons in Greene County (Wolfe, 2011). Other glacial-drift deposits consist of clay; silt; pebbles; cobbles and boulders; glacial till; and organic matter, such as peat or fossil plant and animal remains.

A major gap or unconformity in the rock record occurs at the contact between the bedrock and glacial drift throughout the region. Some 420 to 450 million years of Earth history are missing at this contact, depending on where you are in the Dayton region (fig.1). For example, if the bedrock/drift contact occurs at the base of the Brassfield, then about 440 million years of Earth history are missing, while at the top of the Cedarville Dolomite roughly 420 million years are missing.

A second major gap occurs at the contact between the Late Ordovician-age Drakes Formation and the Early Silurian-age Brassfield Formation. Geologists estimate about one million years are missing at this unconformity. At Oakes Quarry Park, you will able to walk on and study both of these major gaps in Earth history. At Clifton Gorge State Nature Preserve (SNP), only the major gap between the bedrock and glacial drift is present.

Underlying the glacial drift of the Dayton region are the highly fossiliferous limestones and shales of the Late Ordovician or the limestones, dolomites, and shales of the Early to



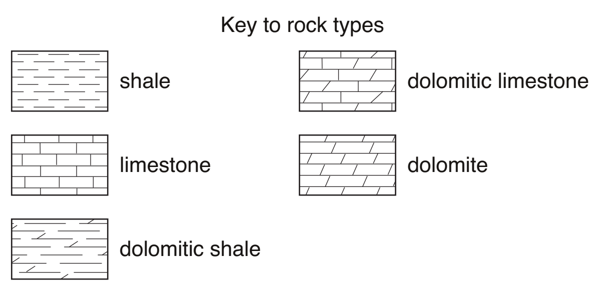


FIGURE 1.—Bedrock near-surface and subsurface stratigraphy of the Dayton region. Stratigraphic units highlighted with an asterisk (*) are generally buried under glacial drift infilling the ancestral valleys of the Great Miami and Mad Rivers. Geologic time scale modified from Gradstein and others (2004).

Late Silurian. A total of 17 geologic units, nine Ordovician and eight Silurian, have been mapped by the Survey from rocks of the Dayton region (fig. 1). You will have the opportunity to examine many of these units in core during the workshop, and you will examine outcrops of the Brassfield Formation and the Euphemia, Springfield, and Cedarville Dolomites at Oakes Quarry Park and Clinton Gorge SNP during the afternoon field trip.

During the Late Ordovician, one of Earth's warmest periods, shallow tropical seas covered the Dayton region and contained abundant and highly diverse sea plants and creatures. Large hurricanes formed in the Iapetus Sea, located east of ancestral North America, and swept across the Dayton region (fig. 2). Hurricane waves eroded the bottom sediments, suspending the finer-grained materials, and transported the coarser material (called *bed load*) along the sea bottom. The prolific types of plants and animals living in this sea, at the sea bottom or within the bottom sediments, were unearthed, dislodged, toppled, and covered in the sediment-laden bed load. As the hurricane moved away and wave energy decreased, the bed load of coarse-grained sediment and plants and animals settled out as a shelly layer. This shelly layer was buried under a layer of finer-grained sediments that was in turn buried under a thin layer of mud. This process generally takes less than a day to complete and occurred countless times during the Late Ordovician. The net result was the deposition of over 900 feet of alternating, coarser-grained fossiliferous limestone and sparsely fossiliferous shale beds or laminations.

Near the end of the Ordovician, Earth's climate rapidly cooled allowing the polar climate zone to expand considerably north across the supercontinent of Gondwana. Large continental glaciers formed, locking up considerable amounts of water and causing the sea level to lower. Also, along the ancestral margin of North America the Taconic Mountains were being uplifted, causing the sea to retreat. In the Dayton region, the Ordovician seas drained away and dry land emerged for about one million years because of the combined effects of glaciation and regional uplift associated with mountain building. No sediments were deposited as the Late Ordovician landscape slowly eroded away. Because geologists do not have rocks from this time of erosion to study, Earth's history in the Dayton region is unknown for about a million years.

During the Early Silurian, Earth's climate alternated from warm and cool periods, resulting in the Gondwana continental glaciers advancing and retreating across the continent. Worldwide sea level would rise as the glaciers melted and then fall when the glaciers advanced. The repeated fluctuations of sea level caused the seas to advance and retreat a number of times along the coastal lowlands associated with the eastern flank of the uplifted Cincinnati Arch of western Ohio. Lagoonal, intertidal, and shallow-marine environments formed as sea level inundated the coastal lowlands, allowing the accumulation of limestone, dolomite, and shale characterizing the Silurian mapped units of the Dayton region. The Brassfield Formation; Dayton Limestone; Osgood Shale; Laurel Dolomite; Massie Shale; and Euphemia, Springfield, and Cedarville Dolomites all were deposited during times of rising sea level. As sea level fell, minor gaps in Earth's history would form within these units or at the contacts between some of them.

Regional uplift associated with the onset of a second episode of mountain building, known as the Acadian Orogeny, drained the seas from western Ohio during the Late Silurian; this is the beginning of a long period of erosion that was occasionally interrupted by a return of the seas during the 420 million years of Earth history missing from the Dayton region. Any rocks deposited during these periods of higher sea level have been removed by later erosion. Caves and sinkholes have been developing on the eroding Silurian rocks for a long time and continue to form today (fig. 3).

Beginning about two million years ago, the mighty Teays River and its tributaries drained the Dayton region, eroding the local landscape. The climate was cooling rapidly, resulting in large continental glaciers forming in modern-day Canada. The glaciers advanced at least four times over the Dayton region, leaving behind a relatively thin blanket of glacial drift on the upland areas and largely filling the ancient valley of the Teays River and its tributaries with thick accumulations of drift (Hansen, 1995, 1997a). The advance and retreat of these large glaciers continued until about 16,000 years ago, when the glaciers finally melted away from the Dayton region. The blanket of glacial drift

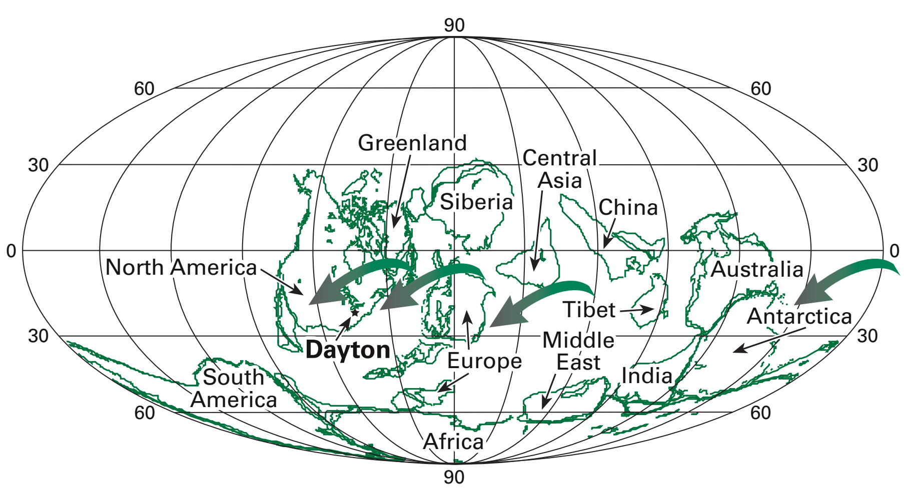


FIGURE 2.—Location of the Dayton region in Ordovician time. Large arrows depict the probable Ordovician hurricane tracks. Modified from Coogan (1996).

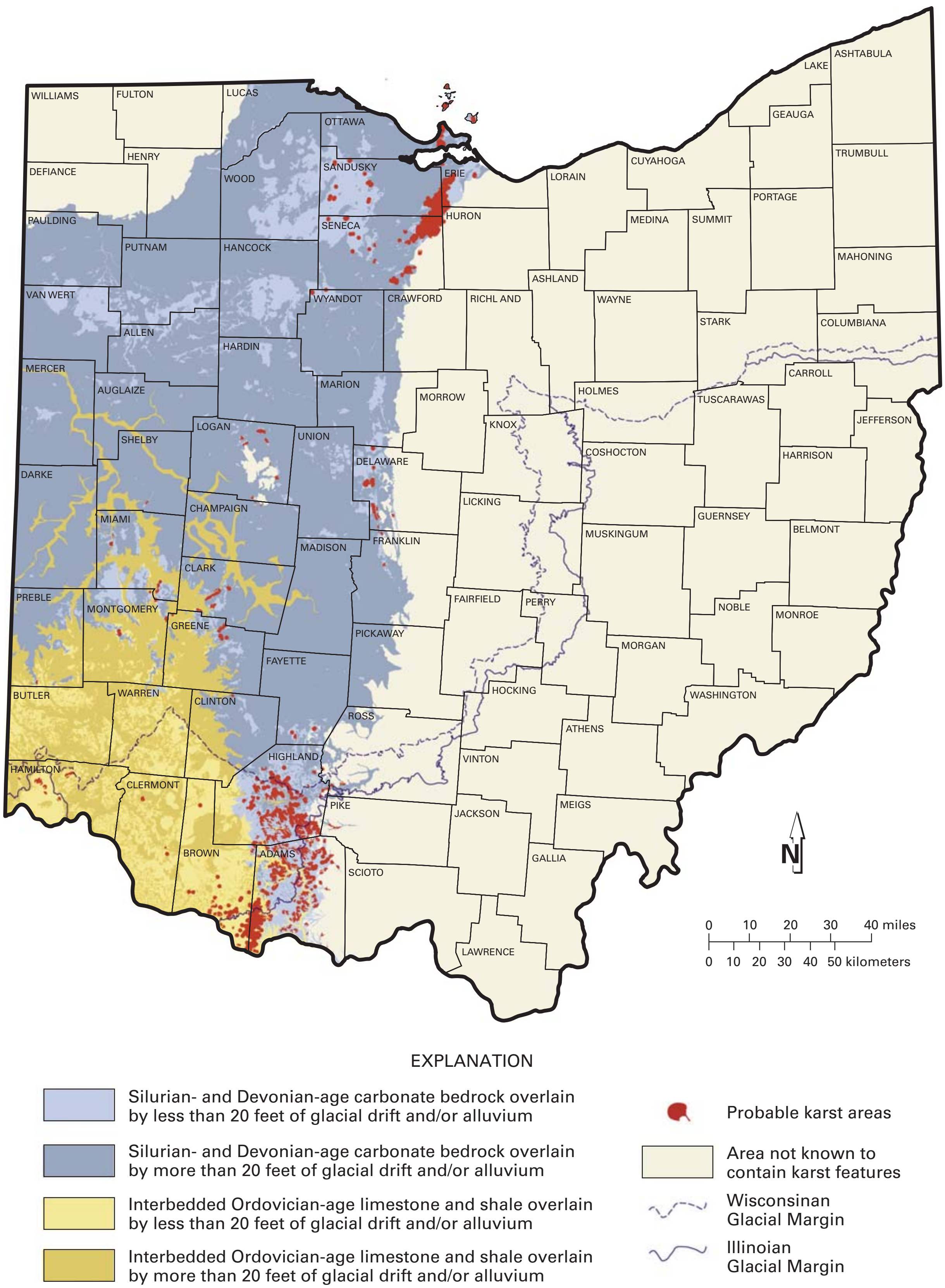


FIGURE 3.—Ohio karst areas. The area illustrating probable karst in Greene County is located in the vicinities of Clifton and Cedarville, Ohio.

slowly began to erode away and form the fertile soils of Ohio and the modern alluvium present in the valleys of the Great Miami, Little Miami, and Mad Rivers and their tributaries.

For interested readers there are many publications that address the geology of the Dayton region. The following listing is by no means comprehensive but provides a basis to start learning about the interesting and complex geology of the Dayton region: Foerste, 1915; Horvath and Sparling, 1967; Hull, 1982; Ausich, 1987; Hansen, 1997b, 1998; Camp, 2006; McLaughlin and others, 2008; Schumacher, 2008; Sandy, 2012.

WHAT GEOLOGIC MAPS SHOULD I USE TO DETERMINE THE GEOLOGY BENEATH MY FEET?

One of the questions commonly asked by callers requesting geologic information from the Survey is: "What is the geology of my property?" Survey geologists have thousands of published geologic maps and reports, open-file materials, considerable personal knowledge, and field experience at their fingertips to answer many of the geologic questions commonly asked by Ohio citizens. Digitally scanned images of Survey open-file geologic maps, accessed via desktop computers, enable a staff geologist to quickly and efficiently answer most questions with just a few clicks of a computer mouse.

What is an open-file geologic map? Open-file geologic maps consist of data and interpretations portrayed on 1:24,000-scale (1 inch = 2,000 feet), 7.5-minute topographic quadrangle maps issued by the U.S. Geological Survey (see Hansen, 2011). The land area of Ohio is subdivided into 788 7.5-minute quadrangles, each 6.5 miles wide (east to west) and 8.7 miles high (north to south). Quadrangle maps show the locations of cultural features, such as schools, homes, barns, places of worship, fence lines, roads, rail lines, and pipelines; political boundaries, such as county, township, and section boundaries and boundaries of cities and towns; and natural features, such as lakes, ponds, rivers, and forested areas. Quadrangle maps, commonly referred to as "topo maps," also depict topographic contours. Topographic contours (generally brown in color) represent lines of equal surface elevation relative to mean (i.e., average) sea level. For example, all points along a line labeled "800" are 800 feet above sea level. Because of the wealth of information portrayed on a topographic map and the relationship of topography to geology, topographic quadrangles are the primary base maps used by Survey geologists for compilation and presentation of geologic-map information.

Beginning in 1985 and continuing through 1997, Survey geologists produced bedrock-geology, bedrock-topography, and structure-contour maps for each of Ohio's 788 topographic quadrangles (Swinford, 2007). After the completion of the statewide bedrock-mapping program in 1997, and continuing through today, surficial-geology maps have been produced for many topographic quadrangles to create small-scale (1:100,000), print-on-demand surficial-geology maps, such as Map SG-2: *Surficial Geology of the Ohio Portions of the Cincinnati-Falmouth 30 X 60 Minute Quadrangles* (Brockman and others, 2004).

What are bedrock-geology, bedrock-topography, and surficial-geology maps? Bedrock-geology maps show the distribution of the hard, layered sedimentary rocks that may be exposed at the land surface or, more commonly, buried beneath a blanket of soil and surficial materials overlying the bedrock. Ohio's bedrock units consist primarily of shale, sandstone, limestone, dolomite, coal, and clay. These bedrock units can be thought of as the layers of a devil's food cake. The icing on top of the cake represents the surficial materials, primarily soil, alluvium, and glacial drift, which have been deposited over the western and northern three-quarters of Ohio (See Schumacher and Hull, 2006).

Bedrock-topography maps depict the irregular surface of bedrock buried under the overlying surficial materials (Swinford, 2001, 2003). Elevation contours are used to represent equal elevation on the buried bedrock surface in the same manner that contours are used to depict elevations on the land surface of topo maps. In other words, the bedrock-topography map is analogous to producing a contour map of the irregular upper surface of our devil's food cake underlying the chocolate icing.

Surficial-geology maps delineate the composition and distribution of unconsolidated sediments, deposited by rivers, streams, and Ice-Age continental glaciers upon the bedrock surface. These maps, sometimes called *stack maps*, illustrate the major sediment and the thickness of the map unit in a polygon. For example, the stack for the surficial sediments mapped under the Dayton Convention Center is 5 to 15 feet of modern alluvium, underlain by sand-and-gravel deposits that range in thickness from 35 to 105 feet, underlain by a discontinuous till deposit that ranges from 10 to 30 feet, underlain by 0 to 120 feet of sand-and-gravel deposited in a trough shaped sediment body.

Bedrock-geology maps, bedrock-topography maps, surficial-geology maps, and many other types of geologic maps are available for purchase or public inspection at the Survey's Geologic Records Center located at 2045 Morse Road, Building C, Columbus, Ohio, 43229. In addition, Survey geologists will gladly respond to phone-in requests for brief descriptions of the geology for any area of the state. For assistance, call (614) 265-6576 and request to be transferred to a geologist in the Geologic Mapping and Industrial Minerals Group.

WHAT IS ROCK CORING?

The bedrock of the Dayton region is largely buried under a blanket of soil and glacial drift, making it difficult to study the characteristics of the underlying bedrock geologic units. Exposures that do exist occur in natural stream exposures and man-made quarries, highway and railroad cuts, and other excavations. In areas where the glacial drift and bedrock is not exposed by natural or man-made excavations, core drilling is one way to acquire samples for study and various geologic and engineering analyses.

A typical coring bit would be attached to a series of drilling pipes called *drill rods* (fig. 4). A large drill rig with powerful motors supplies the power to turn the drill rods and coring bit as it drills its way into the earth. The cylinder of rock produced by core bit drilling into the earth is removed by a second pipe, called the *inner barrel*, which receives the core as it passes into the drill rods. Once a length (usually ten feet) of core is drilled, drilling stops and the drill rods are

FIGURE 4.—Typical drill bits. Core drill bit with example of drilled core (right) and tri-cone drill bit with an example of well cuttings collected from a boring for an oil-and-gas well.

unscrewed and moved aside. The inner barrel is removed by dropping a tool that fastens to the top of the inner barrel and lifts the core out of the inner barrel by means of a long cable. Once the core is removed, the inner barrel is returned to the inside of the drill rod and allowed to sink to the bottom of the hole. The drill rig is reattached to the drill rods and drilling the next ten feet of core begins; this process is repeated until the desired depth (or *total depth*) in the earth is reached. The total depth depends on what the geologist or engineer is interested in learning about the area they are studying. For example, if the Survey is interested in determining the near-surface stratigraphic section in the Dayton region, between 300 and 500 feet of core would need to be drilled. By contrast, a core of five to 10 feet may be all that is necessary to provide the necessary geotechnical data for an engineering firm to design a new highway.

Core can be drilled at a variety of diameters ranging from 1 inch to over 36 inches, but the majority of core is drilled in the 2–4-inch diameter range. Coring is very expensive, so it is relatively rare when continuous core is taken from a bore hole. Typically, there needs to be a direct purpose for drilling core. Examples may include a large engineering project; expansion of a quarry or sand-and-gravel operation; testing for possible ground resources; or exploration for oil, gas, or coal resources.

The development of side-wall coring has replaced continuous coring in many boreholes because it is considerably cheaper and less time consuming. Boreholes subject to side wall coring are drilled using standard tri-cone drilling bits and then geophysically logged to determine, for example, porous zones within the borehole. A drilling tool containing the side-wall coring device is lowered into the borehole to the level of a porous zone and then the coring device drills into the wall of the borehole to remove the side-wall core. The core is brought to the surface for additional study and to conduct a variety of tests to determine many geologic properties of the rocks of the borehole, including the permeability of porous zones.

FIELD TRIP ROAD LOG

Depart from Dayton Convention Center at 1 P.M. sharp!

Cumulative Miles	
0.0	Start at Dayton Convention Center parking lot
0.1	West Fifth Avenue south to St. Clair Street
0.4	St. Clair Street south to interchange with U.S. 35 East
6.0	U.S. 35 east to I-675 north
15.7	I-675 north to S.R. 235 east, Exit 22
15.9	S.R. 235 east to Oakes Quarry Park
	STOP 1: OAKES QUARRY – 1 hour, 20 minutes; water & snacks
18.5	Depart Oakes Quarry, left on S.R. 235, drive to Dayton-Yellow Springs Road
22.7	Northeast on Dayton-Yellow Springs Road to U.S. 68
25.7	North on U.S. 68 then east on S.R. 343 to Clifton Gorge SNP parking lot
	STOP 2: CLIFTON GORGE – 1 hour, 20 minutes; bathroom break. Loop trail along gorge rim and into gorge; **departure time at 4:20 P.M.**
28.7	S.R. 343 west to junction with U.S. 68 & Dayton-Yellow Springs Road
31.7	Dayton-Yellow Springs Road southwest to S.R. 235
34.5	West on S.R. 235 to I-675 south
44.2	I-675 south to U.S. 35 west
48.6	U.S. 35 west to Main Street/Jefferson Street exit
49.8	Jefferson Street north to Dayton Convention Center

Arrive at Dayton Convention Center at 5 P.M.

STOP 1: OAKES QUARRY PARK

INTRODUCTION

Today, we will take a leisurely stroll back in time to learn about the geology of Oakes Quarry Park (Wolfe, 2008a). We will use geologic maps (fig. 5) and fact sheets to answer questions about the characteristics of the Brassfield Formation and overlying glacial drift. Also, we will use our imaginations to explore the Early Silurian world that was very different from our world today.

As we explore Oakes Quarry Park, you may want to think about the following questions and where you may find the answers to these questions. Why was the Brassfield Formation mined at Oakes Quarry and at other quarries in the Fairborn area? What do the cracks or *joints*, as geologists call them, tell us and how do they relate to the uplift of the ancestral Appalachian Mountains? Why does the quarry floor consist of an undulatory surface of highs and lows and how does this relate to the Ordovician-Silurian gap in the geologic record? Why are unconformities in Ohio important to oil and gas production?

To experience the Early Silurian world, we will use our imaginations as we board a luxury cruise ship to sail the southern Silurian seas that covered the Dayton region some 440 million years ago. Our experienced captain will navigate through the shallow, reef-filled, tropical waters teeming with many strange and exotic creatures that are extinct today. You may want to take a few minutes to examine the many blocks of limestone to see how many different types of creatures you can identify. When we walk from the quarry floor to the polished surface forming the top of the highwall, think about why giant fossil shark teeth, coal, and dinosaur fossils are not found in the Dayton region. As we walk to the top of the highwall, keep in mind you will be traveling from beautiful tropical seas that covered the Dayton region during the Early Silurian to investigate how the last major glacier of the Ice Age influenced the geology of Oakes Quarry Park, some 16,000 years ago. Did you find any glacial striations that can be used to determine ice flow direction? Are there one or two directions of ice flow? How does ice flow direction in Oakes Quarry relate to the regional glacial geology of the Fairborn area?

GEOLOGY OF THE OAKES QUARRY PARK

Early Silurian

As we enter Oakes Quarry, keep in mind that the surface you are walking on was once covered by 20 to 40 feet of the Brassfield Formation that was mined away during quarrying (fig. 6). The Brassfield Formation is classified as a high-calcium limestone or a limestone that contains less than 5 percent dolomite or magnesium carbonate. High-calcium limestone has many industrial uses and, according to Wolfe (2008b), is described as the “duct tape” of geological materials. The limestone mined at Oakes Quarry was used to manufacture Portland cement that has been used to literally hold together the many concrete roads and brick and stone buildings in the Dayton region. The abundance of inexpensive Portland cement has stimulated construction and economic growth throughout the area since the 1920s. Today, high-calcium limestone is in great demand for use in electric-generating plants to remove sulfur dioxide from flue gas emissions. So, mining of the Brassfield will continue for decades into the future.

After entering the quarry, you will notice that you are walking on a sandy-looking rock. If we take a small piece, grind it to a powder, and add hydrochloric acid (HCl), the powder would fizz. The fizz is the result of carbon dioxide being liberated as calcium-magnesium carbonate reacts with HCl, forming calcium-magnesium chloride, carbon dioxide, and water. Calcium-magnesium carbonate is commonly called *dolomite*.

The Belfast Member of the Brassfield Formation is what geologists would classify as a *bioturbated dolomite* or a dolomite that has been churned by millions of burrowing organisms that inhabited the near-shore depositional environment that formed the Belfast (fig. 7). Take a moment and count how many burrows occur in a one-square-foot area.

As we walk across the Belfast, you will observe numerous joints penetrating into the Belfast beneath your feet. Also, you will notice that the Belfast is not a flat-laying unit but contains a series of highs and lows, forming an undulatory surface. Some of the joints present in the Belfast were produced by man-made activities, such as the forces generated by the explosive charges used to break up the overlying Brassfield. However, you will notice that other sets of joints occur in a distinct pattern (fig. 7). Pick any joint and follow it until it intersects with a second joint. What is the approximate angle at the intersection of the two joints? In most cases, the joints are offset from one another by about 90º. This offset is caused by the regional stresses applied to these rocks long ago that caused the rocks to break along zones of weakness located about 90º to one another. When the directions of joints are measured, most of the measurements range from N80ºE to N80ºW to N25ºE to N25ºW (fig. 8). What does this prominent joint pattern tell us?

To answer this question we must travel back in time some 435 million years and examine Earth and its land masses. As we cruise the southern seas during the Early Silurian, the Dayton area was located about 25º south of the equator and the North American continent was rotated about 45º clockwise (fig. 9). About 120 million years later, the position of Earth’s continents had changed dramatically. North America moved north and was located on the equator. Africa and Europe were moving away from North America after a collision that produced the Appalachian Mountains (fig. 9). In the Dayton region, the great collision did not cause the formation of a high mountain range but instead gently uplifted the rocks in the area. The stresses applied by this uplift caused widespread expansion of the Belfast rocks, which responded to this stress by breaking in the joint pattern that you just measured.

The uplift of the ancestral Appalachian Mountains (the Taconic Highlands), combined with an Ice Age that occurred in the southern hemisphere during the preceding Late Ordovician and Early Silurian, caused the shallow oceans to

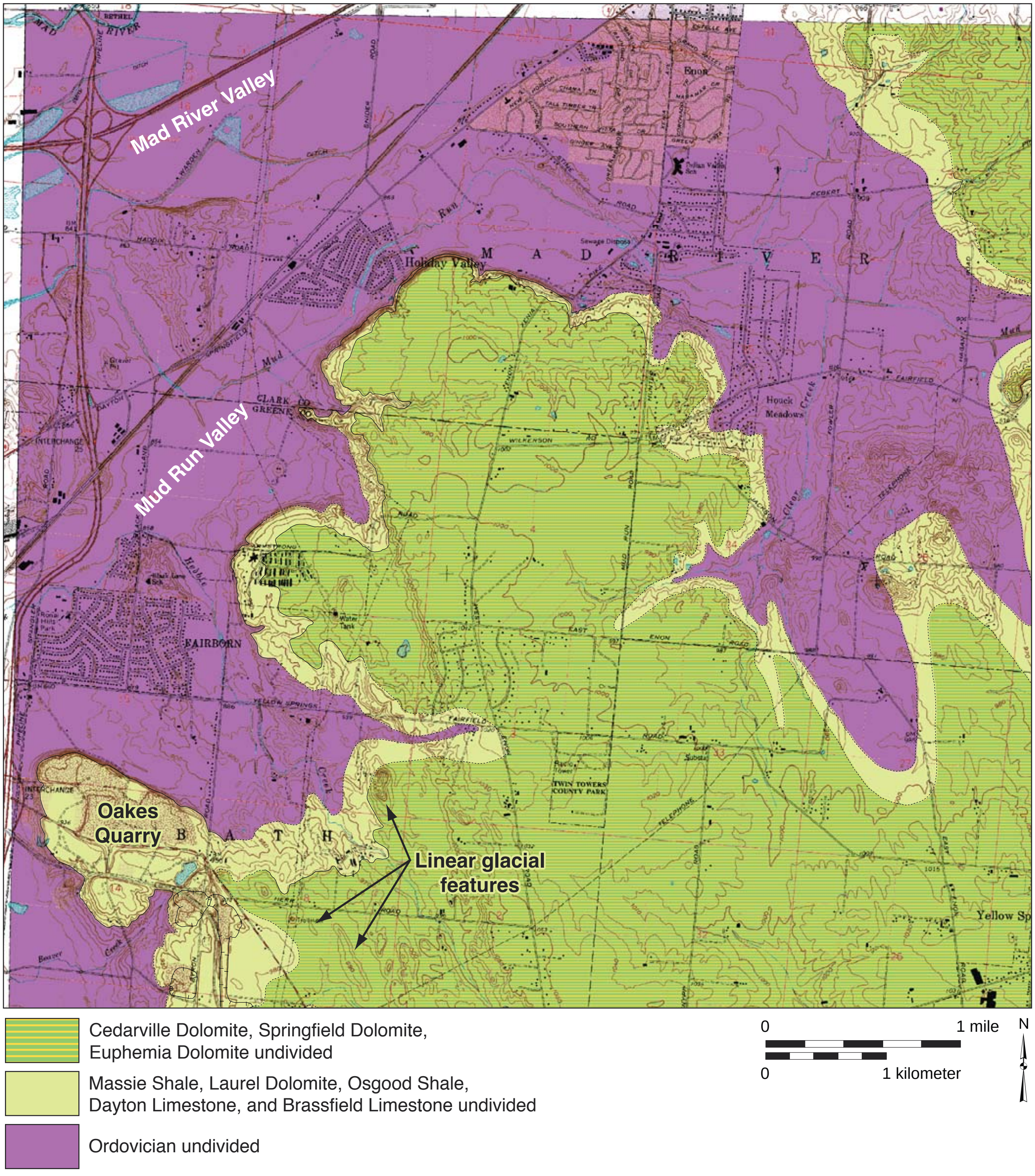


FIGURE 5.—Bedrock geologic map of Oakes Quarry Park area illustrating the broad valleys of Mud Run and the Mad River. These valleys would have been the first areas filled with advancing glacial ice. As the glacial ice thickness increased above the elevation of the adjacent uplands, ice would flow laterally over Oakes Quarry and to areas eastward. The southeastward flowing ice produced linear glacial features that parallel ice and meltwater flow direction.

FIGURE 6.—The eastern highwall of Oakes Quarry Park displaying the characteristic thin- to thick-bedded, fossiliferous, high-calcium limestone of the Brassfield Formation and prominent joints. ***For your safety, please stay away from the highwall and loose talus***!

FIGURE 7.—Belfast Member of the Brassfield Formation in Oakes Quarry Park floor. The darker, pitted areas are burrows of the trace fossil *Thalassinoides*. Prominent joint pattern is illustrated by the linear cracks that cross the upper surface of the Belfast in multiple directions. Scale is 19.625 inches (0.5 meters) long.

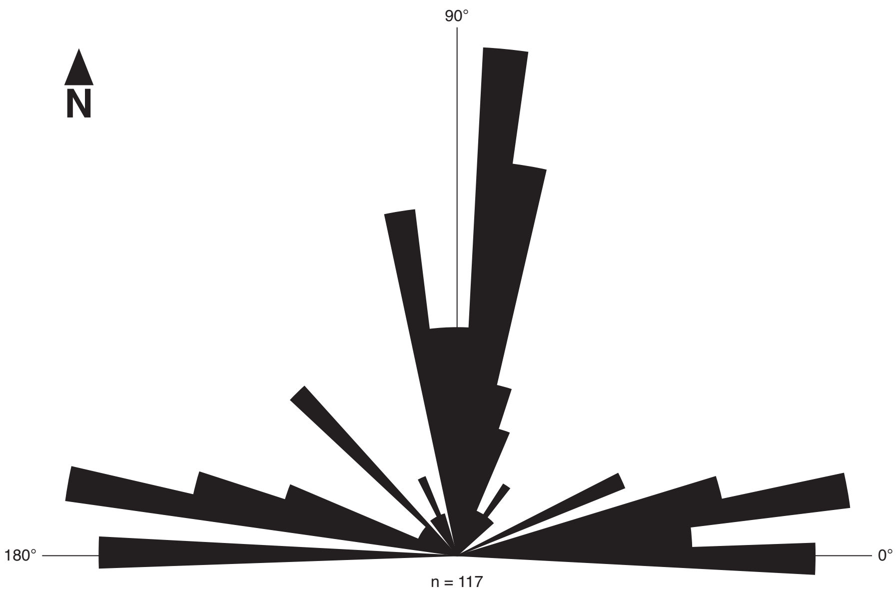
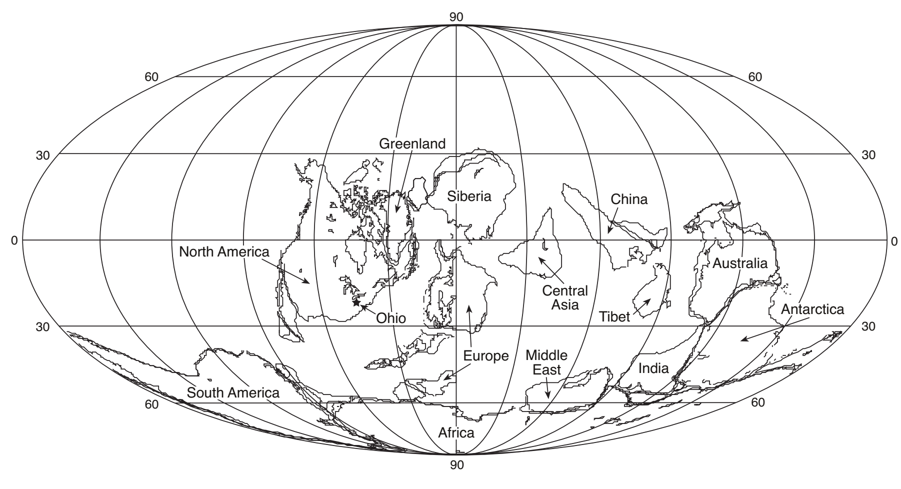


FIGURE 8.—Rose diagram illustrating the prominent joint orientations preserved within the Belfast Member of the Brassfield Formation as exposed in the floor of Oakes Quarry Park. Measured by Emily Denlinger, Matt Erenpriess, Jonathan Pratt, Steve Riley, Greg Schumacher, and Claire Westervelt.



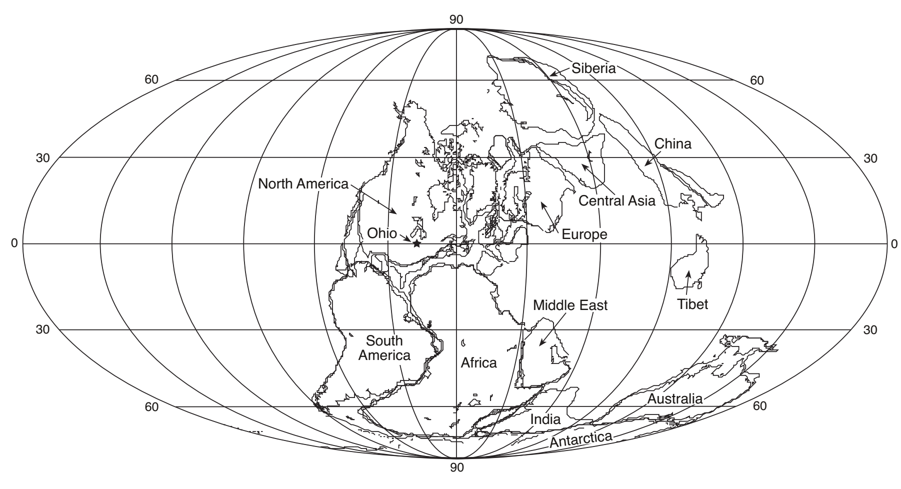


FIGURE 9.—Postulated position of the continents during the Late Ordovician/ Early Silurian (~443 mya; top) and Middle Pennsylvanian (~310 mya; bottom). Modified from Scotese and Denham, 1988.

drain away from the Dayton area. The Ordovician landscape was largely barren of vegetation except for algae and fungi because flowering plants and trees did not evolve until millions of years later. This landscape was subjected to a period of erosion that likely created a landscape of low hills and valleys with streams and rivers that flowed to distant seas. In the Early Silurian, the seas returned to the Dayton region and the Belfast Member and Brassfield Formation were deposited over the Ordovician landscape. The contact between the Belfast and the underlying Ordovician rocks is a break in the rock record of some one million years, and the Ordovician-Silurian unconformity, just a few feet beneath your feet, represents the eroded landscape, some 440 million years ago. Thus the highs and lows exhibited by the Belfast were, in part, created by deposition on top of the ancient Ordovician landscape, by stresses associated with the building of the Appalachian Mountains, and by stresses associated with glacial ice movement during the most recent Ice Age.

Unconformities in Ohio's limestone and dolomite rocks create increased porosity and permeability through dissolution of these rocks by acidic rainwater. Many of Ohio's major oil-and-gas fields occur in the porous limestone and dolomite rocks below major unconformities. Many of the unconformity-bound oil-and-gas fields across Ohio are now depleted. However, recent advances, such as horizontal drilling and hydraulic fracturing, may result in additional oil and gas being produced from these depleted reservoirs.

Past production practices left large amounts of oil in the ground because they burned off the natural gas present in the reservoir. The natural gas was used to heat homes and fuel street lights, and oil was a byproduct. Pressure is required to force the oil from the ground to the surface. Removal of natural gas depressurized many reservoirs. If the reservoirs could be pressurized again, this lost oil could be produced. Considerable research in the injection of carbon dioxide as a pressurizing agent is under way not only to sequester the carbon dioxide, preventing it from being released into the atmosphere, but also to enhance the recovery of oil currently lost in these old fields (Wickstrom, 2007).

Informative signs explaining the geology and fossils of Oakes Quarry Park are located near the east highwall of the quarry. You may want to take a few minutes to read these signs and examine the highwall, but do so **from a distance** to avoid the hazard of falling rocks. **Do not climb on the rubble below the highwall.** Also, you may want to examine the loose rocks piled on the floor of the quarry.

Notice how the bedding of the Brassfield Formation becomes tilted or cross-bedded as you look up the section. Also, notice the abundant fossilized remains of extinct sea creatures that make up the major part of each piece of limestone. These are important clues to understanding the geology of the Brassfield Limestone. You likely found representatives of the following strange and exotic creatures: crinoids, corals, stromatoporoids, brachiopods, bryozoans, mollusks, and rare trilobite fossils.

As mentioned earlier, the Belfast Member of the Brassfield Limestone was deposited very near an Early Silurian shoreline. Water depths ranged from inches to only a few feet deep. There were periods when the Belfast sediments were exposed to the atmosphere. The Belfast environment is interpreted as being very similar to the modern tidal flats in tropical regions. On modern tidal flats many different types of organisms burrow through the sediments for food and shelter. The burrows of these organisms are readily apparent and often are preserved in the fossil record, as we see in the Belfast. The deposition of the Belfast Member stopped when sometime later, sea level rose as continental glaciers melted in Gondwana, causing the warm tropical seas, teeming with organisms, to flood over the Belfast mud flats. The calcium-rich skeletons of crinoids, corals, stromatoporoids, brachiopods, bryozoans, mollusks, and rare trilobites flourished in these tropical waters. Their skeletons, some of which you collected today, accumulated to a thickness of 20 to 40 feet in the quarry. Near the top of the rocks exposed at Oakes Quarry are thicker-bedded limestone beds that are tilted or cross-bedded. These cross-bedded limestone beds consist of the broken pieces of the strange creatures that lived during the Early Silurian. As water depths decreased, this skeletal material was moved around by wave action into large sand bars very similar to those seen offshore from many of the beaches along the modern Atlantic and Gulf of Mexico coasts. In the Brassfield, cross-bedding provides evidence that sea level was falling near the top of this unit.

Geologists know that the Brassfield was deposited in warm tropical seas with a normal marine salinity because distant relatives of many of the fossils you collected are found only in tropical climate zones today. Corals continue to form patch reefs today just as they did during the Early Silurian.

Ice-Age

Our cruise ship has now returned to port. We will disembark and follow the trail to the top of the east highwall of the quarry. At the top of the highwall is the glacially polished surface of the upper part of the Brassfield Formation. This polished surface represents the second major unconformity present in the quarry (fig. 10). Approximately 435 million years of geologic time is missing. Geologists assume that younger Silurian, Devonian, and maybe Carboniferous rocks were deposited on top of the Brassfield Formation at Oakes Quarry. However, these rocks have been eroded away during the 435 million years of extensive erosion, leaving only the Brassfield Formation and the overlying thin deposits of glacial drift. Thus the long period of erosion creating this major unconformity removed any rocks that may have contained coal or the fossils of giant sharks or dinosaurs.

You will notice two types of scratches or striations present in the polished surface. The lighter striations were produced by earth-moving equipment as the 10–20 feet of overlying clay-rich glacial drift, called *glacial till,* were removed to allow mining of the Brassfield Formation. The darker striations, which parallel one another, were produced as multiple continental glaciers moved across Oakes Quarry during the Pleistocene Epoch, some 24,000–16,000 years ago. Measurements of these striations with a compass should range between N40ºW to N60ºW (fig. 11).

About 16,000 years ago, the last of four major advances of large continental glaciers retreated from the Dayton region. As the glacier retreated, sediment-laden meltwater flowed down the nearby Mad River and Mud Run valleys,

FIGURE 10.—The polished upper surface of the Brassfield Formation as exposed at Oakes Quarry Park by the removal of the overlying glacial drift. This surface represents a major gap in geologic time of about 435 million years. The surface of the Brassfield was polished by glaciers and by meltwater moving boulders, cobbles, gravel, and sand repeatedly back and forth across this surface. The dark striations were produced by large boulders and cobbles gorging the Brassfield surface.

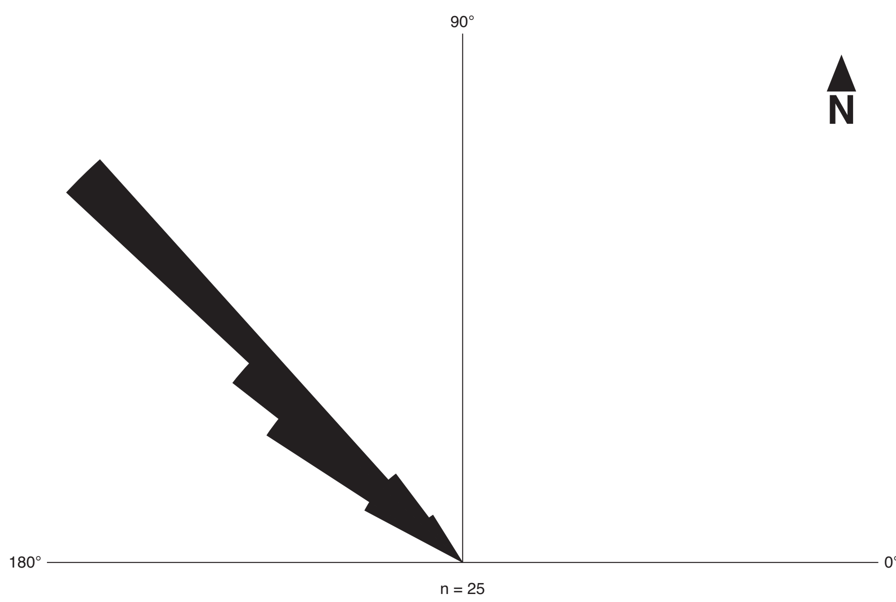


FIGURE 11.—Rose diagram showing that the movement of glacial ice and meltwater at Oakes Quarry Park was from the northwest to the southeast. Figure 5 illustrates a similar pattern of linear glacial features that correspond to a northwest–southeast ice or meltwater flow.

filling them with hundreds of feet of sand and gravel and finer-grained sediments. At Oakes Quarry, located near the top of the Mud Run valley wall, only a thin veneer of glacial till was deposited.

Initially, as the glacier advanced into the Dayton region from the north, the thin, leading edge of the glacier would be channeled down the valleys of Mad River and Mud Run. As the glacier continued moving south, the ice thickness increased to the point that ice would become higher than the adjacent valley walls and adjacent uplands. The ice would then flow out onto the upland areas like Oakes Quarry Park.

The base of this glacier was often "dirty" with large quantities of sediment, ranging from huge boulders to clays. The sediment-laden base acted as a giant piece of sandpaper and sanded or polished the upper part of the Brassfield Formation. Often the larger boulders and pebbles would gouge into the Brassfield forming the striations we examined today.

So which direction did the glacier move to form the striations measured today? The glacier flowed from the northwest to the southeast across this part of Oakes Quarry. In fact, the topographic features present on the geologic map also display a northwest–southeast lineation (fig. 5). Thus during the glacial advances of the Ice Age, ice flowed from the Mad River and Mud Run valleys over Oakes Quarry land surface prior to quarrying and southeastward toward the Little Miami River valley.

STOP 2: CLIFTON GORGE STATE NATURE PRESERVE

The geology at Clifton Gorge SNP highlights the erosive power of large amounts of meltwater from retreating glaciers of the last Ice Age combined with the ongoing erosion of Little Miami River. Clifton Gorge SNP was dedicated in 1970 to protect one of the most scenic gorges in western Ohio. The preserve contains 269 acres and is best accessed from a paved parking lot and trail located 0.5 miles west of Clifton, Ohio, just south of State Route 343.

The gorge originates east of Clifton, just upstream from the State Route 72 bridge over the Little Miami River (fig. 12). The river channel is confined to a narrow gorge that is nearly 100 feet deep in the portion of the gorge examined on this field trip. Carman (1946) has summarized the various stages of gorge formation using a series of cross sections beginning east of Clifton and continuing to John Bryan State Park (SP; fig. 13).

As we walk along the rim trail, imagine some 14,000 to 18,000 years ago when great torrents of water were rushing over the polished upper surface of the Cedarville Dolomite of the region. Soon these waters began to erode weaker portions of this polished surface. As you examine Figure 12, notice how Little Miami River is confined to a gorge made up of more or less straight segments between the bends of the river. These linear segments compare favorably to the joint pattern measured at Oakes Quarry Park (fig. 8), indicating that the regional joint pattern controls the drainage of Little Miami River in Clifton Gorge SNP and John Bryan SP.

The narrow vertical gorge was produced by water eroding away the weaker broken rock adjacent to the joints in the otherwise erosion-resistant Cedarville Dolomite. With time, the river cut through the Cedarville, Springfield, and Euphemia Dolomites into the softer and more easily eroded interbedded shale, limestone, and dolomite beds of the underlying Massie Shale, Laurel Dolomite, and Osgood Shale. The rapid erosion of these units undercut the overlying resistant dolomites. As undercutting continues, the dolomite gorge wall becomes unstable and topples into the gorge forming huge dolomite boulders. We will walk through one of these boulder fields as we traverse the gorge trail to Amphitheater Falls.

Carman's classic interpretation of the formation of Clifton Gorge may be only part of the answer as to how the gorge formed. Meltwater flowing from a retreating glacier no doubt played a major role. However, Ritter (2012) suggests that some of Clifton Gorge may have been cut by meltwaters flowing under the overlying glaciers or that perhaps the gorge is part of the pre-Ice Age drainage system of the region.

At Amphitheater Falls, we will utilize Figure 12 and the fact sheets to study the characteristics of the Springfield and Cedarville Dolomites exposed in the gorge wall. The majority of the gorge wall is comprised of the massive beds of the Cedarville Dolomite. Why does the Cedarville Dolomite appear to have very few pores or vugs, which were so abundant in the core samples we examined? Upon closer inspection, the gorge wall at Amphitheater Falls is following a joint exposed when the Cedarville on the river side of the joint toppled into the gorge. The porosity of the Cedarville has been plugged by calcium carbonate that precipitates from mineral-laden ground water as it evaporates into the atmosphere after seeping from the gorge wall.

What distinguishes the Springfield Dolomite from the overlying Cedarville Dolomite? The Springfield Dolomite, which is exposed near the base of the gorge wall, weathers to a diagnostic brick-like pattern highlighting the horizontal bedding of the unit and the vertical joints that cut through the individual beds. The Springfield has been quarried for many years for use as a building stone because bed thickness ranges from 4 to 12 inches and the bedding planes are parallel (Bownocker, 1915). Many of the walls and stone buildings in the Clifton Gorge SNP and John Bryan SP are constructed of the Springfield Dolomite.

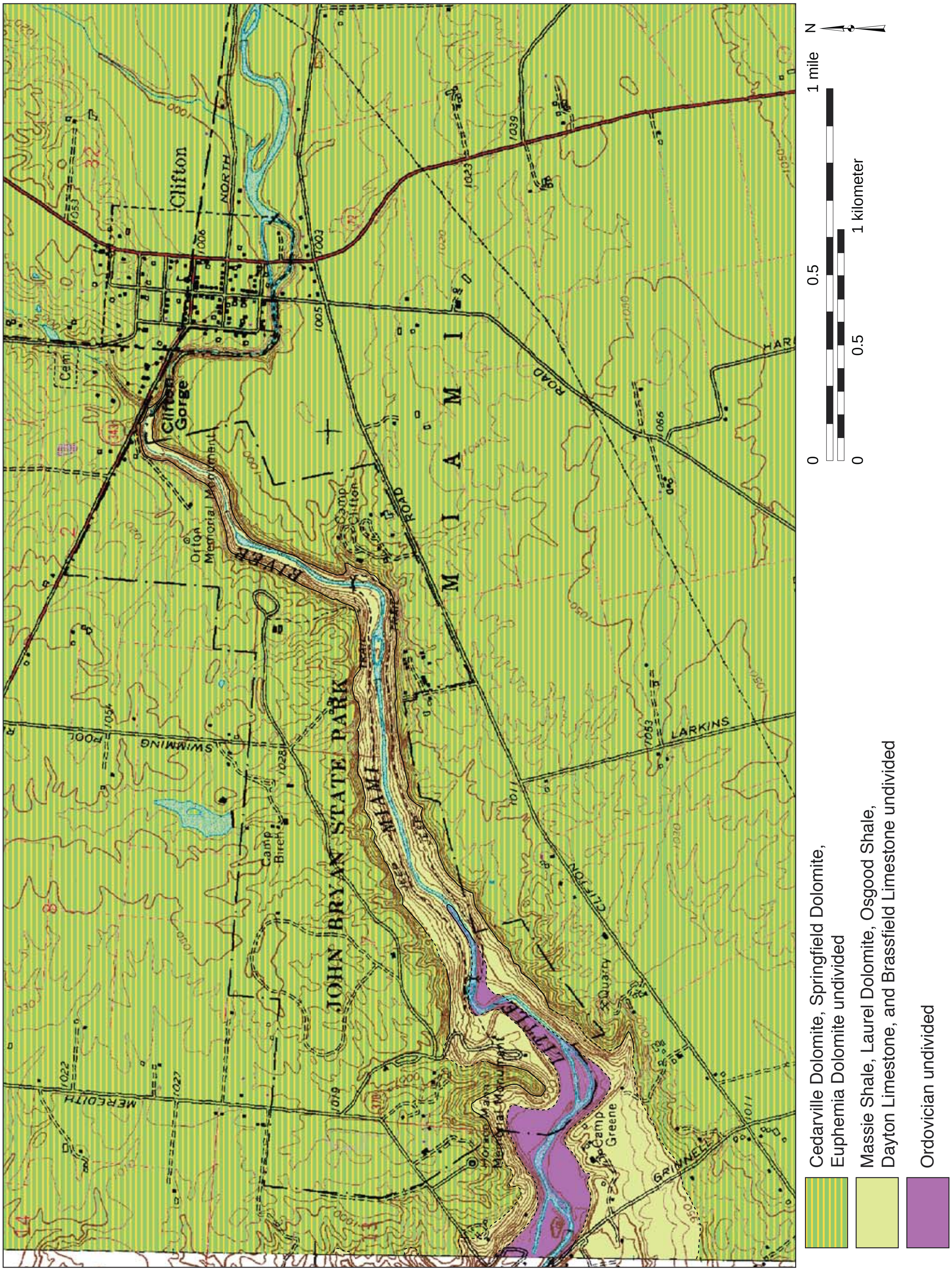
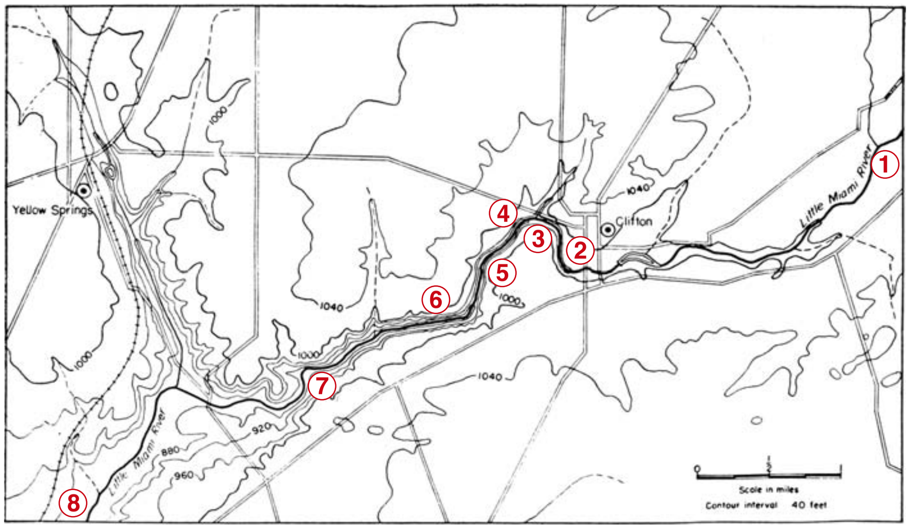


FIGURE 12.—Bedrock geologic map of the Clifton Gorge State Nature Preserve area illustrating the joint-controlled drainage of the Little Miami River.



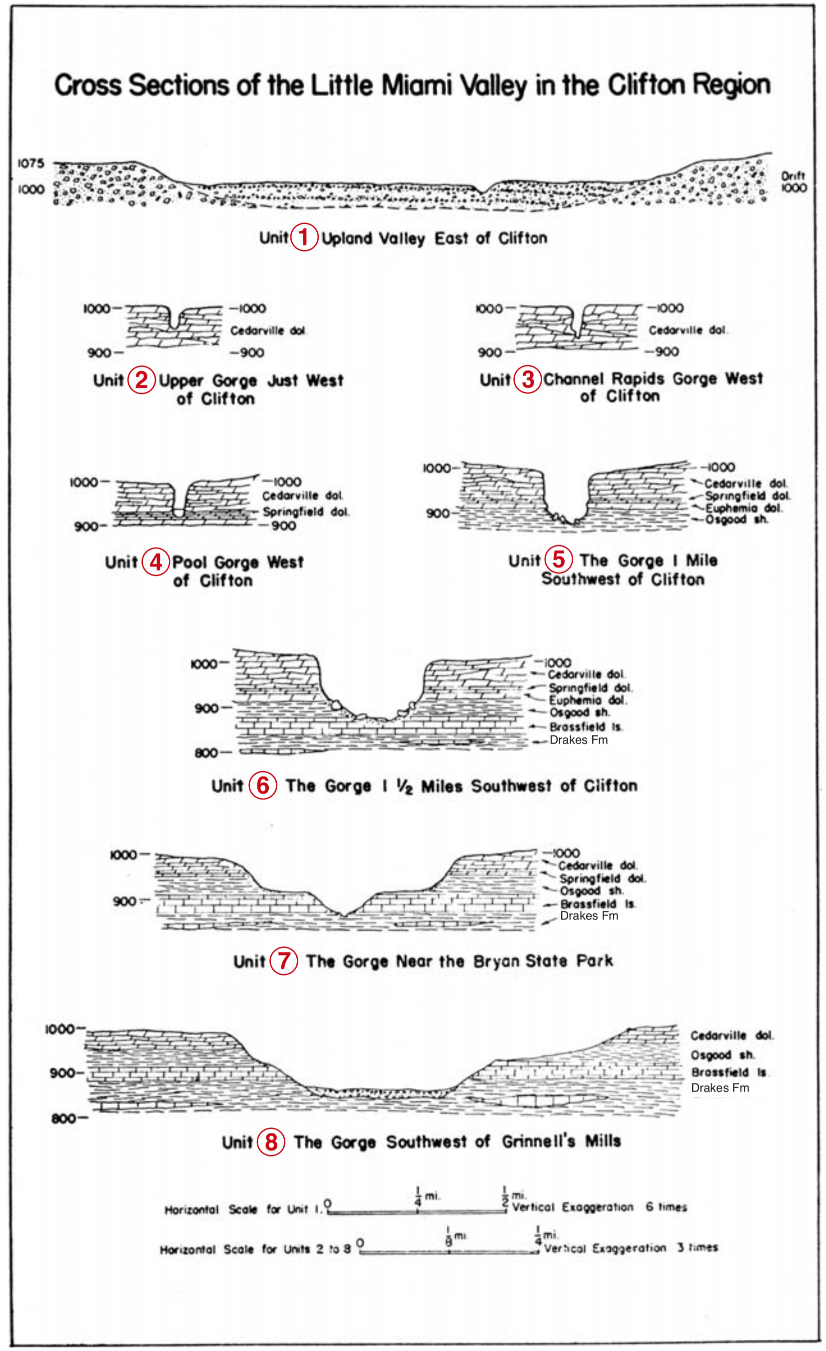


FIGURE 13.—Stages of gorge formation of Little Miami River in the Clifton, Ohio, area as illustrated by a series of cross sections modified from Carmen (1946). Topographic map of the Little Miami River Valley in the Clifton-Yellow Springs region shows the location of the cross-sections. We will examine the gorge of the Little Miami River as illustrated by units (or locations) four and five.

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Special thanks to Ed Kuehnle, Lisa Van Doren, and Chuck Salmons for editing and assisting in the production of this workshop and field guide.

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Glacial Till

Till is an unsorted, non-stratified (non-bedded) mixture of sand, gravel, silt, and clay deposited directly by the ice sheet. At the land surface, till accounts for two primary landforms: ground moraine and end moraine. Ground moraine (till plain) is relatively flat to gently rolling. End moraines are ridge-like with terrain that is steeper and more rolling or hummocky. Typically, till is thinner in areas of ground moraine and thicker in end moraines.

Diagnostic features:

- Typically will be defined texturally or according to grain-size as a silty clay or clayey silt.
- May have a significant proportion of fine to coarse sand and gravel, pebbles, or cobbles surrounded by a "matrix" of finer-grained materials.
- Typically lacks bedding, sorting, or laminations.
- May be highly compacted, massive, dense (lodgment till) and range to more loosely compacted, friable, and disaggregating relatively easily (ablation till, "melt-out" till, or highly-weathered till).

General features:

- Gray where unoxidized; brown where weathered; mottled colors may represent variable water table conditions.
- Important to note the structure (massive, blocky, prismatic, etc.).
- Important to note moisture content (damp, moist, sticky, plastic, saturated, etc.).

Lithologic variations:

- Uppermost unit is typically more clayey in northern Ohio.
- Uppermost unit is typically loamier in southwestern Ohio.
- Till units typically are more compacted and pebbly with depth.
- Carbonate content of matrix and pebbles increases in western Ohio, based on underlying bedrock units.

Fossil content:

- Fossils not inherent.
- May contain wood, tree trunks, and stumps overridden and eroded by advancing ice sheet.
- May contain durable fossils eroded from underlying bedrock (e.g., horn corals).

Weathering characteristics:

- Note degree of oxidation, mottling of colors, presence of fractures/jointing, rotting of pebbles, pres-

Loamy glacial till in outcrop along the Auglaize River (Defiance County).

ence of secondary carbonate or gypsum coatings/crystals.
- Weathering affects hydrogeologic properties, mainly secondary permeability and porosity.
- Rotting pebbles/ghosts may skew results of textural analysis.

Stratigraphic contacts:
- Contacts may vary from very sharp to gradational. Sharp contacts may feature a "stone line" of cobbles.
- Till may incorporate or scoop up materials from underlying units, making contacts appear even more transitional.
- Be careful not to base contacts only on color changes.

Stratigraphic context:
- Typically uppermost surficial unit. Soils survey and ODNR Division of Geological Survey maps are best sources of information on this topic.
- Till may be encountered in buried valleys to depths up to 400 ft in central Ohio.
- Multiple till units may be encountered. Non-till lithologies may/may not occur between till units.

Engineering properties:
- Unconfined Compressive Strength—Variable.
- Depends upon degree of saturation.
- Depends on nature of till (lodgment vs. ablation, etc.).

Hydrogeologic properties:
- Generally considered to be an aquitard or aquiclude, not an aquifer.
- Historically, dug wells have produced yields from till, and monitor wells in the saturated zone will maintain water levels.
- Recharge variable.
- Laboratory tests record permeability ranging from 10^{-7} to 10^{-9} cm/sec^2.
- *In-situ* slug texts/long-term pumping tests reveal permeabilities ranging from 10^{-5} to 10^{-7} cm/sec^2 for weathered, fractured tills.
- Wells completed in till utilize small bodies, seams, or lenses of interbedded sand and gravel; size, nature, and geometry of these lenses, plus interconnection between lenses, determines the corresponding yield.

Environmental hazards:
- Slumping may occur along steep slopes and under saturated, high water table conditions.
- Presence of a high water table determines a number of building constraints on basements, foundations, septic systems, leach fields, etc.
- Soils surveys and ODNR Division of Geological Survey maps are good sources of information regarding characteristics of till locally.

Economic geology:
- Important fill materials for a number of activities, such as highway embankments, earthen dams, levees, etc.
- Where fine-grained, may be suitable as a liner for ponds, landfills, manure containment, and reservoirs when compacted adequately.
- May be suitable as cover material for landfill operations.

Scenic geology:
- Indurated, erosion-resistant tills can produce scenic, steep bluffs, commonly found along the margins of downcutting streams in areas of thick glacial drift. Examples include outcrops in Defiance, Geauga, Franklin, Licking, and Preble Counties.

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Glacial Sand and Gravel Deposits

Sand is a particle that ranges in size from 0.0625 mm to 2 mm. It is subdivided into categories ranging from very fine grained to medium grained to very coarse grained. Gravel ranges in size from 2 mm to 64 mm. Very fine gravel is referred to as *granules*, larger gravel sizes are referred to as *pebbles*. Cobbles range in size from 64 mm to 256 mm, and boulders are considered to be greater than 256 mm. Cobbles and boulders are commonly disseminated throughout glacial till deposits. Cobbles and boulders within a sand-and-gravel deposit indicate a very high-energy environment and typically rapid deposition. It may indicate an outwash deposit very close to the energy source (melting glacier) or perhaps more likely an ice-contact deposit, such as a kame or esker.

Diagnostic features:

- Sand, gravel, or a combination of the two, are dominant over fine-grained materials, such as till, lacustrine, or modern, finer-grained alluvium.
- Deposits may vary from relatively loose and friable to very dense and cohesive.
- Sand and gravel can vary from well to poorly sorted to chaotic. Deposits may be relatively uniform or highly variable. Deposits may be viewed as being "clean" or "dirty."
- Bedding can be highly variable and massive, parallel, cross-bedded, gradational, or otherwise.

General features:

- Surficial geomorphology and setting are important in helping determine the nature and origin of a sand-and-gravel deposit. Typically, outwash deposits are more highly influenced by fluvial processes than by processes associated with ice wastage.

Lithologic variations:

- Outwash deposits are usually associated with broad valleys and underlie wide modern floodplains and adjacent terraces.
- Kame and ice contact features are more likely found along the margins of valleys; adjacent to end moraines; marking outflow areas associated with former intermorainal lakes; or in regions of obvious ice-marginal, ablational (ice-wastage) terrain.
- Deposits in both the surface and subsurface reflect changes in water energy and bedload.
- Change from coarse to very fine-grained sediments can vary from sharp to gradual in both surface and subsurface.

Fossil content:

- Fossils are typically uncommon due to the high-energy environment.

Weathering characteristics:

- Weathering and predominant coloration of sand and gravel bodies is important in determining position of the water table, areas within the zone of recharge, and maximum extent of atmospheric oxygen in the profile.

Sand-and-gravel pit illustrating thick, cross-bedded sand beds underlying an extensive sand-and-gravel deposit (Hamilton County).

- Degree of weathering is important in determining the hydrogeologic properties of the material, including permeability and porosity.
- Weathering characteristics are important. Highly weathered units will develop a fine-grained weathering zone at the top surface.
- Highly weathered materials might show bright iron or manganese stains; may contain some rotting pebbles.

Stratigraphic contacts:
- Contacts may be sharp or gradational and vary with water energy. Contacts with outwash-type deposits are likely to be sharper than ice contact deposits.
- Sand and gravel bodies interbedded within glacial till will have very irregular boundaries that may be hard to discern.
- Grain size, sorting, and bedding make better indicators of contacts than coloration changes.

Stratigraphic context:
- Surficial sand-and-gravel deposits typically occupy distinctive geomorphic settings, such as outwash plains, terraces, kame fields, eskers, etc. Soil surveys and ODNR Division of Geological Survey maps are a good source of information in determining the geomorphic setting.
- In the subsurface, the nature of sand and gravel has to be inferred from its characteristics and determining the origin or setting becomes more difficult. How thick or laterally continuous a particular unit is requires information from additional nearby borings or well records or by other methods, such as geophysics.
- Extreme care needs to be taken to separate "washed" or disturbed sand and gravel and fines in the upper portion of the split-spoon from undisturbed, natural materials. This artificial washing may misrepresent the degree of sorting, bedding, proportion of fines, etc. in the sample interval.

Engineering properties:
- Unconfined Compressive Strength—Variable.
- Depends upon degree of saturation.
- Sorting, cohesiveness, and nature of bedding have large impact on properties. Typically, coarser materials have more favorable engineering properties.
- The angle of repose may be of some importance for very coarse, steep-sided deposits.
- A high percentage of boulders and cobbles may prove to be an obstacle to excavation.
- Subject to liquefaction and fluidization.

Hydrogeologic Properties:
- Can vary from relatively poor aquifers to some of the best aquifers found in the state.
- Wells completed in the various seams, lenses, or bodies of sand interbedded in glacial till or glacio-lacustrine units produce highly variable yields. The size, nature, and geometry of these sand bodies can vary significantly as well the corresponding yield. Yields for these sand bodies can vary from 3 gpm to over 500 gpm.
- Yields for sand-and-gravel wells in general are also dependent upon the diameter of the well; proper well construction techniques, particularly the use of properly-sized well screens

and gravel filter packs; and thorough development of the well. Aquifer ratings for sand and gravel interbedded in till vary from 4 to 7; ranges of hydraulic conductivity vary from 100–300 gpd/ft^2 to 700–1,000 gpd/ft^2.

- Wells completed in sand-and-gravel units within ice-contact features also vary considerably depending upon the proportion of till to sand and gravel and the sorting, relative coarseness, and nature of the deposits. Another important factor is that kames and other ice-contact features may locally occupy topographically higher positions in the landscape and be located above the water table. In such situations, the deposits represent a relatively permeable vadose zone more so than an aquifer. Aquifer ratings for ice-contact deposits typically range from 6 to 7; ranges of hydraulic conductivity vary from 300–700 gpd/ft^2 to 700–1,000 gpd/ft^2.
- Wells completed in sand-and-gravel units within thick, well-sorted, coarse outwash deposits represent some of the highest-yielding aquifers in the state. Aquifer ratings vary from 7 to 10; ranges of hydraulic conductivity vary from 700–100 gpd/ft^2 to >2,000 gpd/ft^2. Important to note moisture content (damp, moist, sticky, plastic, saturated, etc.). Oxidized or unoxidized colors might help indicate the position of the water table and the extent of potential atmospheric influence; this may have implications as to recharge and ground-water flow.

Environmental hazards:

- Typically, deposits at the surface or in the subsurface represent relatively few hazards as far as building or construction with the exception of a very high water table.
- At depth, the presence of very fine-grained, saturated sand to silty sand may prove difficult for drilling. These fine grained deposits have been referred to as “heaving,” “shooting,” or “quicksand.”
- Along slopes, similar fine-grained, saturated sand units may create unstable conditions and be prone to slumping or flowing. Small areas of organic deposits and kettles may be associated with sand-and-gravel deposits, particularly ice-contact deposits.
- Soil survey or ODNR Division of Geological Survey maps are useful to consult for building purposes. Perhaps the most significant threat from sand-and-gravel deposits is that their high permeability and porosity make them conduits for ground-water contamination.

Economic geology:

- Very important sources of aggregates.
- Very important as aquifers for water supply.
- Provide excellent recharge for underlying aquifers.

Scenic geology:

- Sand-and-gravel deposits, particularly kames, eskers, and outwash terraces, often provide scenic areas favorable for home sites.
- The inherently good drainage of these deposits also is favorable for home sites.
- On occasion, sand-and-gravel deposits can produce scenic, steep bluffs. These are commonly found along the margins of downcutting streams in areas of thick glacial drift.

Further reading:

Hansen, M.C., 1997, The Ice Age in Ohio: Ohio Department of Natural Resources, Division of Geological Survey Educational Leaflet 7.

White, G.W., 1982, Glacial geology of northeastern Ohio: Ohio Department of Natural Resources, Division of Geological Survey Bulletin 68, scale 1:250,000.

ODNR Division of Geological Survey—Numerous Bulletins, Reports of Investigations, and Information Circulars pertaining to the glacial geology specific counties (scale 1:62,500) and quadrangles (scale 1:24,000).

ODNR Division of Geological Survey—Digital Map Series SG-2, 30 x 60-minute quadrangle series (scale 1:100,000).

ODNR Division of Soil and Water Resources—Numerous Bulletins and Ground Water Pollution Potential (GWPP) Reports (scale 1:62,500)

Glacial Sand Deposits

Sand is a particle ranging in size from 0.0625 mm to 2 mm. It is subdivided by categories ranging from very fine grained to medium grained to very coarse grained. Gravel is coarser and ranges from 2 mm to 64 mm. Silt is finer grained, less than 0.025 mm. True sand deposits typically lack gravel and pebbles on the coarse end and lack silt and clay on the fine end. Such deposits show an intermediate energy level between the lower energy levels associated with the deposition of silt and clay and the higher energy level associated with deposition of sand and gravel.

Examples of sand deposits in Ohio include deltas, alluvial fans, and most beach ridges found in northern Ohio. The shoreline or beach environment includes beach ridges, bars, spits, and wind-blown sand, which creates dunes.

Diagnostic features:

- Dominant over fine-grained materials, such as till, lacustrine, or modern, finer-grained alluvium.
- Dominant over coarser-grained materials, such as gravel, pebbles, and cobbles.
- May vary from relatively loose and friable to very dense and cohesive.
- Sand deposits can vary from well to poorly sorted; may be relatively uniform or highly variable. Deposits may be viewed as “clean” or “dirty.”
- Bedding can be highly variable and massive, parallel, cross-bedded, gradational, or otherwise.

General features:

- Surficial geomorphology and setting are important in helping determine the nature and origin of the sand deposit.
- Examples include beach ridges and dunes. Sandy deltaic deposits commonly lay landward of the finer-grained lacustrine deposits.

Lithologic variations:

- Sandy deltaic deposits are usually associated with margins of lake plains or broad valleys.
- Sandy beach ridges and dunes typically lie along the edge of paleo lakes and help mark ancient shorelines.

Fine-grained, cross-bedded sand overlying coarse sand and thin gravel beds in a gravel pit near Lodi (Wayne County).

- Sand deposits in both the surface and subsurface reflect changes in water energy and bedload.
- The change from coarse to very fine-grained sediments can vary from sharp to gradual in both surface and subsurface.

Fossil content:
- Fossils are typically uncommon due to the high-energy environment and turbid nature of water.

Weathering characteristics:
- Weathering and predominant coloration of sand bodies is important in determining position of the water table, areas within the zone of recharge, and maximum extent of atmospheric oxygen in the profile.
- Degree of weathering is important in determining the hydrogeologic properties of the material, including permeability and porosity.
- Weathering characteristics are important. Highly weathered units will develop a fine-grained, argillic weathering zone at the top surface.
- Highly weathered materials might show bright iron or manganese stains and may contain some rotting pebbles.

Stratigraphic contacts:
- Contacts may be sharp or gradational and vary with water energy. In rare instances, the various deltaic beds (topsets, foresets, etc.) may be visible in outcrop.
- Sand bodies interbedded within glacial till will have very irregular boundaries that may be hard to discern.
- Grain size, sorting, and bedding make better indicators of contacts than coloration changes.

Stratigraphic context:
- Surficial deposits typically occupy distinctive geomorphic settings, such as deltas, alluvial fans, beach ridges, and dunes. Soil surveys and ODNR Division of Geological Survey maps are a good source of information in determining the geomorphic setting.
- In the subsurface, the nature of the sand deposit has to be inferred from its characteristics, and determining the origin or setting becomes more difficult. How thick or laterally continuous a particular sand unit is usually requires information from additional nearby borings or well records or by other methods, such as geophysics.
- Extreme care should be taken to separate "washed" or disturbed sand and associated minor fines in the upper portion of the split-spoon from undisturbed, natural materials. This artificial washing may misrepresent the degree of sorting, bedding, proportion of fines, etc. in the sample interval.

Engineering properties:
- Unconfined Compressive Strength—Variable.
- Depends upon degree of saturation. Saturated deposits may have a tendency to flow.
- Sorting, cohesiveness, and nature of bedding have a large impact on properties.
- Typically, coarser materials have more favorable engineering properties.

- Angle of repose may be of some importance for very coarse, steep-sided deposits.
- Subject to liquefaction and fluidization.

Hydrogeologic Properties:

- Can vary from relatively poor aquifers to good aquifers.
- Moisture conditions and presence of minor fines can greatly increase stickiness and cohesiveness.
- Important to note moisture content (damp, moist, sticky, plastic, saturated, etc.). Oxidized or unoxidized colors might help indicate the position of the water table and the extent of potential atmospheric influence; this may have implications as to recharge and ground-water flow.
- Wells completed in the various seams, lenses, or bodies of sand interbedded in glacial till or glacio-lacustrine units produce highly variable yields. The size, nature, and geometry of these sand bodies can vary significantly as can the corresponding yield. Yields for these sand bodies can vary from 3 gpm to >100 gpm.
- Yields for sand wells in general are also dependent upon the diameter of the well; proper well construction techniques, particularly the use of properly sized well screens and gravel filter packs; and thorough development of the well. Use of screens and filter packs is particularly essential for finer-grained sands. Aquifer ratings for sand interbedded in till vary from 4 to 7; ranges of hydraulic conductivity vary from 100–300 gpd/ft^2 to 700–1,000 gpd/ft^2.Yields from wells completed in sand deposits, such as deltas, beaches, and fans, vary considerably based upon the coarseness and degree of sorting. Finer-grained sands perform much poorer as aquifers than coarser-grained sands.
- Saturated, fine-grained sands or silty-sand mixes can become problematic when drilled. Wells penetrating such units are subject to the sand flowing or rising back up the well casing, causing problems in advancing the well.

Environmental hazards:

- Sand deposits at the surface or in the subsurface represent relatively few hazards as far as building or construction with the exception of a very high water table.
- At depth, the presence of very fine-grained saturated sand to silty sand may prove difficult for drilling. These fine-grained deposits have been referred to as “heaving,” “shooting,” or “quicksand.”
- Along slopes, similar fine-grained, saturated sand units may create unstable conditions and be prone to slumping or flowing. Small areas of organic deposits and kettles may be associated with sand deposits.
- Soil survey or ODNR Division of Geological Survey maps are useful for building purposes. Perhaps the most significant threat from sand deposits is that their high permeability and porosity make them conduits for ground water contamination.

Economic geology:

- Important sources of aggregate.
- Important as aquifers for water supply.
- Provide excellent recharge for underlying aquifers.

Scenic geology:

- Sand deposits often provide scenic areas favorable for home sites.
- Inherently good drainage, favorable for home sites.

Further reading:

Hansen, M.C., 1997, The Ice Age in Ohio: Ohio Department of Natural Resources, Division of Geological Survey Educational Leaflet 7.

White, G.W., 1982, Glacial geology of northeastern Ohio: Ohio Department of Natural Resources, Division of Geological Survey Bulletin 68, scale 1:250,000.

ODNR Division of Geological Survey—Numerous Bulletins, Reports of Investigations, and Information Circulars pertaining to the glacial geology specific counties (scale 1:62,500) and quadrangles (scale 1:24,000).

ODNR Division of Geological Survey—Digital Map Series SG-2, 30 x 60-minute quadrangle series (scale 1:100,000).

ODNR Division of Soil and Water Resources—Numerous Bulletins and Ground Water Pollution Potential (GWPP) Reports (scale 1:62,500)

Glacial Lacustrine Deposits

Lacustrine deposits tend to be laminated (or *varved*) and contain various proportions of silts and clays. Thin layers of fine sand interbedded with the clayey to silty lacustrine deposits may reflect storm or flood events; the net effect being a "wafer-like" appearance. Permeability is preferentially horizontal due to the laminations and water-laid nature of these sediments. The inherent vertical permeability is slow; however, secondary porosity features (e.g., fractures, joints, root channels) help increase the vertical permeability.

Diagnostic features:
- Typically will be defined texturally or according to grain-size as a silty clay or clayey silt.
- Typically may display thin bedding, laminations, or varves.
- May appear massive and uniform and lack bedding.
- Tend to be less compacted and dense than till.
- Relatively soft, plastic, and sticky.
- Generally lack the gravel, cobble, and coarse-sand content of till.
- Sand typically appears in discrete bands or laminae as opposed to being disseminated throughout the matrix.

General features:
- Individual layers tend to be well-sorted and uniform.
- Gray where unoxidized; brown where weathered; mottled colors may represent variable water table conditions.

Lithologic variations:
- Intermorainal lakes may be predominantly silty or clayey; this depends upon the nature of surrounding till and other adjacent materials supplying sediment to the lakes.
- Lacustrine deposits in the subsurface demonstrate similar variability, especially if they are interbedded with sand-and-gravel deposits that represent rapid shifts in water energy.
- County Soil Surveys and ODNR Division of Geological Survey glacial geologic maps are good sources of information on differentiating various surficial lacustrine deposits.

Fossil content:
- Fossils are typically uncommon.
- In rare instances, a discrete layer may contain abundant gastropods and related mollusks.

Weathering characteristics:
- Important to note weathering characteristics, degree of oxidation, mottling of colors, presence of fractures and joints, presence of secondary carbonate or gypsum.
- Degree of weathering is important in determining hydrogeologic properties of the material including permeability.

Thin-bedded and laminated lacustrine deposits (Sandusky County).

Stratigraphic contacts:
- Contacts may be sharp or gradational depending upon the type of adjacent materials.
- Contact with till may be very gradational; contact with sand and gravel is typically more distinct.
- Rare for lacustrine deposits to sit directly upon bedrock; however, where this occurs, contact is typically sharp.

Stratigraphic context:
- May represent the uppermost surficial unit in low-lying areas.
- For deposits in the subsurface, soil survey and ODNR Division of Geological Survey maps are best source of information on this topic.
- Subsurface deposits interbedded with till may indicate former intermorainal lakes or blockage of drainage by advancing ice.
- Deposits interbedded with coarser, water-laid sands and gravels indicate a substantial change in water energy and a local change in drainage.

Engineering properties:
- Unconfined Compressive Strength—Variable. Clays may range from 0 to >4.5 TSF (63 psi) which is very good for a soil.
- Depends upon degree of saturation.

Hydrogeologic properties:
- Generally considered to be an aquitard or aquiclude, not an aquifer.
- Historically, dug wells have produced minor yields from lacustrine deposits, and monitor wells in the saturated zone will maintain water levels.
- Recharge variable.
- Laboratory tests record permeability ranging from 10^{-7} to 10^{-9} cm/sec^2.
- *In-situ* slug tests/long-term pumping tests reveal permeabilities ranging from 10^{-6} to 10^{-7} cm/sec^2 for weathered, fractured tills.
- Primary flow and permeability is preferentially horizontal, along laminations, bedding planes, and varves, as opposed to vertical.
- Secondary permeability and flow may be vertical due to joints and fractures.
- Shallow ground-water flow in these deposits will typically flow toward the nearest shallow stream or drainage ditch.
- Primary porosity in lacustrine deposits is typically horizontal.
- Secondary porosity may add to the vertical component.

Environmental hazards:
- Slumping may occur along steep slopes and under saturated, high water table conditions. Higher bluffs may be particularly unstable.
- Presence of a high water table determines a number of building constraints on basements, foundations, septic systems, leach fields, etc.
- Soils surveys and ODNR Division of Geological Survey maps are good sources of information regarding characteristics of till locally.

Economic geology:
- May be suitable as important fill materials for a number of earthen structures, such as highway embankments, earthen dams, and levees.

- Where fine-grained clay content is high, these materials may be suitable as a liner for ponds, landfills, manure containment, and reservoirs when compacted adequately.
- May be suitable as cover material for landfill operations.

Scenic geology:

- Lacustrine deposits are notorious for slumping and covering the rest of an outcrop.
- On occasion, lacustrine deposits can produce scenic, steep bluffs, commonly found along the margins of downcutting streams in areas of thick glacial drift.
- Steep lacustrine bluffs are common along the Lake Erie shoreline.

Further reading:

Hansen, M.C., 1997, The Ice Age in Ohio: Ohio Department of Natural Resources, Division of Geological Survey Educational Leaflet 7.

Weatherington-Rice, J. and Christy, A.D., 2000, Ohio's fractured environment—Introduction to The Ohio Journal of Science's special issue on fractures in Ohio's glacial till: Ohio Journal of Science, v. 100, no. 3 and 4, p. 36–38.

White, G.W., 1982, Glacial geology of northeastern Ohio: Ohio Department of Natural Resources, Division of Geological Survey Bulletin 68, scale 1:250,000.

ODNR Division of Geological Survey—Numerous Bulletins, Reports of Investigations and Information Circulars pertaining to the glacial geology specific counties (scale 1:62,500) and quadrangles (scale 1:24,000).

ODNR Division of Geological Survey—Digital Map Series SG-2, 30 x 60-minute quadrangle series (scale 1:100,000).

ODNR Division of Soil and Water Resources—Numerous Bulletins and Ground Water Pollution Potential (GWPP) Reports (scale 1:62,500)

Glacial Silt Deposits

(includes loess; see also "Glacial Lacustrine Deposits")

Silt is a term that geologists use for fine-grained particles with a particle size greater than 4 microns (.0039 mm) and less than 62.5 microns (0.0625 mm). Engineers consider the size distinction between clay and silt particles as being 5 microns (0.005 mm) and the distinction between silt and sand at 75 microns (0.075 mm or #200 sieve). Soil scientists put the distinction between clay and silt at 2 microns (0.002 mm) and at 50 microns (0.05 mm) for silt and sand.

Clay and silt very commonly occur together and may be difficult to differentiate in outcrop and in water well log reports. Textural analysis may be necessary to help determine the correct proportion of particle sizes in a particular sample. Silt deposits require low- to moderate-energy environments for these fine particles to settle out; the required energy level falls between that of a true clay and sand. Silt deposits re most commonly associated with glacial lacustrine environments. Silt also is a common particle size for most fluvial/alluvial deposits. Typically, alluvium that is predominantly clay or predominantly sand requires much lower velocities or finer parent materials for the clay or higher velocities and coarser parent materials for the sand.

Silt deposits also are transitional with sand deposits, particularly in a deltaic environment. Much like the break between clay and silt, the break between sand and silt may also require textural analysis to determine the grain size.

Loess deposits are windblown and are typically composed of silt particles that tend to be more angular and less rounded in nature.

The natures of various lacustrine deposits are discussed under the description for "Glacial Lacustrine Deposits."

Diagnostic features:

- Typically may require laboratory analysis to separate fine silt from clay.
- May require laboratory analysis to separate coarse silt from very fine sand.
- Tend to be less compacted and dense than till. May not be as plastic or sticky as clays. Silt lacks the grainy, gritty feel of sand on fingertips; however, may feel somewhat gritty against teeth.
- Important to note moisture content (damp, moist, sticky, plastic, saturated, etc.).
- Silt does not create ribbons or worms (when rolled between hands) near as well as clay. Cracks or breaks in the ribbon or worm tend to suggest silt-sized particles mixed with in the clay-sized particles.

Massive-bedded silt deposit found in a gravel pit near Lodi (Wayne County).

General features:
- Typically soft to moderately firm, depending upon saturation. Somewhat "runny" or "soupy" when wet.
- Exhibits *dilatancy*, a property of silt that distinguishes it from clays. If a part of wet silt is shaken, it exudes water and becomes shiny. If the pat is then pressed, the water re-enters the silt. Fine sands exhibit this property as well.
- Gray where unoxidized; brown where weathered; mottled colors may represent variable water table conditions.

Lithologic variations:
- Typically rather uniform deposits; may be gradational with clay deposits. Differentiating between clay and silt in a typical lacustrine deposit may be difficult or impractical. Differentiating between very fine sand and silt in a typical deltaic deposit may also be difficult or impractical.
- County Soil Surveys and ODNR Division of Geological Survey glacial geologic maps are good sources of information on differentiating various surficial lacustrine deposits.

Fossil content:
- Fossils typically uncommon.
- In rare instances, a discrete layer may contain abundant gastropods and related mollusks.

Weathering characteristics:
- Degree of oxidation; mottling of colors; presence of fractures and joints; presence of secondary carbonate or gypsum.
- Degree of weathering is important in determining hydrogeologic properties of the material, including permeability.

Stratigraphic contacts:
- Contacts may be sharp or gradational depending upon the type of adjacent materials. Contacts with clay, especially in lacustrine deposits, may be difficult to determine. Contacts with fine sand may be difficult in a deltaic environment.
- Contact with till may be very gradational; contact with sand and gravel is typically more distinct.
- Rare for silt deposits to sit directly upon bedrock; however, where this occurs, contact is typically sharp.

Stratigraphic context:
- May represent the uppermost surficial unit in low-lying areas.
- In the subsurface, soil survey and ODNR Division of Geological Survey maps are best source of information on this topic.
- Deposits in the subsurface interbedded with till may indicate former intermorainal lakes or blockage of drainage by advancing ice.
- Deposits interbedded with coarser, water-laid sands and gravels indicate a substantial change in water energy and a local change in drainage

Engineering properties:
- Unconfined Compressive Strength—Variable.
- Depends upon degree of saturation.
- Considered unsuitable material due to its physical properties.
- Subject to liquefaction and fluidization.
- Differential ground-water pressure causes ground (silt) boils.

Hydrogeologic properties:

- Generally considered to be an aquitard or aquiclude, not an aquifer.
- Historically, dug wells have produced minor yields from silt deposits, and monitor wells in the saturated zone will maintain water levels.
- Recharge low to variable.
- Laboratory tests record permeability ranging from 10^{-6} to 10^{-8} cm/sec^2.
- *In-situ* slug texts/long-term pumping tests reveal permeabilities ranging from 10^{-5} to 10^{-7} cm/sec^2 for weathered, fractured tills.
- Primary flow and permeability is preferentially horizontal, along laminations, bedding planes, and varves, as opposed to vertical, except for loess. Shallow ground-water flow in these deposits will typically flow towards the nearest shallow stream or drainage ditch.
- Secondary permeability and flow may be vertical due to joints and fractures.

Environmental hazards:

- Slumping may occur along steep slopes and under saturated, high-water table conditions. Higher bluffs particularly unstable.
- Presence of a high water table determines a number of building constraints on basements, foundations, septic systems, leach fields, etc.
- Soils surveys and ODNR Division of Geological Survey maps are good sources of information regarding characteristics of till locally.

Economic geology:

- Considered an unsuitable material due to its physical and engineering properties.
- Silt is typically not as useful for the ceramic, pottery, and pigment industries.

Scenic geology:

- Notorious for slumping and covering the rest of an outcrop.
- On occasion, silt deposits can produce scenic, steep bluffs that are commonly found along the margins of downcutting streams in areas of thick glacial drift. In areas of loess, the loess may give steep bluffs or high hilltops a somewhat more rounded appearance. Such bluffs typically are downwind (usually to the east, based upon prevailing wind direction) from a major valley source.
- Steep silt bluffs are common along the Lake Erie shoreline.
- It is rare to see a truly pure silt deposit on the surface. Typically, lacsutrine deposits also contain clay, and deltaic/fluvial and fluvial deposits also contain some sand.

Further reading:

Hansen, M.C., 1997, The Ice Age in Ohio: Ohio Department of Natural Resources, Division of Geological Survey Educational Leaflet 7.

Weatherington-Rice, J. and Christy, A.D., 2000, Ohio's fractured environment—Introduction to The Ohio Journal of Science's special issue on fractures in Ohio's glacial till: Ohio Journal of Science, v. 100, no. 3 and 4, p. 36–38.

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ODNR Division of Geological Survey—Digital Map Series SG-2, 30 x 60-minute quadrangle series (scale 1:100,000).

ODNR Division of Soil and Water Resources—Numerous Bulletins and Ground Water Pollution Potential (GWPP) Reports (scale 1:62,500)

Glacial Clay Deposits

(see also "Glacial Lacustrine Deposits")

Clay is a term geologists use for fine-grained particles with a particle size less than 4 microns (0.0039 mm). Engineers consider the size distinction between clay and silt particles as being 5 microns (0.005 mm), whereas soil scientists put the distinction at 2 microns (0.002 mm).

Clay and silt very commonly occur together and may be difficult to differentiate in outcrop and in water well log reports. Textural analysis may be necessary to help determine the correct proportion of particle sizes in a particular sample. Clay deposits require very low-energy environments for these fine particles to settle out. They are most commonly associated with glacial lacustrine environments. Slow-moving, impeded rivers also can deposit clay in features referred to as *oxbow lakes*. Also, slow-moving runoff can selectively carry clay particles to sluggish streams resulting in a very clay-rich alluvium.

Clay deposits have inherently poor drainage. Surface water readily collects or ponds on clay deposits.

The nature of various lacustrine deposits is discussed under the description for "Glacial Lacustrine Deposits." Clay deposits typically were deposited in the quietest, deepest parts of lakes or ponds, furthest from any stream inputs.

Diagnostic features:

- Typically require textural analysis to separate from silt; separating may not be practical depending upon the degree of study. Appear massive and uniform and lack bedding; may contain varves. May also contain fine sand and silt, with sand on the bottom followed by silt then progressively finer clay particles. Individual intervals tend to be uniform and well sorted.
- Laboratory analysis required to differentiate between fat and lean clays.
- Tend to make nice, elongated worms or ribbons between one's hands. Cracks or breaks in the ribbon or worm suggest the presence of silt-sized particles along with clay-sized particles.
- Tend to be less compacted and dense than till. Relatively soft, plastic, and sticky. Lack the gravel, coble, and coarse sand content of till. Silt is coarser to the touch and not as sticky or plastic as clay.
- Primary porosity in clay deposits is typically horizontal. Secondary porosity may add to the vertical component.
- Important to note moisture content (damp, moist, sticky, plastic, saturated, etc.).

Thick, lacustrine-related clay deposit located in a clay pit southeast of Alliance (Columbiana County).

General features:

- Typically very clayey, soft when saturated, sticky, plastic.
- Gray where unoxidized, brown where weathered; mottled colors may represent variable water table conditions.

Lithologic variations:

- Clay deposits are typically rather uniform. They may be gradational with silt deposits. Differentiating between clay and silt in a typical lacustrine deposit may be difficult or impractical. Care must be taken between clay deposits related to glacial, lacustrine, and fluvial processes and clay resulting from weathered bedrock (see earlier discussion on soils).
- County Soil Surveys and ODNR Division of Geological Survey glacial geologic maps are good sources of information on differentiating various surficial lacustrine deposits.

Weathering characteristics:

- Degree of oxidation; mottling of colors; presence of fractures and joints; presence of secondary carbonate or gypsum.
- Degree of weathering is important in determining hydrogeologic properties of the material, including permeability.

Stratigraphic contacts:

- Contacts may be sharp or gradational depending upon type of adjacent materials. Contacts with silt, especially in lacustrine deposits, may be difficult to determine.
- Contact with till may be very gradational; contact with sand and gravel typically more distinct.
- Rare to sit directly upon bedrock; however, where this occurs, contact is typically sharp.

Stratigraphic context:

- May represent the uppermost surficial unit in low-lying areas.
- In the subsurface, soil survey and ODNR Division of Geological Survey maps are the best source of information on this topic.
- Deposits in the subsurface interbedded with till may indicate former intermorainal lakes or blockage of drainage by advancing ice.
- Deposits interbedded with coarser, water-laid sands and gravels indicate a substantial change in water energy and a local change in drainage.

Engineering properties:

- Unconfined Compressive Strength—Variable.
- Depends upon degree of saturation.
- Clays have been referred to as "fat" and "lean" clays.
- Fat clays have higher laboratory values for liquid limits and plasticity, and mineralogy that causes the clays to swell.
- Lean clays have lower laboratory values for liquid limits and plasticity, and mineralogy where the clay does not swell.

Hydrogeologic properties:

- Generally considered to be an aquitard or aquiclude, not an aquifer.
- Historically, dug wells have produced minimal yields from clay deposits, and monitor wells in saturated zone may maintain water levels.
- Recharge low.
- Laboratory tests record permeability ranging from 10^{-7} to 10^{-9} cm/sec^2.
- *In-situ* slug texts/long-term pumping tests reveal permeabilities ranging from 10^{-6} to 10^{-7} cm/sec^2 for weathered, fractured tills.
- Primary flow and permeability is preferentially horizontal, along laminations, bedding planes, and varves, as opposed to vertical.
- Secondary permeability and flow may be vertical due to joints and fractures.
- Shallow ground-water flow in these deposits will typically flow towards the nearest shallow stream or drainage ditch.

Environmental hazards:

- Slumping may occur along steep slopes and under saturated, high water table conditions. Higher bluffs may be particularly unstable.
- Presence of a high water table determines a number of building constraints on basements, foundations, septic systems, leach fields, etc.
- Soils surveys and ODNR Division of Geological Survey maps are good sources of information regarding characteristics of till locally.

Economic geology:

- May be suitable as important fill materials for a number of earthen structures, such as highway embankments, earthen dams, levees, etc.
- Due to low permeabilities, clays may be suitable as a liner for ponds, landfills, manure containment, and reservoirs when compacted adequately.
- May be suitable as cover material for landfill operations.
- Valuable for the ceramics, tile, and pottery industries.
- Valuable for products such as pigments, coloring, and cosmetics.

Scenic geology:

- Notorious for slumping and covering the rest of an outcrop.
- On occasion, clay deposits can produce scenic, steep bluffs, commonly found along the margins of downcutting streams in areas of thick glacial drift.
- Steep clay bluffs are common along the Lake Erie shoreline.
- It is rare to see a truly pure clay deposit on the surface. Typical lacustrine and fluvial deposits contain some silt.

Further reading:

Hansen, M.C., 1997, The Ice Age in Ohio: Ohio Department of Natural Resources, Division of Geological Survey Educational Leaflet 7.

Weatherington-Rice, J. and Christy, A.D., 2000, Ohio's fractured environment—Introduction to The Ohio Journal of Science's special issue on fractures in Ohio's glacial till: Ohio Journal of Science, v. 100, no. 3 and 4, p. 36–38.

White, G.W., 1982, Glacial geology of northeastern Ohio: Ohio Department of Natural Resources, Division of Geological Survey Bulletin 68, scale 1:250,000.

ODNR Division of Geological Survey—Numerous Bulletins, Reports of Investigations and Information Circulars pertaining to the glacial geology specific counties (scale 1:62,500) and quadrangles (scale 1:24,000).

ODNR Division of Geological Survey—Digital Map Series SG-2, 30 x 60-minute quadrangle series (scale 1:100,000).

ODNR Division of Soil and Water Resources—Numerous Bulletins and Ground Water Pollution Potential (GWPP) Reports (scale 1:62,500)

Organic Deposits

(includes peat, sphagnum, muck, gyttja, and marl)

Peat is a material composed primarily of decayed or decomposing vegetation material. It is commonly shades of brown and has visible plant material or debris branches (e.g., wood, bark). Peat moss or *sphagnum* is a form of moss that frequently grows on top of or within a peat deposit. As this material decays and is buried, it may blend with other decaying peat materials. *Muck* is a related deposit that is composed predominately of humus or very fine, decayed organic material. The material composing muck is commonly too fine-grained to identify plant remains. Muck is typically dark gray to black and tends to have a gritty feel. Muck may contain small, silt-sized or fine-sand-sized particles that reflect sunlight and provide a mineral component that accompanies the dominant organic component. *Marl* is a lightweight carbonate deposit, somewhat similar to the tufa or travertine deposited in caverns. Marl is deposited by carbonate-rich groundwater that discharges in bogs or wetlands from springs and seeps. Marl typically is light brown to gray and very porous, resembling pumice.

Diagnostic features:

- The various deposits may exist separately, might variably be mixed together, or repeat cyclically.
- Visible plant (or *sapric*) material indicates peat, while muck has fine-grained organics.
- Marl is distinguished by its lighter color, crusty porous appearance, and carbonate composition, which fizzes readily with dilute acid.

General features:

- Topographic position, wetland conditions, and saturated nature are diagnostically important.
- Proximity to kettles, current ponds, prior lakebeds (lacustrine deposits), and modern floodplains also important.
- Acidic wetlands referred to as *bogs*. Acidity is due to decaying plant materials and humus.
- Alkaline wetlands referred to as *fens*. Alkaline nature is typically due to high carbonate/sulfate in springs or seeps.

Lithologic variations:

- Deposits may be relatively uniform or gradational with each other. Size of plant material in peat may vary from small twigs, leaves, and needles up to much larger branches, logs, and tree trunks.
- Muck may be composed of almost entirely organic materials or contain appreciable amounts of clay, silt, and very fine-grained sand particles.

Fragments of peat (woody material) overlying fine-grained, dark muck deposit in a sand-and-gravel pit near Lodi (Wayne County).

- Marl deposits may have small leafs and twigs cemented in place in the carbonate matrix.
- County Soil Surveys maps are good sources of information on differentiating various surficial organic deposits.

Fossil content:
- Excellent sources of plant fossils, including limbs, leaves, pine cones, and especially pollen.
- Excellent potential source of both invertebrate fossils, such as mollusks and beetles, and vertebrates, ranging from rodents to the largest mammals. Most of Ohio's largest vertebrate finds, including mammoths, mastodons, beaver, and elk, have been found in peat bogs.
- Zones of calcareous mollusks, particularly snails, may be common in areas where organic deposits and lacustrine deposits interfinger or interbed.

Weathering characteristics:
- Decay is almost as important a process as weathering in more highly organic deposits. It is important to note the amount of decomposition and the relative percentage of organic versus non-organic constituents.
- Degree of weathering is important in determining the hydrogeologic properties of the material, including permeability.
- Organic deposits typically indicate a very low-energy depositional environment.

Stratigraphic contacts:
- Contacts may be sharp or gradational depending upon the type of adjacent materials. Contacts between various organic deposits may be gradational.
- Contacts with non-organic deposits, such as silt, clay, or sand, are typically sharper.

Stratigraphic context:
- May represent the uppermost surficial unit in low-lying areas.
- Soil survey and ODNR Division of Geological Survey maps are best sources of information on this topic.
- Organic deposits may be encountered in the subsurface while drilling or excavating. Organic deposits typically underlie lacustrine or till deposits. Organic deposits typically lie below the water table and are saturated in the sub-surface.

Engineering properties:
- Organic deposits rate a special engineering classification. Low strength and high saturation make them highly unsuitable for most engineering and construction purposes at the land surface and in the shallow subsurface. Thicker accumulations in the subsurface may also constitute engineering or foundation problems.
- Engineers and soils scientists refer to peat and related deposits as *histosols*.

Hydrogeologic properties:
- At or near the surface, deposits are typically too close to the surface to comprise an aquifer for drilled wells. Water quality may be objectionable.
- Deposits at depth may yield water, but the organic, decaying nature of these deposits makes it difficult or objectionable to complete a well in them.

- Peat is typically very permeable, especially for deposits with coarser, larger plant fibers.
- Muck, when dry, becomes quite hard and can behave as an aquitard. Permeability is commonly low when these deposits are wet.
- Recharge may be moderately high or very low, depending upon relative amount of coarser, peaty materials or finer-grained muck material present.
- Laboratory tests record permeability ranging from 10^{-4} to 10^{-9} cm/sec^2.
- *In-situ* slug tests/long-term pumping tests reveal permeabilities ranging from 10^{-5} to 10^{-8}cm/sec^2.

Environmental hazards:

- Many of these areas include or are adjacent to ecologically sensitive areas, including wetlands, nature preserves, and wildlife refuges.
- Presence of a high water table determines a number of building constraints on basements, foundations, septic systems, leach fields, etc.
- Soils surveys and ODNR Division of Geological Survey maps are good sources of information regarding characteristics of organic deposits locally.

Economic geology:

- Peat and peat moss, and to a lesser extent muck, have been valued for gardening and nursery purposes. Many of the historic peat deposits have been mined out and remaining deposits are now preserved or are actively used for truck farms and vegetable crops.
- Marl had historical limited use as a source of carbonate or lime and also limited use as a decorative rock or building stone along Sandusky Bay.

Scenic geology:

- Many remaining peat and muck deposits occupy kettles, wetlands, bogs, and other scenic areas. Many of these areas now serve as nature preserves, wildlife refuges, and parks frequently visited by birders, hikers, and fishermen.

Further reading:

Dachnowski, Alfred, 1912, Peat deposits of Ohio, their origin, formation, and uses: Ohio Department of Natural Resources, Division of Geological Survey Bulletin 16, 424 p.

Hansen, M.C., 1997, The Ice Age in Ohio: Ohio Department of Natural Resources, Division of Geological Survey Educational Leaflet 7.

Stout, Wilbur, 1940, Marl, tufa rock, travertine, and bog ore in Ohio: Ohio Department of Natural Resources, Division of Geological Survey Bulletin 41, 56 p.

Weatherington-Rice, J. and Christy, A.D., 2000, Ohio's fractured environment—Introduction to The Ohio Journal of Science's special issue on fractures in Ohio's glacial till: Ohio Journal of Science, v. 100, no. 3 and 4, p. 36–38.

White, G.W., 1982, Glacial geology of northeastern Ohio: Ohio Department of Natural Resources, Division of Geological Survey Bulletin 68, scale 1:250,000.

ODNR Division of Geological Survey—Numerous Bulletins, Reports of Investigations and Information Circulars pertaining to the glacial geology specific counties (scale 1:62,500) and quadrangles (scale 1:24,000).

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ODNR Division of Soil and Water Resources—Numerous Bulletins and Ground Water Pollution Potential (GWPP) Reports (scale 1:62,500)

Cedarville Dolomite

The Cedarville Dolomite is characterized white to light-gray, porous dolomite occurring in thick to massive beds that weather to a pitted and corroded surface. These rocks were deposited in a shallow tropical sea containing abundant marine plants and animals. Their skeletons and skeletal fragments accumulated into thick beds of limestone that were later changed into dolomite as magnesium-rich, high-salinity waters were circulated through these sediments. The Cedarville occurs in a 1- to 15-mile (1.6- to 24-km) wide band extending southeastward from western portions of Clark and Champaign Counties to southern portions of Clinton County. The Cedarville Dolomite was introduced in the 1870s to replace the local term of *Pentamerus* Limestone for the rocks being quarried in the Cedarville, Ohio, area. The Cedarville ranges in thickness from 0 to 100 feet (0 to 30 meters).

Diagnostic features:
- White to gray dolomite.
- Thick to massive bedding.
- Abundant porosity and large vugs.

General features:
- Abundant fine to coarse dolomite crystals.
- Abundant fossil molds and casts.

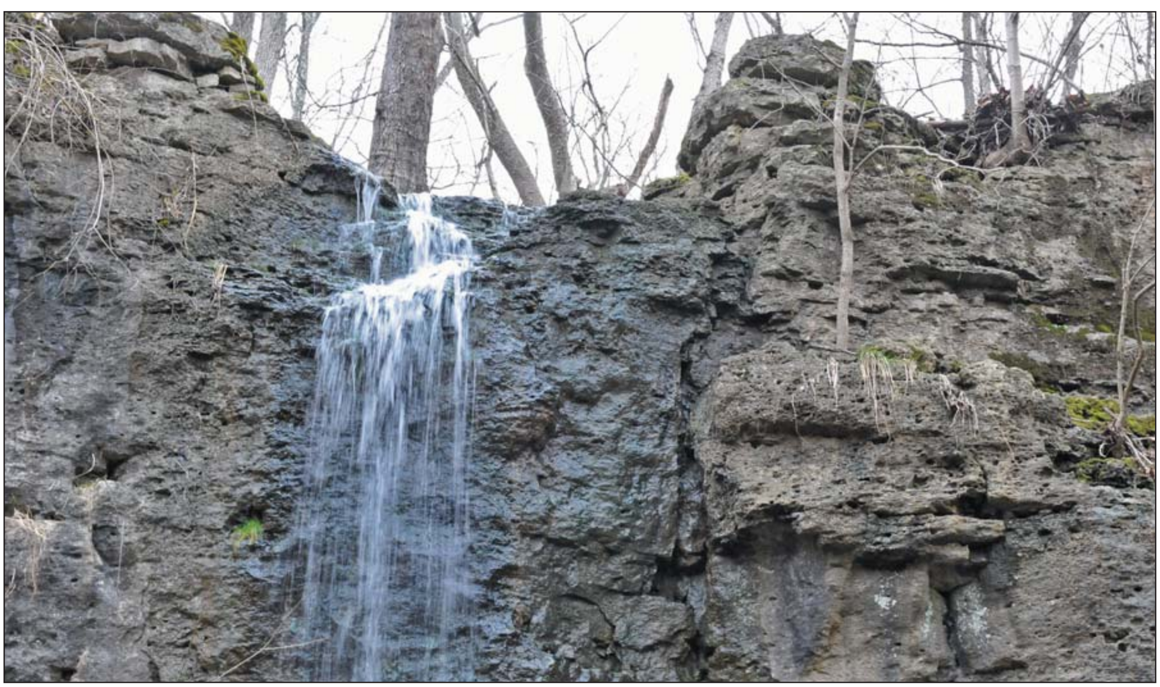
Lithologic variations:
- Rare medium to thin bedding in some exposures.
- Grades laterally into the Lockport Dolomite of western and northern Ohio and Peebles Dolomite of southern Ohio.

Fossil content:
- Diverse marine fauna with crinoids, cystoids, and brachiopods dominating.
- Coral, bryozoans, bivalves, cephalopods, gastropods, and trilobites common.
- The diagnostic brachiopod *Pentamerus* is abundant throughout the unit.

Weathering characteristics:
- Resistant to weathering.
- Weathered surfaces often are pitted and corroded creating a honeycomb effect.
- Forms cliffs, waterfalls, and gorges in streams and road cuts.
- Large, abundant slump blocks of dolomite.

Stratigraphic contacts:
- Sharp to gradational upper contact.
- Sharp lower contact.

Stratigraphic context:
- Underlain by Springfield Dolomite.
- Overlain by Salina Group.
- Similar units: Euphemia Dolomite, Peebles Dolomite, Lockport Dolomite.



The thick- to massive-bedded, vuggy Cedarville Dolomite as exposed in the western gorge wall at Amphitheater Falls in Clifton Gorge State Nature Preserve.

Engineering properties:

- Unconfined Compressive Strength—Unweathered dolomite will have a high to very high compressive strength; weathered dolomite will have a moderate to high compressive strength.
- Slake Durability—Expected to have high to very high durability.
- Rippability—Resistant to ripping. Blasting, breaking, or cutting is required for rock excavation.

Hydrogeologic properties:

- Moderate to relatively good aquifer.
- May be utilized independently or mapped and drilled together as a hydrologic unit with overlying units.
- Average yields for domestic wells completed in this aquifer range from 10 to 25 gpm.
- Maximum yields for deeper, larger diameter wells completed in this formation range from 25 to 100 gpm.
- Aquifer rating: 5–7.
- Vadose zone: 5–7.
- Hydraulic conductivity varies from a range of 1–100 gpd/ft^2 to 100–300 gpd/ft^2. Areas in the northern extent of this aquifer may reach 300–700 gpd/ft^2, especially when combined in an interval with other higher-producing aquifers.

Environmental hazards:

- Falling rocks from cliff and gorge walls, especially during winter and spring freeze/thaw cycles.
- People and animals falling from cliffs and gorge walls.
- Potential for solution-enlarged joints and sinkhole development in areas of thin to absent glacial drift.

Economic geology:

- Quarried for nearly 200 years for road and building construction, Portland cement, agricultural lime, asphaltic cement, and riprap.
- Source of abundant, hard groundwater.

Scenic geology:

- Cedarville forms the gorge walls of Clifton Gorge SNP, Glen Helen Nature Preserve, Clark Run gorge, Massie's Creek Gorge, and upper Gorge walls of John Bryan SP.
- Main unit forming abundant massive slump blocks, such as Steam Boat Rock in Clifton Gorge SNP and the top of Pompey's Pillar at Glen Helen Nature Preserve.
- Amphitheater Falls in Clifton Gorge SNP and many other waterfalls.

Further reading:

Horvath, A.L., and Sparling, D., 1967, Guide to the Forty-Second Annual Field Conference of the section of geology of the Ohio Academy of Science—Silurian Geology of western Ohio: University of Dayton, Ohio, 25 p.

Sandy, M.R., 2012, Golden olden days of the Ordovician, Silurian seas, and Pleistocene ice—An introduction to the geology of the Dayton area, *in* Sandy, M.R., and Goldman, D., eds. On and around the Cincinnati Arch and Niagara Escarpment—Geological Field Trips in Ohio and Kentucky for the GSA North-Central Section Meeting, Dayton, Ohio, 2012: Geological Society of America Field Guide 27, p. 55–86.

ACTUAL SIZE

Springfield Dolomite

The diagnostic features of the Springfield Dolomite are medium- to thick-bedded, fine-crystalline dolomite that weathers to a distinctive brick-like pattern. These rocks were deposited in a shallow, tropical sea containing marine plants and animals. The Springfield was originally deposited as a limestone that was later changed into dolomite as magnesium-rich, high-salinity waters were circulated through the limestone. The Springfield occurs in a narrow (less than 1 mile wide) band extending southeastward from the Clark-Champaign County line to the Clinton-Highland County line. The Springfield was introduced in 1871 as a name for the building stone being quarried in the Springfield region. The Springfield ranges in thickness from 5 to 15 feet (2 to 5 meters).

Diagnostic features:
- Fine-crystalline dolomite.
- Medium to thick bedding.
- Weathers to brick-like appearance.

General features:
- Some burrow mottling.
- Fossil molds and casts.
- Rare to moderate amount of quartz silt.

Lithologic variations:
- Highly variable in thickness from outcrop to outcrop.
- Some sections contain minor amounts of chert.
- Grades laterally into the Lockport Dolomite of western and northern Ohio and Peebles Dolomite of southern Ohio.

Fossil content:
- Marine fauna with brachiopods dominating.
- Coral, echinoderms, bryozoans, bivalves, cephalopods, gastropods, and trilobites present.
- The diagnostic brachiopod, *Pentamerus*, occurs scattered throughout the unit.

Weathering characteristics:
- Less resistant to weathering than Euphemia and Cedarville Dolomites.
- Forms shallow reentrants in cliff exposures.
- Weathers to brick-like appearance pattern.

Stratigraphic contacts:
- Sharp to gradational upper contact.
- Sharp lower contact.

Cliff exposure located in Clark County illustrating the medium- to thick-bedded, brick-like weathering Springfield Dolomite and overlying thick- to massive-bedded, vuggy Cedarville Dolomite.

Stratigraphic context:
- Underlain by Euphemia Dolomite.
- Overlain by Cedarville Dolomite.

Engineering properties:
- Unconfined Compressive Strength—Unweathered dolomite will have a high to very high compressive strength; weathered dolomite will have a moderate to high compressive strength.
- Slake Durability—Dolomite is expected to have high to very high durability.
- Rippability—Springfield Dolomite is resistant to ripping. Blasting, breaking, or cutting is required for rock excavation.

Hydrogeologic properties:
- Moderate to relatively good aquifer.
- Due to thin nature of this unit, it is most likely mapped and drilled together as a hydrologic unit with overlying/underlying units.
- Average yields for domestic wells range from 10 to 25 gpm.
- Maximum yields for deeper, larger-diameter wells completed in this formation range from 25 to 100 gpm.
- Aquifer rating: 5–7.
- Vadose zone rating: 5–7.
- Hydraulic conductivity varies from a range of 1–100 gpd/ft^2 to 100–300 gpd/ft^2. Areas in the northern extent of this aquifer may reach 300–700 gpd/ft^2 especially when combined in an interval with other higher producing aquifers.

Environmental hazards:
- Falling rocks from cliff and gorge walls, especially during winter and spring freeze-thaw cycles.
- People and animals falling from cliffs and gorge walls.
- Potential for solution-enlarged joints and sinkhole development in areas of thin to absent glacial drift.

Economic geology:
- Historically, quarried for dimension stone.
- Agricultural lime, asphaltic cement, crushed stone, and riprap.

Scenic geology:
- The Euphemia, Springfield, and Cedarville Dolomites form the gorge walls of Clifton Gorge SNP, Glen Helen Nature Preserve, Clark Run Gorge, Massie's Creek Gorge, and the upper gorge walls of John Bryan SP.

Further reading:

Bownocker, J. A., 1915, Building Stones of Ohio: Ohio Department of Natural Resources, Division of Geological Survey Bulletin 18, 160 p.

Sandy, M.R., 2012, Golden olden days of the Ordovician, Silurian seas, and Pleistocene ice—An introduction to the geology of the Dayton area, *in* Sandy, M.R., and Goldman, D., eds. On and around the Cincinnati Arch and Niagara Escarpment—Geological Field Trips in Ohio and Kentucky for the GSA North-Central Section Meeting, Dayton, Ohio, 2012: Geological Society of America Field Guide 27, p. 55–86.

Euphemia Dolomite

The Euphemia Dolomite is distinguished from the overlying Springfield Dolomite by thin to massive bedding and porous dolomite with some mottling and from the underlying Massie Shale by the lack of shale. When exposed, the Euphemia weathers to a pitted and corroded surface with large vugs. These rocks were deposited in a shallow, tropical sea containing abundant marine life. Their skeletons and skeletal fragments accumulated into thick beds of limestone that were later changed into dolomite as magnesium-rich, high-salinity waters were circulated through the limey sediments. The thin Euphemia is exposed in a narrow band, generally less than 1 mile wide, extending southeastward from the Clark-Champaign County line to the Clinton-Highland County line. The Euphemia Dolomite, named after the village of Euphemia, Ohio, was introduced in 1917 to separate these rocks from the overlying well-bedded Springfield Dolomite. It ranges in thickness from 5 to 15 feet (2 to 5 meters).

Diagnostic features:
- Gray dolomite.
- Thin to massive bedding.
- Abundant porosity and large vugs.
- Some mottling.

General features:
- Abundant fine to coarse fossil grains.
- Fossil molds and casts.

Lithologic variations:
- Mixture of lenticular, irregular, and rare planar beds that vary in abundance from exposure to exposure.

Fossil content:
- Diverse marine fauna with crinoids, corals, and brachiopods dominating.
- Bryozoans and trilobites less common.
- The brachiopod *Pentamerus* occurs throughout and is more common near the top of the unit.

Weathering characteristics:
- The Euphemia is resistant and forms prominent salient under the less resistant Springfield.
- Weathered surfaces often are pitted and corroded creating a honeycomb effect.
- Forms resistant base of the high gorge walls and small cliffs, waterfalls, and riffles in streams.
- Small slump blocks may occur on colluvium-rich slopes weathered from the Massie Shale, Laurel Dolomite, and Osgood Shale.

The Euphemia-Springfield contact is well-exposed along the road to the lower picnic area in John Bryan State Park. The sharp contact between these units separates the thick to massive bedding of the Euphemia Dolomite from the medium to thick bedding and brick-like weathering of the Springfield Dolomite.

Stratigraphic contacts:
- Sharp to gradational upper contact.
- Sharp lower contact.

Stratigraphic context:
- Underlain by Massie Shale.
- Overlain by Springfield Dolomite.
- Similar units: Cedarville Dolomite, Peebles Dolomite, and Lockport Dolomite.

Engineering properties:
- Unconfined Compressive Strength—Unweathered dolomite will have a high to very high compressive strength; weathered dolomite will have a moderate to high compressive strength.
- Slake Durability—Dolomite is expected to have high to very high durability.
- Rippability—Euphemia Dolomite is resistant to ripping. Blasting, breaking, or cutting is required for rock excavation.

Hydrogeologic properties:
- Moderate to relatively good aquifer.
- Due to overall thin nature of this unit, the Euphemia Dolomite may be mapped and drilled together as a hydrologic unit with overlying units.
- Average yields for domestic wells range from 10 to 25 gpm.
- Maximum yields for deeper, larger-diameter wells completed in this formation range from 25 to 100 gpm.
- Aquifer rating: 5–6.
- Vadose zone: 5–6.
- Hydraulic conductivity varies from a range of 1–100 gpd/ft^2 to 100–300 gpd/ft^2.

Environmental hazards:
- Falling rocks from cliffs and gorge walls, especially during winter and spring freeze-thaw cycles.

Economic geology:
- Historically, used sparingly as a building stone.
- May be quarried with overlying Springfield and Cedarville Dolomites for aggregate in road and building construction, and railroad ballast.

Scenic geology:
- Euphemia forms basal portion of the gorge walls of Clifton Gorge SNP, Glen Helen Nature Preserve, Clark Run Gorge, Massie's Creek Gorge, upper gorge walls of John Bryan SP.
- Forms small slump blocks.

Further reading:

Hansen, M. C., 1998, Geology of Ohio—The Silurian: Ohio Department of Natural Resources, Division of Geological Survey, Ohio Geology, Spring 1998, p. 1–7.

Sandy, M.R., 2012, Golden olden days of the Ordovician, Silurian seas, and Pleistocene ice—An introduction to the geology of the Dayton area, *in* Sandy, M.R., and Goldman, D., eds. On and around the Cincinnati Arch and Niagara Escarpment—Geological Field Trips in Ohio and Kentucky for the GSA North-Central Section Meeting, Dayton, Ohio, 2012: Geological Society of America Field Guide 27, p. 55–86.

ACTUAL SIZE

Massie Shale

The Massie Shale is characterized by gray, calcareous, fossiliferous shale interbedded with rare fossiliferous limestone and silty limestone. These rocks were deposited in a vast, shallow tropical sea with an abundant fauna of sea creatures, which burrowed into the sea floor or lived on the sea floor or within the tropical sea. The Massie Shale occurs in Clark, Clinton, and Greene Counties. Generally, it is poorly exposed except in the Little Miami River and Massie Creek Gorges. The Massie was named for the excellent exposures located in the Massie Creek Gorge, about 0.5 miles (0.8 km) west of Cedarville, Ohio. The Massie ranges in thickness from 0 to 10 feet (0 to 3 meters).

Diagnostic features:
- Gray calcareous, fossiliferous shale.
- Rare, fossiliferous dolomitic limestone and silty dolomitic limestone.

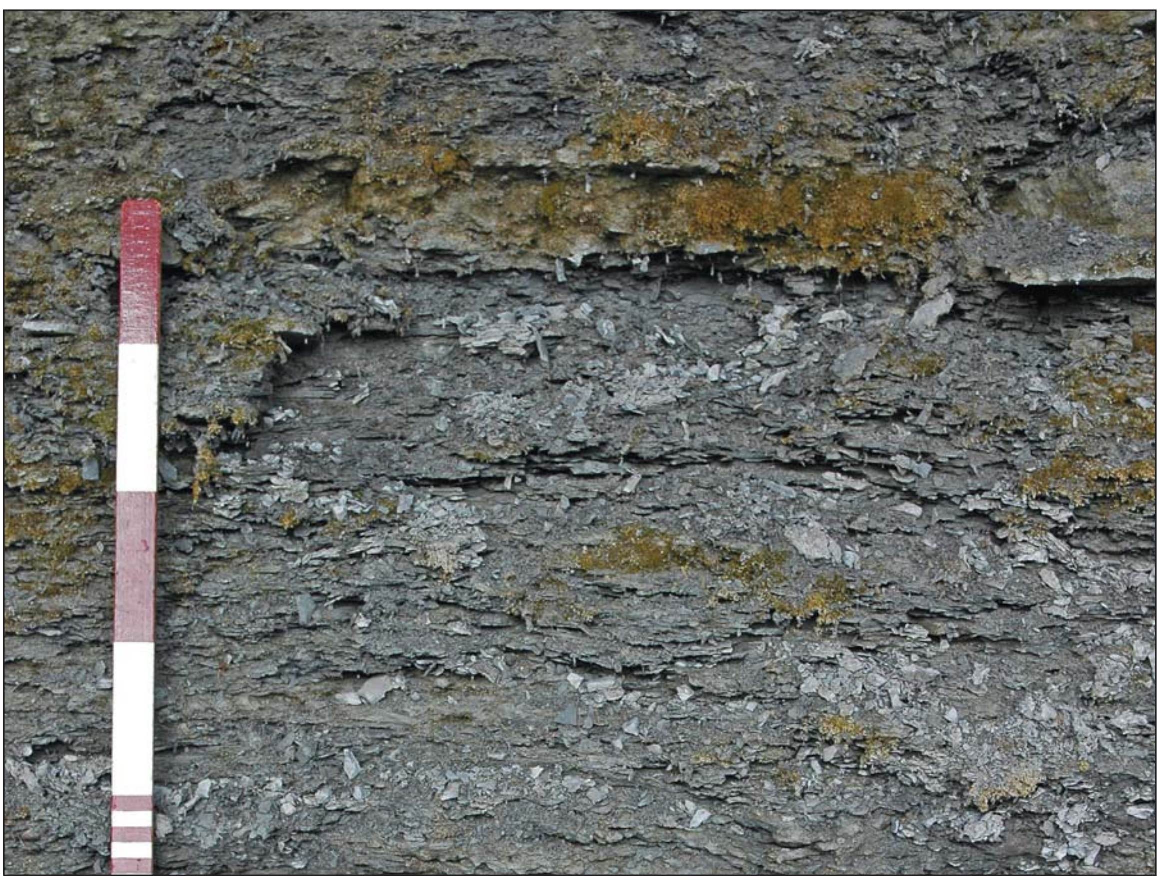
General features:
- Medium to thick bedded.
- Limestone beds laminated to thin bedded.
- Fissile to platy partings in shale beds.

Lithologic variations:
- Dolomitic limestone and dolomite beds increase in the western part of Clark and Greene Counties and central Clinton County.

Fossil content:
- Brachiopods, bryozoans, crinoids, and snails common.
- Trilobites less common.

Weathering characteristics:
- Not resistant.
- Weathers rapidly, forming abundant colluvium.
- Forms prominent reentrants under the overlying resistant dolomite units.

Stratigraphic contacts:
- Sharp upper contact.
- Sharp lower contact.



Gray, thick-bedded, fossiliferous Massie Shale and rare thin, dolomitic limestone beds exposed along the gorge walls of Massies Creek Gorge in Greene County Parks District Indian Mound Reserve Park located west of Cedarville, Ohio.

Stratigraphic context:
- Underlain by Laurel Dolomite.
- Overlain by Euphemia Dolomite.
- Similar unit: Osgood Shale.

Engineering properties:
- Slightly interbedded formation containing primarily weak with few thin strong beds. Weaker shales should be considered as the controlling rocks in this formation.
- Unconfined Compressive Strength—Unweathered shale has a moderate to high compressive strength; weathered shale will have a very low to moderate compressive strength.
- Slake Durability—Shales of this formation subject to more rapid degradation after exposure. Slake durability of the shale of this formation ranges from low to extremely high. Limestone would has extremely high slake durability.
- Rippability—Weathered shale beds, particularly those near the surface, can be ripped with some difficulty by conventional earth-moving equipment. Unweathered shales may require blasting, breaking, or cutting for rock excavation.

Hydrogeologic properties:
- Relatively poor aquifer.
- Due to thin nature (<10 feet), unit is typically not considered an individual hydrologic unit and is mapped and drilled together with underlying and overlying units, which feature better aquifer characteristics.
- The hydrologic interval, which includes the Massie, typically produces yields in the 10–25 gpm range and is suitable for most domestic and small farming needs.
- Aquifer rating: 4–5.
- Vadose zone: 3–4.
- Hydraulic conductivity: 1–100 gpd/ft^2.

Environmental hazards:
- Danger of falling rocks from overlying cliff-forming dolomite.

Economic geology:
- Not used as a raw material for manufacturing or other commercial activities.

Scenic geology:
- Small rock shelters under overhanging dolomite cliffs.
- Boulder fields of huge dolomite blocks, resulting from rapid lateral and vertical stream erosion that has undercut and toppled the resistant blocks into the gentle slopes formed by the erosion of the less resistant Massie Shale, Laurel Dolomite, and Osgood Shale.

Further reading:

Ausich, W.I., 1987, John Bryan State Park, Ohio—Silurian stratigraphy, *in* Biggs, D.L. ed., Centennial Field Guide, Volume 3: Boulder, Colo., Geological Society of America, p. 419–430.

Stout, Wilbur, 1941, Dolomites and limestones of western Ohio: Ohio Department of Natural Resources, Division of Geological Survey Bulletin 42, p. 35–36.

Osgood Shale

The Osgood Shale is characterized by blue-gray to gray, calcareous shale interbedded with sparsely fossiliferous, fine-grained limestone and dolomitic limestone. These rocks were deposited in near-shore areas of a shallow tropical sea with a reduced fauna of sea creatures. These creatures either lived in the sea bottom sediments, on the sea floor, or in the overlying sea. The Osgood Shale occurs in a narrow band generally less than 1 mile (1.6 km) wide in Clark, Clinton, and Greene Counties. The Osgood was named for the exposures occurring near Osgood, Indiana. The unit ranges in thickness from 3 to 25 feet (0.9 to 7.6 meters).

Diagnostic features:
- Blue-gray to gray, calcareous shale.
- Sparsely fossiliferous, fine-grained limestone and dolomitic limestone.

General features:
- Thin to medium bedded.
- Lenticular to planar bedding.
- Burrow mottling.
- Fissile to platy partings in shale beds.

Lithologic variations:
- Limestone beds increase in the upper part of the unit.

Fossil content:
- Sparse fauna of brachiopods, bryozoans, crinoids, corals, and trilobites.

Weathering characteristics:
- Not resistant to weathering.
- Rapid weathering produces abundant colluvium.
- Forms gentle slopes.
- Rapid stream erosion of the Osgood undercuts the overlying, resistant dolomite units, causing gorge wall collapse and the formation of abundant slump blocks.

Stratigraphic contacts:
- Sharp upper contact.
- Sharp lower contact.

Stratigraphic context:
- Underlain by Dayton Formation.
- Overlain by Laurel Dolomite.
- Similar unit: Massie Shale.

The upper part of the Osgood Shale characterized by blue-gray, thin to thick-bedded shale with interbedded thin bedded limestone. This exposure occurs in an unnamed tributary of the Little Miami River termed the south section of Ausich (1987) located in John Bryan State Park.

Engineering properties:
- Interbedded formation with primarily weak and strong beds. Weaker shales are considered as the controlling rocks in the Osgood.
- Unconfined Compressive Strength—Unweathered shale will have a medium to high compressive strength; weathered shale will have a low to medium compressive strength; limestone will have a high compressive strength.
- Slake Durability—Shales from formation are subject to degradation after exposure. Slake durability of shale of this formation can range from medium to high. Limestone beds have a high to extremely high slake durability.
- Rippability—Weathered shale beds, particularly near the surface, can be ripped by conventional earth-moving equipment. Unweathered shales and limestone of the formation would require blasting, breaking, or cutting for rock excavation.

Hydrogeologic properties:
- Relatively poor aquifer.
- Typically not considered an individual hydrologic unit due to the thin nature (<25 feet).
- Mapped and drilled together with underlying and overlying units, which feature better aquifer characteristics.
- The hydrologic interval that includes the Osgood Shale typically produces yields varying from a 3–10 gpm to 10–25 gpm range and is suitable for most domestic and small farm needs.
- Aquifer rating for the hydrologic interval ranges from 4 to 5.
- Vadose zone rating for the hydrologic interval ranges from 3 to 4.
- Hydraulic conductivity: 1–100 gpd/ft^2

Environmental hazards:
- Landslide development in thick colluvium derived from the Osgood.
- Rock falls in areas with overhanging, resistant dolomite cliffs.

Economic geology:
- Not used as a raw material for manufacturing or other commercial activities.

Scenic geology:
- Huge boulders of dolomite littering the gentle slopes of the Osgood.

Further reading:

Ausich, W.I., 1987, John Bryan State Park, Ohio—Silurian stratigraphy, *in* Biggs, D.L. ed., Centennial Field Guide, Volume 3: Boulder, Colo., Geological Society of America, p. 419–430.

ACTUAL SIZE

Brassfield Formation

The Brassfield Formation is characterized by fossiliferous limestone, dolomite, cherty limestone, and minor iron-rich limestone interbedded with rare to abundant, sparsely fossiliferous to fossiliferous shale. These rocks were deposited in a vast, shallow sea that teemed with abundant plants and animals. In Ohio, the Brassfield occurs along a narrow 0.5- to 2.0-mile (0.8- to 3.2-km)-wide band extending in an arc from the Ohio-Indiana line in Butler and Preble Counties through the Dayton, Ohio, region and then extending southeastward to the Ohio River in Adams County. Several small "islands" of Brassfield occur overlying the Ordovician rocks in Preble, Montgomery, Warren, and Brown Counties, Ohio. In the Dayton region, occasional reefs and shoals developed producing well-sorted, calcium-rich limestone beds containing little, if any, shale. In southern Ohio, the limestone beds contain more dolomite and clay and are interbedded with abundant sparsely fossiliferous to fossiliferous shale beds. The Brassfield was first used to describe the limestone and dolomite rocks exposed in the Louisville & Atlantic Railroad cuts near the town of Brassfield in Madison County, Kentucky. In Ohio, the Brassfield ranges in thickness from 12 to 50 feet (4 to 15 meters).

Diagnostic features:
- Fine- to coarse-crystalline, fossiliferous limestone.
- High-calcium, fossiliferous limestone in west-central Ohio.
- Limestone interbedded dolomite, chert, and shale in Adams and Highland Counties.

General features:
- Planar, irregular, lenticular, and nodular bedding.
- Thin to thick bedded.
- Color varies from white to light gray through darker shades of gray, tan, pink, red, and brown.

Lithologic variations:
- Basal Belfast Member characterized by silty, granular dolomite and dolomitic limestone with locally abundant burrows.
- Nodular- to irregular-bedded chert is abundant in the lower portion of the unit in Adams and Highland Counties.
- Near the top of the Brassfield, iron-rich limestone beds form a distinctive stratigraphic marker that has been mapped throughout Adams and Highland Counties.
- Large distinctive crinoid columns, resembling beads, occur in great abundance in the uppermost Brassfield in southern Ohio.

The eastern highwall of the Fairborn Parks and Recreation Department Oakes Quarry Park displaying the characteristic thin- to thick-bedded, fossiliferous, high-calcium limestone of the Brassfield Formation with prominent joints.

Fossil content:
- Abundant fossils are crinoids, corals, stromatoporoids, brachiopods, and bryozoans and trace fossils.
- Less common are trilobites, gastropods, bivalves, cephalopods.
- In the Fairborn region, the Brassfield contains over 26 genera and 29 species of crinoids representing one of the world's most diverse Early Silurian crinoid faunas.

Weathering characteristics:
- Resistant to weathering.
- Forms cliffs, waterfalls, and gorges in streams and road cuts.
- Commonly weathers reddish-gray to light gray.

Stratigraphic contacts:
- Sharp to gradational lower contact.
- Sharp upper contact.

Stratigraphic context:
- Underlain by Drakes Formation.
- Overlain by Dayton Limestone in west-central Ohio or undifferentiated rocks of the Downing Creek Formation in southern Ohio.

Engineering properties:
- Strong beds with very little interbedding of weaker shales.
- Unconfined Compressive Strength—Unweathered limestone will have a high to very high compressive strength. Weathered limestone will have a moderate to high compressive strength.
- Slake Durability—Brassfield Formation is expected to have high to very high durability. The porosity of this formation makes it susceptible to freeze thaw break down.
- Rippability—Brassfield Formation is resistant to ripping. Blasting, breaking, or cutting is required for rock excavation.

Hydrogeologic properties:
- A moderate to relatively poor aquifer, due to its variable nature.
- May be utilized on its own or mapped and drilled together as a hydrologic unit with overlying units.
- Better aquifer than underlying Ordovician units.
- Yields typically range from 3 to 10 gpm; in limited areas where the formation is thicker, yields may reach 25 gpm.
- Suitable for most domestic and small farming needs.
- Aquifer rating: 4–5.
- Vadose zone: 3–4.
- Hydraulic conductivity: 1–100 gpd/ft^2.

Environmental hazards:
- In Preble County, basal Brassfield may contain petroleum, asphalt, and natural gas, thus downgrading ground-water quality.
- Rock falls, especially during the freeze/thaw cycles of the late winter and early spring.
- Falls from cliff tops by people and livestock.

Economic geology:
- Major source of high-calcium limestone (<95% calcium carbonate) in Fairborn region.
- High-calcium limestone is used in the manufacture of Portland cement.
- Brassfield is also a source of crushed stone.

Scenic geology:
- Abundant, specular waterfalls and cascades; many available for public viewing in state, county, and municipal park districts. Some examples include: inner gorge at John Bryan SP; Martindale and Patty Falls, Englewood Metro Park; Charleston Falls, Miami Park District; Ludlow Falls, Ludlow, Ohio.
- Forms abundant cliff exposures along streams especially in southern Ohio beyond the limit of glaciation.
- Small rock shelters under the base of the unit as the less resistant Drakes Formation is removed by rapid erosion.

Further reading:

Ausich, W.I., 2009, These are not the crinoids your granddaddy knew: Mid-American Paleontology Society Digest, Expo XXXI Edition, v. 32, no.1, p. 4–17.

Swinford, E. M., 1985, Geology of the Peebles Quadrangle, Adams County, Ohio: Ohio Journal of Science, v. 85, no. 5, p. 218–230.

Wolfe, M.E., 2008, High-calcium limestone in Ohio. Ohio Department of Natural Resources, Division of Geological Survey GeoFacts 25.

Typical of Dayton region.

Typical of southern Ohio.

Drakes Formation

The Drakes Formation is dominated by dolomitic shale with minor interbedded, fossiliferous limestone and dolomitic limestone, and it caps the Late Ordovician rocks preserved in Ohio. The unit was deposited during a time of mountain building along the present-day Appalachian Mountains and widespread continental glaciation that covered much of a supercontinent known as *Gondwana*, located in the Southern Hemisphere. The Drakes was deposited in very shallow seas or on adjacent mud flats as sea level migrated back and forth across southwestern Ohio. Finally, the former sea bed and mud flats became dry land as the sea retreated from Ohio. Fossil evidence indicates that a major unconformity occurs at the top of the Drakes, where rocks of the latest Ordovician and earliest Silurian rocks were never deposited or were eroded away in southwestern Ohio.

Soil and glacial sediments frequently cover the Drakes Formation along much of its narrow outcrop extending northwestward from the Ohio River in central Adams County to the Dayton region, then southwestward through Montgomery, Preble, and Butler Counties. In Adams County, the Drakes is well exposed in stream cuts and road cuts because of the overlying, cliff-forming Brassfield Formation. The unit was named for a dirt road exposure near Drakes Creek in south-central Kentucky. The Drakes is divided into the Rowland Member and overlying Preachersville Members; only the Preachersville Member extends into Ohio. In Ohio, the thickness of the Drakes ranges from 20 to 30 feet (6 to 9 meters).

Diagnostic features:
- Greenish-gray to reddish, dolomitic shale.
- Shale comprises 80–90% of the unit.

General features:
- Thin to thick bedded.
- Platy to fissile partings.
- Disseminated pyrite.
- Interbedded, fossiliferous limestone and dolomitic limestone with and sparsely fossiliferous shale.

Lithologic variations:
- Fossiliferous limestone beds decrease vertically through the unit.
- Dolomitic limestone beds increase vertically through the unit.

Fossil content:
- Brachiopods, bryozoans, trilobites, molluscs, and echinoderms in fossiliferous limestone beds.
- Fossil content decreases in the upper part of unit.

The upper part of the greenish-gray to reddish, shale of the Drakes Formation and overlying Brassfield Formation exposed in a road cut for S.R. 41, approximately 0.4 miles (0.6 km) south of the intersection with Logan Road. The contact of the Drakes and Brassfield occurs at the top of the uppermost greenish shale within the prominent reentrant midway through the road cut. Geologist Gregory Schumacher avoids the potential rock fall hazard present in the prominent reentrant created by the rapid erosion of the non-resistant Drakes by the small waterfall.

Weathering characteristics:
- Rapidly weathers to light yellowish-gray clay because of wetting/drying and freeze/thaw cycles.
- Forms thin to thick colluvium when not extensively covered with glacial sediments.

Stratigraphic contacts:
- Sharp upper contact.
- Gradational lower contact.

Stratigraphic context:
- Underlain by Whitewater Formation in western Ohio.
- Underlain by Waynesville F ormation in southern Ohio.
- Overlain by Brassfield Formation.
- Similar units: Kope Formation and Miamitown Shale.

Engineering properties:
- Interbedded formation with very weak and strong beds. Weaker shales should be considered as the controlling rocks in the Drakes. Shales of this formation are anticipated to weather rapidly after exposure.
- Unconfined Compressive Strength—Unweathered shale will have a medium to high compressive strength; weathered shale will have a low to medium compressive strength; limestone will have a high compressive strength.
- Slake Durability—Shale beds from the Drakes are subject to rapid degradation after exposure. Shale slake durability can range from low to high. Limestone would have an extremely high slake durability.
- Rippability—Weathered shale beds, particularly those near the surface, can be ripped by conventional earth-moving equipment.

Hydrogeologic properties:
- Typically poor aquifer with minimal yields; suitable for limited household and small farm usage.
- Average yield is 3–5 gpm with a maximum yield of roughly 10 gpm.
- Yields provided by a combination of joints and fractures as they intersect bedding planes.
- Due to soft, clayey nature of this unit, weathered portion may or may not be higher yielding than unweathered portions.
- Wells may be drilled deeper into underlying units to increase well bore storage.
- For groundwater modeling purposes, unit may be considered a lower-confining unit or boundary unit.
- Similar hydrogeologic properties to underlying Ordovician units and typically mapped together. Individual units in the Ordovician are commonly too thin to constitute an individual hydrogeologic unit.
- Aquifer rating: 2–3.
- Vadose zone rating: 2–3.
- Hydraulic conductivity: 1–100 gpd/ft^2.

Environmental hazards:
- Rapid weathering and stream erosion of softer, shale-rich Drakes produces undermining of the resistant cliff-forming Brassfield Formation, causing large rock falls particularly in stream valleys and road cuts.
- Small landslides possible in colluvium derived from this unit.

Scenic geology:
- Colorful reddish-gray and maroon shale beds where unit is exposed.

Further reading:

Weir, G.W., Greene, R.C., and Simmons, G.C., 1965, Calloway Creek Limestone and Ashlock and Drakes Formations (Upper Ordovician) in south-central Kentucky: U.S. Geological Survey Bulletin 1224-D, 36 p.

ACTUAL SIZE

Whitewater Formation

The Whitewater Formation is characterized by highly fossiliferous, wavy- to irregular-bedded limestone interbedded with fossiliferous shale. These rocks were deposited in a vast, shallow sea that teemed with abundant marine life. Occasional shoals developed, producing well-sorted limestone beds containing minimal amounts of shale. The Whitewater is best developed in the vicinity of Richmond, Indiana, and is named for the abundant exposures found in the gorge of the Whitewater River at Richmond. In Ohio, the Whitewater occurs in a 10- to 20-mile (16- to 32-km)-wide band extending in an arc from the Ohio-Indiana line in Butler and Preble Counties through the Dayton, Ohio, region, then extending southeastward to the Clinton-Highland County line where the unit thins and grades laterally into the Liberty and Waynesville Formations. The Whitewater ranges in thickness from 0 to 80 feet (0 to 24 meters).

Diagnostic features:
- Wavy-, nodular-, or irregular-bedded limestone.
- Wavy- to irregular-bedded shale.
- Limestone comprises 60–70% of the formation.
- Highly fossiliferous limestone and shale beds.

General features:
- Thin bedded.
- Discontinuous limestone and shale beds.
- Fissile partings in shale beds.
- Thin zones containing abundant colonial corals.

Lithologic variations:
- Percentage of shale increases southeastward from Dayton region to the Clinton-Highland County line.
- Number of continuous, irregular- to planar-bedded limestone beds increases from the Dayton region to the Clinton-Highland County line.

Fossil content:
- Brachiopods, bryozoans, and horn corals very abundant.
- Trilobites, bivalves, cephalopods, gastropods, and echinoderms less common.
- Abundance and variety of fossils declines near top of the unit.
- Fossil collecting is allowed at Hueston Woods SP, Caesar Creek SP, and Cowan Lake SP. **Please check with park officials prior to collecting fossils**.

The cliff-forming; highly fossiliferous; wavy-, nodular-, and irregular-bedded limestone and shale beds of the Whitewater Formation exposed in Beasley Run. The small gorge is located along Camden Road about 500 feet (152 meters) south of the intersection with Somers Road.

Weathering characteristics:
- Resistant to weathering.
- Forms cliffs, riffles, and gorges in streams and road cuts.

Stratigraphic contacts:
- Sharp to gradational upper contact.
- Sharp lower contact.

Stratigraphic context:
- Underlain by Liberty Formation.
- Overlain by Drakes Formation.
- Similar units: Grant Lake Limestone, Bellevue and Straight Creek Members; Grant Lake Formation, Bellevue Member.

Engineering properties:
- Interbedded formation composed mostly of strong and limited weak beds. Shales considered the controlling rocks in this formation. Shales of this formation are anticipated to weather rapidly after exposure.
- Unconfined Compressive Strength—Unweathered shale will have a moderate compressive strength; weathered shale will have a moderate to compressive strength, weathered shale will have a low to moderate compressive strength.
- Slake Durability—Shales of this formation are subject to rapid degradation after exposure. Slake durability of shale of this formation can range from moderate to high. Limestone slake durability is high to extremely high.
- Rippability –Formation is considered resistant to ripping. Blasting, breaking or cutting would be required for rock excavation.

Hydrogeologic properties:
- Typically a poor aquifer with minimal yields; suitable for limited household and small farm usage.
- Average yield is 3–5 gpm with a maximum yield of roughly 10 gpm.
- Yields provided by a combination of joints and fractures as they intersect bedding planes.
- Wells may be drilled deeper into underlying units to increase well bore storage.
- For groundwater modeling purposes, unit may be considered a lower-confining unit or boundary unit.
- Similar hydrogeologic properties to overlying and underlying Ordovician units and typically mapped together. Individual units in the Ordovician are commonly too thin to constitute an individual hydrogeologic unit.
- Aquifer rating: 2–3.
- Vadose zone rating: 2–3.
- Hydraulic conductivity: 1–100 gpd/ft^2.

Environmental hazards:
- Danger of falling rocks from cliff and gorge exposures, especially in spring.
- Potential for solution enlargement of joints and minor sinkhole development in areas of thin to absent glacial drift.

Economic geology:
- Currently, not quarried for industrial or commercial purposes.
- Historically, limestone was used in road building or agricultural lime.

Scenic geology:
- Whitewater and underlying Liberty Formations form gorges of Whitewater River and tributaries at Richmond, Indiana; streams in Hueston Woods SP and Camden, Ohio, regions; Caesar Creek; and Cowan Creek below dam for Cowan Lake.

Further reading:

Hansen, M.C., 1997, The geology of Ohio—The Ordovician: Ohio Department of Natural Resources, Division of Geological Survey, Ohio Geology, Fall 1997, p. 1–6.

Coogan, A.H., 1996, Ohio's surface rocks and sediments, *in* Feldmann, R.M., and Hackathorn, Merrianne, eds., Fossils of Ohio: Ohio Department of Natural Resources, Division of Geological Survey Bulletin 70, p. 31–50 [Revised 2005].

ACTUAL SIZE

Liberty Formation

The Liberty Formation consists of interbedded, planar- to irregular-bedded, fossiliferous limestone and sparsely fossiliferous shale. The unit was deposited in the transitional environment between the shallow-water environments of the Whitewater Formation and the offshore, deeper-water environments of the Waynesville Formation. Major hurricanes frequently swept across southwestern Ohio during Late Ordovician time, creating many of the characteristic interbedded limestone and shale beds and the excellent preservation of fossils characterizing the Liberty.

The Liberty is largely buried under Quaternary-age sediments along a narrow, arching outcrop belt extending from Butler and Preble Counties through the southern Dayton region, then southeastward into central Highland County, where the unit pinches out. The best places to examine the Liberty are river and stream exposures, where the formation forms steep slopes and cliffs along stream valleys and a series of small waterfalls in streams. The unit was named for the excellent exposures in the vicinity of Liberty, Indiana, and ranges in thickness from 20 to 40 feet (6 to 12 meters).

Diagnostic features:
- Planar- to irregular-bedded limestone and shale.
- Sparsely fossiliferous shale.
- Limestone and shale beds each average 50% of unit.

General features:
- Thin to medium bedded.
- Platy to flaggy partings in shale beds.
- Disseminated pyrite.
- Graded bedding and ripple marks common in limestone beds.

Lithologic variations:
- Average amount of shale increases from 50% in Butler and Preble Counties to over 60% in Highland County.
- Average amount of limestone decreases from 50% in Butler and Preble Counties to less than 40% in Highland County.

Fossil content:
- Highly fossiliferous.
- Diverse fauna of primarily brachiopods, bryozoans, bivalves, corals, crinoids, trilobites, cephalopods, gastropods, and abundant trace fossils.
- Excellent preservation of fossils.

Weathering characteristics:
- Fairly resistant to weathering, forming cliffs and steep slopes in stream valleys.
- Forms thin colluvium with abundant slabs of limestone.

Small waterfalls formed by the nearly equal amounts of planar- to irregular-bedded limestone and shale beds of the Liberty Formation. This section is exposed in an unnamed tributary of Paint Creek, 0.75 miles (1.20 km) west of Camden, Ohio, along old S.R. 725.

Stratigraphic contacts:
- Sharp to gradational upper contact.
- Sharp lower contact.

Stratigraphic context:
- Underlain by Waynesville Formation.
- Overlain by Whitewater Formation.
- Similar units: Fairview Formation, Grant Lake Formation-Corryville Member.

Engineering Characteristics:
- Interbedded formation with weak and strong beds. Weaker shales should be considered as the controlling rocks in this formation. Shales of this formation are anticipated to weather after exposure.
- Unconfined Compressive Strength—Unweathered shale will have a moderate to high compressive strength; weathered shale will have a poor to moderate compressive strength; limestone will have a high compressive strength.
- Slake Durability—Shales of this formation are subject to more rapid degradation after exposure; however, the abundance of limestone increases resistance of this formation. Slake durability of shale of this formation can range from moderate to very high. Limestone would have a high to extremely high slake durability.
- Rippability—Weathered shale beds, particularly those near the surface, can be ripped with some difficulty by conventional earth-moving equipment. Limestone and shale that are not significantly weathered are resistant to ripping. Blasting, breaking or cutting would be required for rock excavation.

Hydrogeologic properties:
- Typically poor aquifer with minimal yields; suitable for limited household and small farm usage.
- Average yield is 3–5 gpm with a maximum yield of roughly 10 gpm.
- Yields provided by a combination of joints and fractures as they intersect bedding planes.
- Due to soft, clayey nature of this unit, weathered portion may or may not be higher yielding than unweathered portions.
- For groundwater modeling purposes, unit may be considered a lower-confining unit or boundary unit.
- Similar hydrogeologic properties to overlying and underlying Ordovician units and typically mapped together. Individual units in the Ordovician are commonly too thin to constitute an individual hydrogeologic unit.
- Aquifer rating: 2–3.
- Vadose zone rating: 2–3.
- Hydraulic conductivity: 1–100 gpd/ft^2.

Environmental hazards:
- No environmental hazards are associated with the Liberty.

Economic geology:
- Limestone beds used as building stone in decorative retaining walls and for stepping stones.
- Historically, limestone from the Liberty was used to build foundations for structures, stone walls, and occasionally as building stone for structures.

Scenic geology:
- The resistant Liberty and Whitewater combine to form scenic gorges in Hueston Woods SP; Woodland Trails State Wildlife Area; Camden, Ohio region; and Caesar Creek Gorge SNP.
- Limestone beds form a series of small waterfalls as streams cut through the Liberty.

Further reading:

Feldmann, R.M., and Hackathorn, Merrianne, eds., 2005, Fossils of Ohio: Ohio Department of Natural Resources, Division of Geological Survey Bulletin 70, 577 p.

Tobin, R.C., 1986, An assessment of the lithostratigraphy and interpretative value of the traditional “biostratigraphy” of the type Upper Ordovician of North America: American Journal of Science v. 286, no. 9, p. 673–701.

ACTUAL SIZE

Waynesville Formation

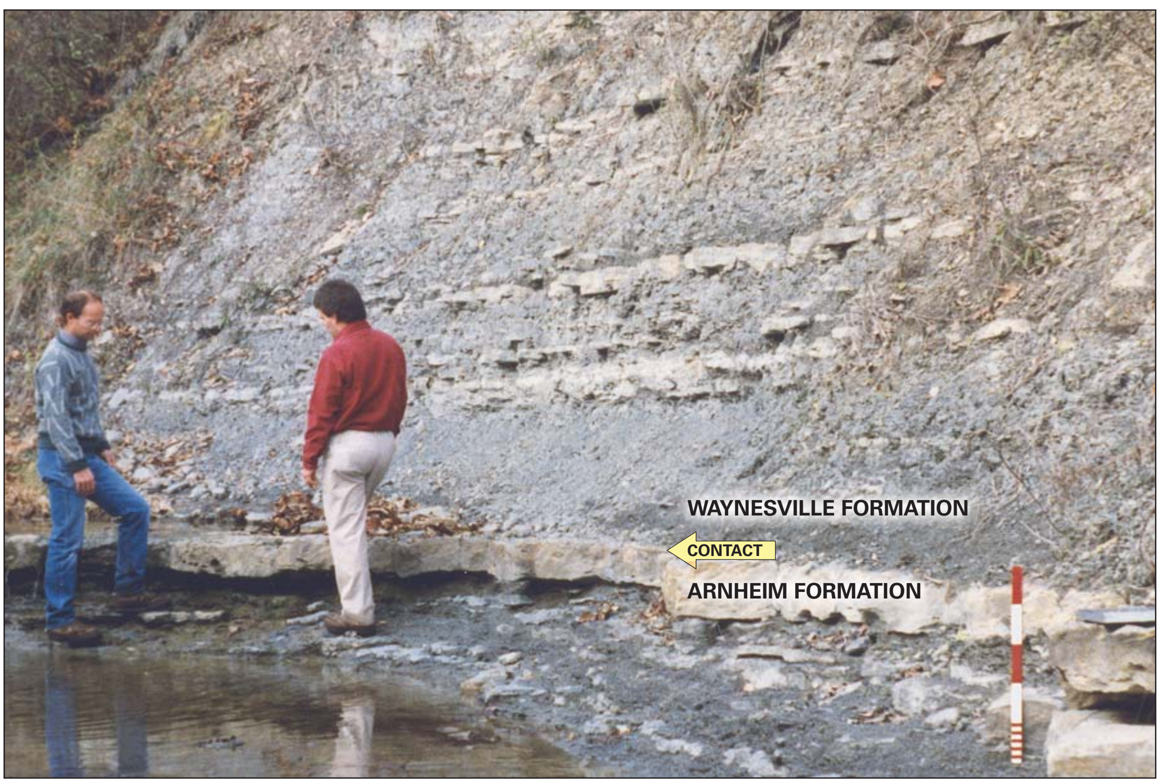
The diagnostic features of the Waynesville Formation are the dominance of shale that occurs in medium to thick beds. Shale averages over 70% of the unit and limestone averages 30%. The Waynesville Formation was deposited in a vast, shallow sea containing abundant and diverse marine life. The offshore environment of the Waynesville contained water depths deeper than the underlying Arnheim and overlying Liberty Formations and was frequently subjected to the passage of major hurricanes. The Waynesville was first described and named for the stream exposures found in the Waynesville, Ohio, region. The unit is exposed in a 2- to 15-mile (3.2- to 24 km)-wide band along the valley walls of the tributaries of the Great Miami River and Little Miami River and the uplands of central Hamilton, Clinton, Highland, Clermont, Brown, and Adams Counties. The Waynesville ranges in thickness from 90 to 120 feet (27 to 37 meters) in thickness and is commonly buried under glacial sediments where it occurs in the upland areas.

Diagnostic features:
- Ratio of 70% shale to 30% limestone.
- Medium- to thick-bedded shale beds.

General features:
- Planar to irregular bedding with occasional nodular-bedded limestone.
- Sparsely fossiliferous shale and highly fossiliferous limestone.
- Calcareous shale beds with minor pyrite nodules or irregular blobs.
- Dominance of thin-bedded limestone.

Lithologic variations:
- Many repeating, well-developed sedimentary cycles consisting of a thicker, shale-dominant interval capped by a thinner interval containing abundant limestone beds.
- Rare intervals of nodular- to wavy-bedded limestone.

Fossil Content:
- Spectacular preservation of fossils, especially trilobites and echinoderms.
- World renowned for abundance of brachiopods, bryozoans, corals, bivalves, gastropods, cephalopods, trilobites, echinoderms, and trace fossils.
- Fragments and rare complete specimens of Ohio's state fossil, the trilobite *Isotelus*, are common.
- Two narrow, widespread, shale-rich zones containing abundant complete specimens of the trilobites



The shale-rich Waynesville and Arnheim Formations are well-exposed in a small stream located at Waynesville, Ohio. The medium- to thick-bedded shale and thin- to medium-bedded limestone of the basal Waynesville Formation is well-exposed overlying the two prominent limestone beds present at the top of the Arnheim Formation.

Flexicalymene and *Isotelus* and well-preserved cephalopods can be traced throughout much of southwestern Ohio and into Indiana.

Weathering characteristics:

- The Waynesville weathers rapidly to light-gray clay with abundant limestone slabs because of repeated wetting/drying and freeze/thaw cycles.
- The unit forms relatively thick colluvium on steeper slopes.

Stratigraphic contacts:

- Sharp to gradational upper contact.
- Sharp lower contact.

Stratigraphic context:

- Underlain by Liberty Formation or Drakes Formation.
- Overlain by Arnheim Formation.
- Similar unit: Kope Formation.

Engineering properties:

- Interbedded formation composed mostly of weak and limited strong beds. Shales considered the controlling rocks in this formation. Shales of this formation are anticipated to weather rapidly after exposure.
- Unconfined Compressive Strength—Unweathered shale will have a moderate to high compressive strength; weathered shale will have a low to high compressive strength.
- Slake Durability—Shales of this formation are subject to rapid degradation after exposure. Shale slake durability can range from low to high.
- Rippability—Weathered shale beds, particularly those near the surface, can be ripped by conventional earth-moving equipment. Limestone and shale that are not significantly weathered are more resistant to ripping. Excavation of limestone and unweathered shale would require blasting, breaking, or cutting.

Hydrogeologic properties:

- Typically poor aquifer with minimal yields; suitable for limited household and small farm usage.
- Average yield is 3–5 gpm with a maximum yield of roughly 10 gpm.
- Yields provided by a combination of joints and fractures as they intersect bedding planes.
- Due to soft, clayey nature of this unit, weathered portion may or may not be higher yielding than unweathered portions.
- For groundwater modeling purposes, unit may be considered a lower-confining unit or boundary unit.
- Similar hydrogeologic properties to overlying and underlying Ordovician units and typically mapped together. Individual units in the Ordovician are commonly too thin to constitute an individual hydrogeologic unit.
- Aquifer rating: 2–3.
- Vadose zone rating: 2–3.
- Hydraulic conductivity: 1–100 gpd/ft².

Environmental hazards:

- Landslides occur in thicker colluvial deposits accumulating on steeper hillsides.

Scenic geology:

- Stream erosion of the less resistant Waynesville forms board picturesque valleys containing wide flood plains of alluvium and glacial sediments.

Further reading:

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Meyer, D.L., and Davis, R.A., 2009, A sea without fish—Life in the Ordovician sea of the Cincinnati Region: Bloomington, Indiana University Press, 346 p.

Shrake, D.L., 1995, *Isotelus*—Ohio's state fossil: Ohio Department of Natural Resources, Division of Geological Survey GeoFacts 6.

Schumacher, G.A., and Shrake, D.L., 1997, Paleoecology and comparative taphonomy of an *Isotelus* (Trilobita) fossil lagerstätten from the Waynesville Formation (Upper Ordovician, Cincinnatian Series) of southwestern Ohio: *in* Brett, C.E., and Baird, G.C., eds., Paleontological Events—Stratigraphic, ecological, and evolutionary implications: New York, Columbia University Press, p. 131–161.

ACTUAL SIZE