Guide to the Serpent Mound Impact Structure, South-Central Ohio

by
Keith A. Milam

Guidebook 22
Columbus 2016

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by
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Front cover: Digital elevation model of the Serpent Mound Impact Structure generated using data from the Ohio Geographically Referenced Information Program (OGRIP) - Ohio Statewide Imagery Program (OSIP). This oblique view is to the northeast. Vertical exaggeration = 4x.

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CONTENTS

FIGURES

ABBREVIATIONS USED IN THIS GUIDEBOOK

Length	
foot/feet	ft
kilometer(s)	km
kilometers per second	km/s
meter(s)	m
mile(s)	mi
miles per second	mi/s
millimeter(s)	mm
Mass	
kilograms per cubic meter	kg/m³
megaton(s)	MT
pound(s)	lb
Other Measurements	
astronomical unit	A.U.
degrees	°
mega annum	Ma
Miscellaneous	
digital elevation model	DEM
east-southeast	ESE
Goddard Spaceflight Center	GSFC
Jet Propulsion Laboratory	JPL
Johns Hopkins University Applied Physics Laboratory	JHUAPL
latitude	lat
longitude	long
Lunar and Planetary Institute	LPI
Lunar Reconnaissance Orbiter Camera	LROC
mean sea level	m.s.l.
National Aeronautics and Space Administration	NASA
north	N
Space Shuttle Radar Topography Mission	SRTM
United States	U.S.
United States Geological Survey	USGS
west	W

PREFACE

FOR FIELD TRIP LEADERS

Welcome to southern Ohio, home of many interesting geologic stories. The rocks here tell the changing tales of vast inland seas, continental ice sheets, retreating oceans, thriving marine ecosystems, anoxic environments, and colliding continents. One of the most interesting stories is that of an ancient collision of an asteroid or comet with Earth, producing a sizeable hole in the surface. In fact, that's the purpose of this field trip, to examine the only confirmed impact site in the state of Ohio—the Serpent Mound Impact Structure.

This field trip guide is organized into three parts, which can be modified to meet the time constraints and logistics for each particular trip. Part I provides field trip participants with the necessary and pertinent introductory information about the local geology and the basics of impact cratering. Part II includes stops that examine much of the local, undisturbed stratigraphy outside of the impact crater, while Part III is a tour of the crater itself. If the group is already familiar with the local stratigraphy, then they may elect to use only Part III of this guide.

When conducting any field trip in Ohio, please make safety a primary concern. Always adhere to federal, local, and state traffic laws. At some stops, participants may be walking on wet, muddy, and uneven terrain with loose rocks and sediment, so appropriate footwear is a must. Shoes or boots with good tread and plenty of ankle support are necessary. Some stops may require hiking through dense brush, some of which may contain briars and poison ivy, so field trip participants are advised to wear clothing appropriate to these environments and changing weather conditions. While many of the stops can be accessed along public right-of-ways, some are on private property. <u>Always obtain permission from property owners before entering a site</u> and comply with any rules they have for the group. For some of the stops, vehicles with high ground clearance might be necessary.

Participants are asked to be conservation-minded during the course of the trip. Not only will doing so protect the environment, but it will maintain good relationships with private property owners, which is a good thing for all of us who lead field trips and do research in the impact structure. Please remove and properly dispose of all trash and recyclables. Groups are asked to restrict movements to developed trails and footpaths so as to minimize damage to the local ecosystem. Field trip participants are encouraged to collect samples only as necessary for teaching or research. Over-collecting can quickly decimate the educational potential and research quality of a site.

FOR FIELD TRIP PARTICIPANTS

Please join the field trip leader in making this a successful trip by asking numerous questions, engaging the trip leader and other participants in insightful discussions, and observing all safety precautions and local laws. While this field guide is designed primarily for a geological audience, it has been customized for the amateur so that more people can appreciate one of Ohio's most unique geologic features—the Serpent Mound Impact Structure. Maps and driving directions, which are *italicized* for ease of recognition, have been included between stops. Additionally, when many new terms are first introduced, they appear in **bold print**. These terms are explained in an easy-to-use glossary at the end of this field guide.

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PART I: INTRODUCTION

The Beginning of a Controversy: History of Serpent Mound Research

Southern Ohio has been a subject of geologic study for well over 170 years. The anomalous nature of the Serpent Mound area (fig. 1) has been known about nearly as long. In the 2nd Annual Report of the Geological Survey of the State of Ohio, John Locke recorded his experience traveling for the first time through the southeastern part of what we now know as the Serpent Mound Impact Structure (Locke, 1838):

> As we decended [sic] into the channel of Crooked creek, I did not find as I had expected, the great **marl stratum**. Although we travelled on that level which should have presented us with the cliff **limestone**, yet we were surprised with its total disappearance as we approached the spring, and in its place was found the **sandstone** in large upturned and broken masses. (p. 266)

Locke also observed evidence for extensive structural deformation in a spring to the northwest of Locust Grove:

> In short, it became evident that a region of no small extent had sunk down several hundred feet, producing faults, dislocations and upturning of the layers of the rocks. The spring has every property of an excellent sulphuretted water; on the west side of it, is a grey limestone, the cliff stone rising about 15 feet, while at the opposite side of it is a slate dipping 30 degrees to the east. Nor is this a mere local deposite [sic], for I found it continuous and at the same dip for five or six hundred feet. (p. 266)

Upon examining a second spring, he continued:

> The slate at this spring dips in a direction opposite to that at the first spring, at the rate of 16 degrees, as follows: Line of bearing, N. 6 degrees W.—Line of dip, W. 6 degrees S. As the top of the slate is found here more than 300 feet lower than in the **strata *in situ*** in the surrounding knobs, and as these strata are broken and upturned, it is evident that this mountain at some remote period of time, has sunk down from its original place, and I ventured to call it the "*Sunken Mountain*." (p. 266–267)

While John Locke and later Edward Orton of the Second Geological Survey (Baranoski and others, 2003) documented the structural deformation at Serpent Mound, neither geologist modeled the geologic process or processes involved in the formation of this anomalous structure. That explanation would come nearly a hundred years later.

During the early twentieth century (1918–1919), the first (unpublished) geologic maps of the Serpent Mound Impact Structure were produced from the combined mapping efforts of August Foerste and Raymond Lamborn (Schumacher, 2002a). It is clear from Foerste's 1919 geologic map and notes that he too observed the downward displacement of strata associated with "Sunken Mountain" and sedimentary beds dipping at angles that exceeded the regional dip (Schumacher, 2002a).

A new era in the study of Serpent Mound began during the early twentieth century, when a University of Cincinnati student challenged the assertion of his former **geology** instructor, Dr. Walter Herman Bucher, that strata of the midcontinent between the Rockies and Appalachian Mountains were all flat-lying (Mark, 1995). In a letter to Bucher, the student wrote that while passing through Adams County in southern Ohio "he had seen much evidence of real faulting" (Bucher, 1936). In the northwestern corner of Adams County, Bucher observed steeply dipping beds and produced a rather detailed geologic map (fig. 2) of this anomalous circular feature in 1920 (Bucher, 1936). Bucher divided the structure into three parts: (1) an uplifted central area surrounded by (2) a circular ring graben with (3) a transition zone in between (Bucher, 1936). The circular hills that correspond to the ring graben, Bucher said, ". . . suggests a lunar crater" (Bucher, 1936). This prophetic statement was largely ignored by Bucher himself during a time when little was known about impact cratering and the notion of catastrophic collisions of **asteroids** or **comets** with Earth was considered fanciful by the geologic community. Bucher convinced himself that this and other similar circular structures located in the United States (e.g., Wells Creek Basin, Tennessee, and Jeptha Knob, Kentucky) and throughout the world were of **cryptovolcanic** origin, similar to that proposed for the Steinheim Basin in

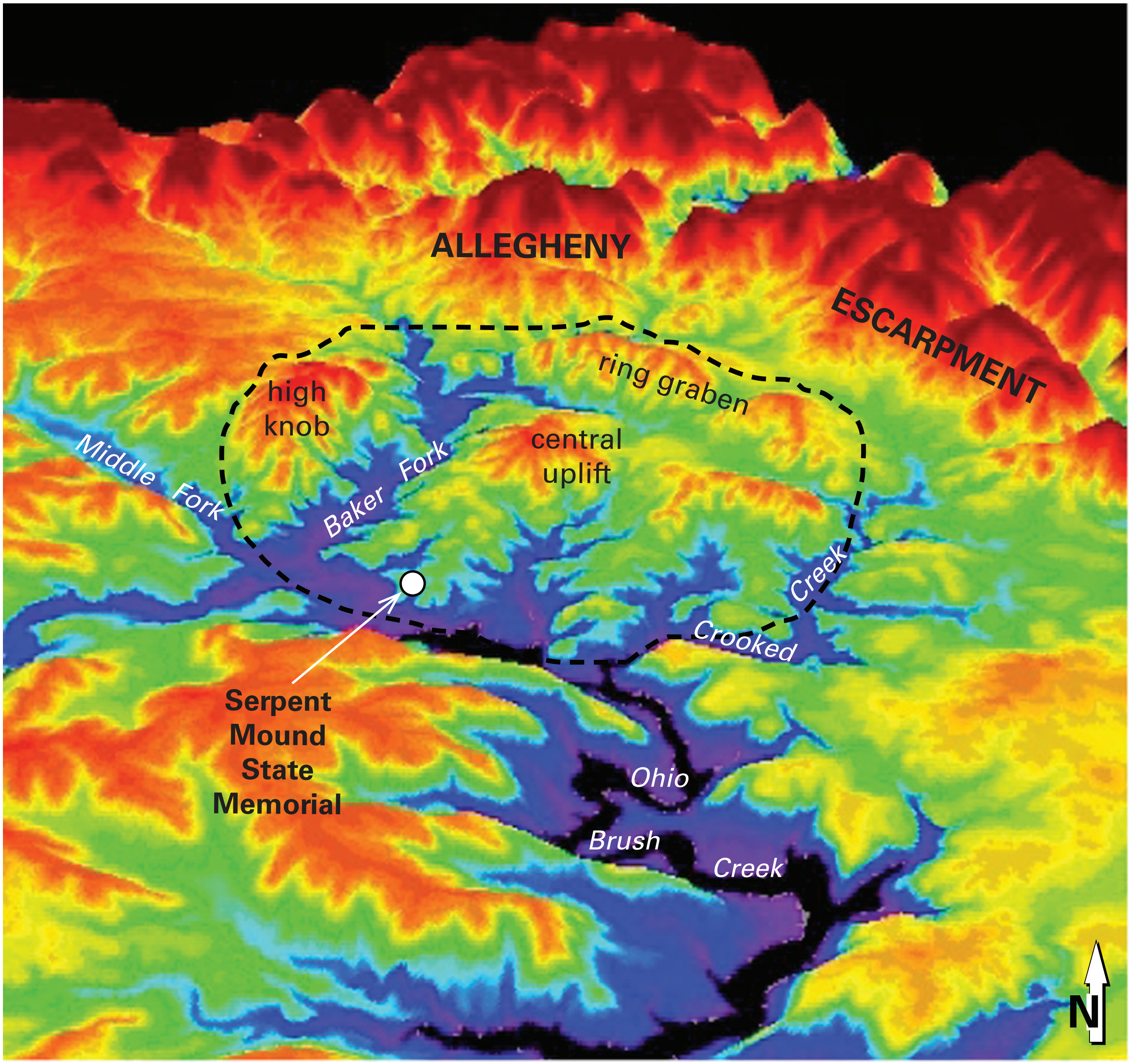
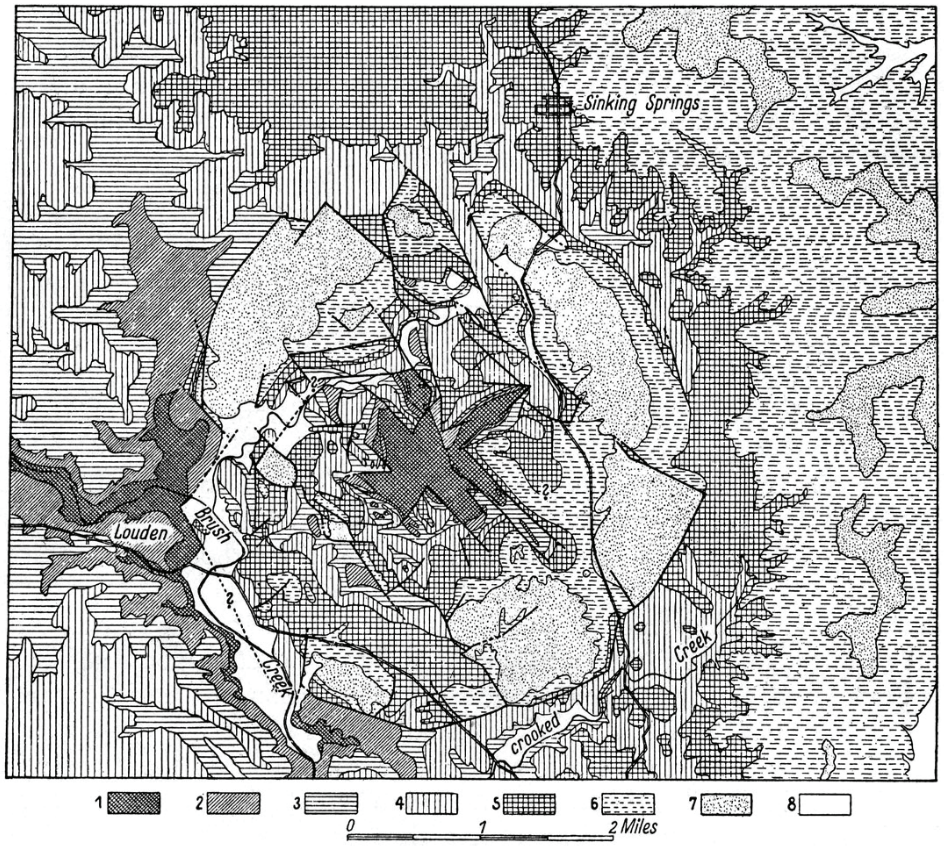


FIGURE 1.—Space Shuttle Radar Topography (SRTM) digital elevation model (DEM) of the Serpent Mound Impact Structure with prominent landforms and locations labeled. Brighter (red) colors indicate points of higher elevation, whereas darker (blue) colors indicate points of lower elevations. The view is to the northeast. Vertical exaggeration = 10x. Image: NASA/USGS/Keith A. Milam.



		Feet	
8.	Alluvium.		
7.	Cuyahoga shales and sandstones (only lower part preserved).	100±	Lower Mississippian
	Sunbury black shale	10±	
	Berea sandstone	30±	
	Bedford shale, with sandstone layers	100±	
6.	Ohio black shale, more or less fissile	260±	
5.	Hillsboro sandstone	0–20	Devonian
	Greenfield dolomite	0–40	Upper Silurian
	Peebles dolomite	40±	Middle Silurian
4.	Lilley dolomite	35	
	Bisher dolomite	45	
3.	Crab Orchard clay shale	120±	
2.	Dayton limestone	0–5	
	Brassfield limestone	40±	Lower Silurian
	Centerville limestone	25±	
1.	Richmond, Maysville, Eden — Shale and limestone alternating in thin layers, total thickness about 800 feet. Only about the upper 100 feet exposed in this region except as explained in text.		Upper Ordovician

FIGURE 2.—Geologic map of the Serpent Mound area produced in 1920 by Dr. Walter Hermann Bucher, University of Cincinnati, Ohio (modified from Bucher, 1936, fig. 4).

Germany (Bucher, 1921; Bucher, 1936). Bucher's initial scientific investigations at Serpent Mound and similar structures led to the beginnings of the cryptovolcano-cryptoexplosion-impact debate in North America.

Nearly 40 years after Walter Bucher's first inquiry into the origin of the Serpent Mound Impact Structure, evidence of **shock metamorphism** was discovered, confirming that it was indeed a heavily-eroded **impact crater**. In November 1959, Robert S. Dietz of the U.S. Navy Electronics Laboratory in San Diego, California, visited the Serpent Mound Impact Structure in search of what is now accepted as the only definitive macro scale indicators of shock metamorphism: **shatter cones** (Dietz, 1960). After an extensive two-day search of the structure, Dietz found shatter cones (fig. 3) in approximately 20 boulders from the crater center that he broke open by hammer; thus Serpent Mound would become only the sixth discovery site in the world for shatter cones at the time (Dietz, 1960). In December 1960, Alvin J. Cohen of the Mellon Institute collected a 2-lb shatter cone from the central uplift of Serpent Mound for **X-ray diffraction** analyses (Cohen and others, 1961). This work revealed the presence of **coesite**, a **polymorph** of the mineral **quartz** that forms only at high pressures resulting from impact (Cohen and others, 1961).

One of the most important studies of the Serpent Mound Impact Structure was the result of geologic mapping

FIGURE 3.—Examples of shatter cones in sedimentary rock from the central peak of the Serpent Mound Impact Structure, south-central Ohio. Photos: Keith A. Milam.

of the most deformed portion of the structure by Stephen Reidel, a student at the University of Cincinnati. The most detailed bedrock geologic map of what we now know to be the central uplift and crater floor was published in 1975 (Reidel, 1975) and followed by a paper in the American Journal of Science (Reidel and others, 1982). Both the map and the paper highlight the extent of uplift and deformation associated with the impact event, including shatter cones and **breccias**; but they ultimately interpret Serpent Mound to represent a cryptoexplosive structure.

Subsequent studies have collected additional evidence in support of an impact origin. Carlton and others (1998) and Koeberl and others (1998) discovered evidence for **shocked quartz** in drill core rocks from the center of the structure. Koeberl and others (1998) discovered an enrichment of certain **siderophile elements** in the same drill core thought to represent traces of the impactor itself. Additional work on Ordovician **carbonate sedimentary rock** collected from within the structure does not support a mixing of a meteorite with crustal material (Widom and Gaddis, 2004).

Before continuing the discussion about the Serpent Mound Impact Structure, it is important to know some basic information about how impact craters are formed. Such knowledge will make it easier to understand the Serpent Mound impact event.

Impact Cratering Basics

Impact craters are the most common and recognizable landforms in the solar system (fig. 4). This relates to the fact that impact cratering is one of the most prominent surface-modifying processes for solid bodies in our solar system. Collisions were and are a commonplace occurrence, resulting from the interception of two bodies in their orbits around the Sun. When the resultant energy release occurs at or near the solid surface of the larger object, an impact crater can be formed.

Most of the time, the two colliding objects exhibit a considerable difference in size, with the larger object being a planet, dwarf planet, or moon (satellite). Therefore, we use the terms **impactor** or **projectile** to describe the smaller of the two objects. The impactor itself may also be an object similar in size to a planet or moon, such as the Mars-sized impactor that collided with Earth to make our Moon (Hartmann and Davis, 1975). More commonly, an impactor is a smaller body, such as an asteroid or comet, whose original orbit has been gravitationally altered, forming a more elliptical orbit. When orbits between the two objects cross each other, the potential for collision then becomes a real possibility.

Modern-day impactors originate primarily from one of three regions in our Solar System: (1) the Main Asteroid Belt, (2) the Kuiper Belt, or (3) the Oort Cloud. The Main Asteroid Belt is a belt of small bodies located between the orbits of Mars and Jupiter, approximately 2–3.5 **astronomical units (A.U.)** from the Sun. Asteroids in this belt tend to be rockier and denser than smaller bodies in the outer solar system. Objects from the Main Asteroid Belt are sent into more elliptical orbits by the gravitational influence of Jupiter. These elliptical orbits can cross paths with those of the planets of the inner solar system (Mercury, Venus, Earth, and Mars).

Small bodies also originate from regions in the outer solar system. The Kuiper Belt is home to countless icy objects that reside beyond the orbit of Neptune (between 30 and 50 A.U.). The Oort Cloud is a spherical shell of small bodies orbiting approximately 50,000 A.U. from the Sun. When an object from either the Kuiper Belt or Oort Cloud is gravitationally perturbed and sent into the inner solar system, it approaches the Sun and begins to display cometary behavior. Near the orbit of Mars, these typically high-porosity, ice-rich bodies begin to **sublimate** forming a **coma** and a **tail**; at that point a comet has formed. Like asteroids, comets can also collide with planets, releasing enormous amounts of **kinetic energy**.

The exact location for that energy release depends upon the layers of differentiated material surrounding the planet and the internal strength of the impactor itself. An atmosphere or hydrosphere surrounding a planet can noticeably impede or stop the forward motion of an incoming asteroid or comet. If the projectile is fast enough or strong enough, it may survive atmospheric passage, but if not, energy release can occur in a planet's atmosphere. This is thought to have happened in the case of the 1908 Tunguska event in Siberia (Chyba and others, 1993). Impacts that occur in fluid reservoirs, such as Earth's oceans, produce different effects. A marine impact event into deep water can excavate a temporary or **transient crater** into the sea only to be quickly filled by a collapsing column of water. When an impact occurs at shallow depths approaching or less than the diameter of the projectile, an impact crater may also be excavated into the seabed itself (Ormö and Lindström, 2000). The rapid collapse of the water column and resultant sedimentary deposition serve to remove traces of marine impact craters. This, in conjunction with their inaccessibility, means that comparatively less is known about marine impact craters than those that form on land.

When energy release occurs at or near the top of the **lithosphere**, an impact crater will form. The size of the impact event is dependent primarily upon the amount of kinetic energy involved. Kinetic energy release is dependent upon the mass and velocity of the impactor. Larger masses and faster speeds of a projectile result in larger amounts of energy release. This sudden burst of energy is responsible for excavating **target rocks** to form an impact crater.

An impact is a near-instantaneous event that scientists often arbitrarily divide into three stages (Melosh, 1989; French, 1998) for ease of understanding: (1) contact/compression, (2) excavation/ejection, and (3) modification

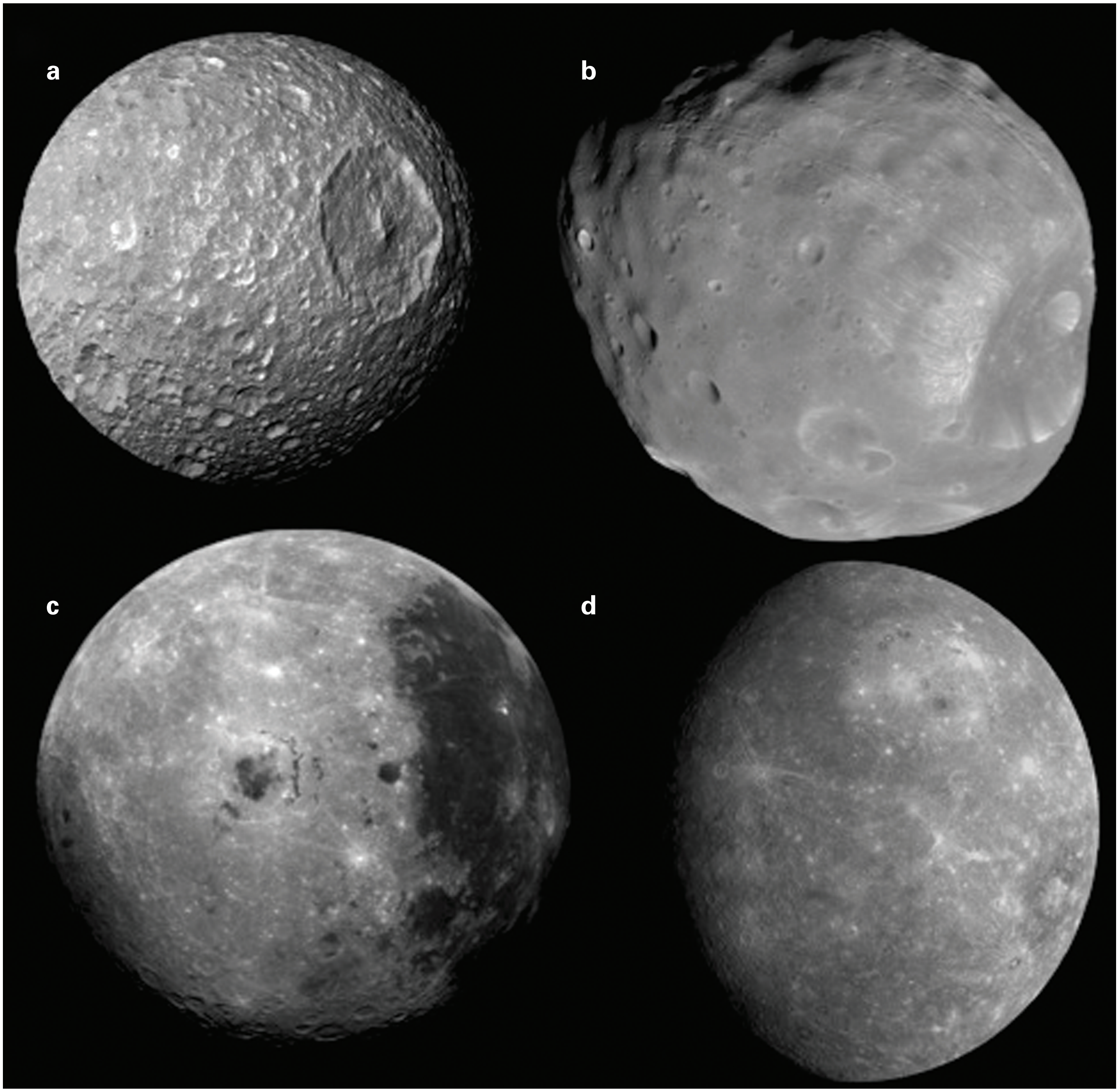


FIGURE 4.—Examples of cratered terrain on solid bodies in the solar system: (a) Mimas, an icy moon of Saturn, is heavily-cratered, with the large (81-mi [130-km diameter]) crater, Herschel, located on the right side of this image (Photo: NASA/JPL/Space Science Institute, image PIA12570); (b) Phobos (13-mi [21-km] illuminated diameter in this view) is a moon of Mars thought to be a captured asteroid that has a cratered surface (Photo: NASA/JPL/University of Arizona, image PIA10368); (c) the Moon, showing its heavily cratered western limb, which includes both the near side and far side in this view (Photo: NASA/JPL, image PIA00225); and (d) the cratered terrain of Mercury as shown in this visible image (Photo: NASA/JHUAPL/Carnegie Institute of Washington, image PIA13840).

(fig. 5). The first stage of impact, the contact/compression stage, begins when the projectile makes first contact with the target. The energy released produces a **shock wave** that spreads through the target rock and the projectile. Much of the energy near the point of impact vaporizes and melts both the projectile and target rock. Compression from the shock wave and subsequent decompression from the rarefaction wave destroys almost all of the impactor, ending the contact/compression stage (French, 1998).

As energy dissipates from the point of impact, the expanding shock wave travels through the target. Where it encounters the open surface of the planet, **rarefaction waves** are generated. As the rock is shocked and released, the kinetic energy generated will move newly-formed rock fragments outward and upward. Nearer to the surface, rock fragments will be moved dominantly upward, whereas those below the point of impact will be moved predominantly downward. Where the amount of kinetic energy imparted to fragmented target rock approaches or exceeds the **escape velocity** of a planet, these fragments will be **ejected** away from the point of impact. These **lithic** fragments, along with melted target rock and remnants of the original projectile, thrown from the point of impact are known as ejecta. Most of the **ejecta** are deposited nearby, within one or two crater radii away, forming a **continuous ejecta blanket**. The amount of energy imparted to moving material will only move larger blocks short distances, so most will land nearby in the continuous blanket. Smaller particles can travel farther from the point of ejection but must cover an increasingly larger area. This results in **discontinuous ejecta** or **crater rays** that radiate away from the crater. For example, a relatively young, unnamed impact crater on the Moon shows both continuous and discontinuous ejecta that have been preserved (fig. 6).

Excavation of target rocks forms a transient crater (Melosh, 1989; French, 1998). Rocks beneath the floor of the transient crater are displaced and compressed downward, while rocks near the transient crater rim are uplifted above normal positions. In some instances, near the boundary between ejected material and the crater rim, rock can be partially ejected or overturned forming an **ejecta flap** around the crater rim. When the transient crater reaches its maximum diameter and ejecta stops falling, the excavation/ejection stage has ended (French, 1998).

The crater modification stage then begins with gravitational collapse of the transient **crater rim** and mass movement of fractured material to partially fill or cover the crater floor. Most geologists consider the modification stage to encompass the initial modification of the crater in the first few minutes following impact; however, modification continues with subsequent erosion and weathering processes that serve to degrade the crater over geologic time.

The type of crater produced during an impact event is the direct result of the size of the impact event, which in turn is affected by the size and speed of the impactor and the gravitational potential of the target planet or

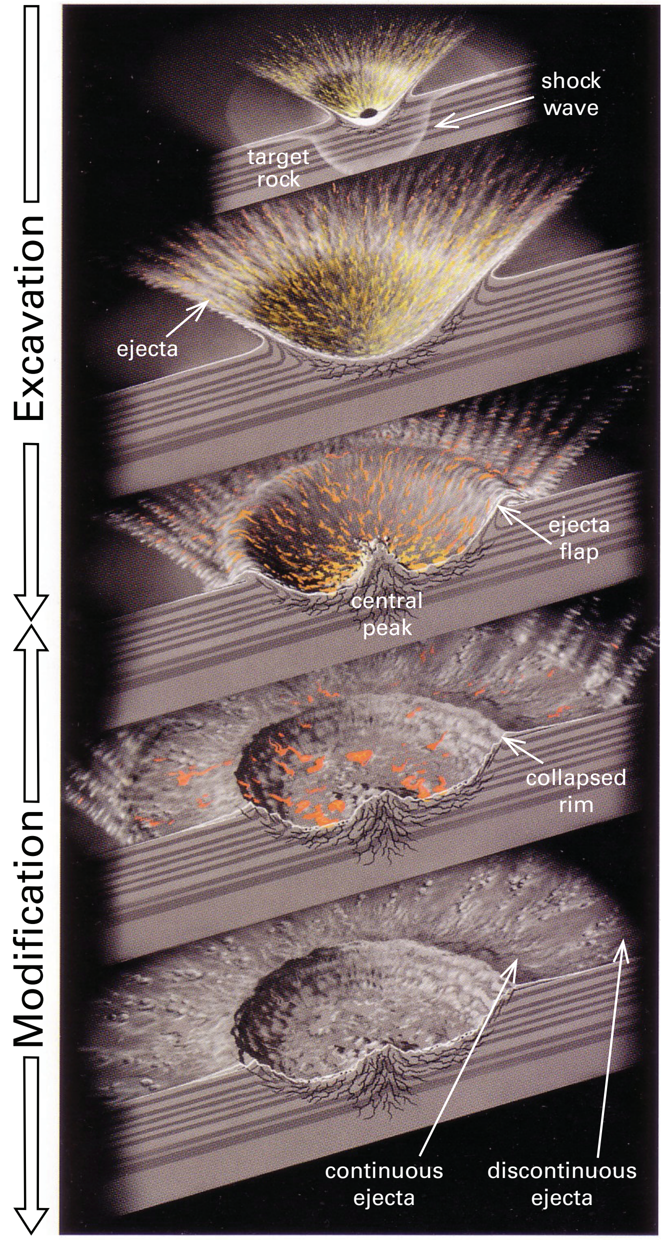


FIGURE 5.—Artistic depiction of the impact cratering process for a complex crater. Each part of the figure represents a single time step during the impact event. The first (upper) time step begins after the contact/compression stage and at the beginning of the excavation stage. The lower three time steps represent the crater modification stage. Illustration: Don Davis.

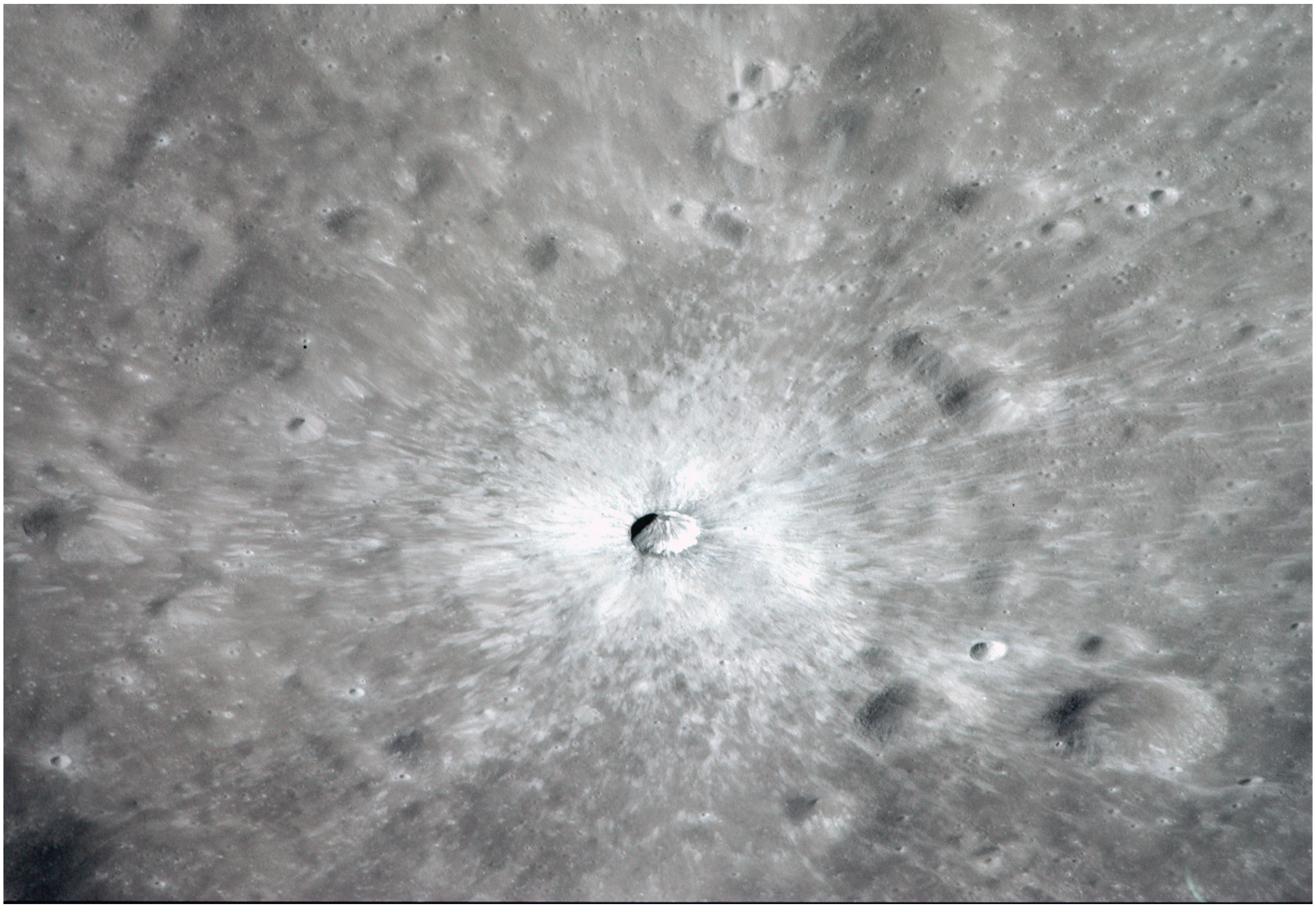


FIGURE 6.—The noticeable impact crater at the center of this image from the far side of the Moon shows the typical distribution of crater ejecta, where most material landed near the crater (1–2 crater diameters) forming a continuous ejecta blanket, while the remainder landed at much greater distances, forming crater rays. Photo: NASA/LPI, image AS17-150-23102.

FIGURE 7.—Panoramic view of Barringer Meteor Crater, a 0.75-mi (1.2-km) diameter impact crater in the desert east of Flagstaff, Arizona. Photo: Wikipedia, user: Tsaiproject (2012).

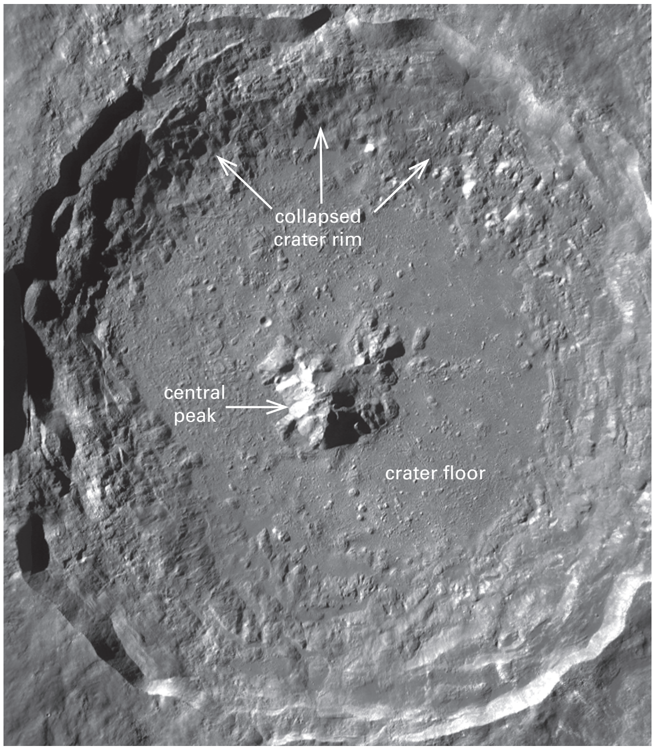


FIGURE 8.—The complex crater Tycho is shown in this Lunar Reconnaissance Orbiter Camera (LROC) visible image of the near side of the Moon. Prominent crater landforms are labeled. Photo: NASA/GSFC/Arizona State University.

FIGURE 9.—Lunar Orbiter IV visible image of Mare Orientale, a 930-km diameter, multi-ring impact basin located near the western limb of the Moon. Photo: NASA.

satellite. Large amounts of energy released during an impact event produce larger impact craters. The amount of energy release also influences the ultimate shape and type of impact crater. The most basic type of impact crater is known as a **simple crater**. Simple craters are bowl-shaped depressions with depth-to-diameter ratios between 0.2–0.33 (Melosh, 1989). Most simple craters on Earth form at diameters below 2–3 mi (3–5 km), depending on target rock type (Melosh, 1989). Probably the best-known example of a simple crater on Earth is Meteor Crater in northeastern Arizona (fig. 7). In larger events, complex craters form. A **complex crater** can be distinguished by its **terraced** crater rim that forms as a result of gravitational collapse along **normal faults** and by a **central peak** that forms as a result of uplift of the crater floor following impact-induced displacement. Several examples of complex craters are found throughout the world. Examples closest to southern Ohio include the Kentland, Indiana; Middlesboro, Kentucky; and Flynn Creek, Tennessee, impact sites. The Serpent Mound Impact Structure is also a complex crater by type. On Earth, most complex craters are extensively eroded, obscuring the key landforms that comprise them. Craters tend to be better preserved on bodies that are less active, geologically speaking. For example, Tycho, a 53-mi (85-km) diameter complex crater on the Moon, consists of a prominent central peak; a relatively flat, melt-filled crater floor; and a collapsed crater rim (fig. 8). Even larger impact events produced other crater forms, such as peak-ring and multi-ring (fig. 9) impact craters. For an in-depth discussion of these crater types, see Melosh (1989) or French (1998).

On Earth, active geologic processes can erode away and fill in impact craters, making identification difficult. As a result, older impact craters may be completely or partially removed from the geologic record, and the density of craters per surface unit area on Earth diminishes over time. Compared to larger ones, smaller impact craters can be preferentially removed by active geologic processes. It is not uncommon for traces of a single impact event to be preserved in one or a few remaining rock exposures at the surface. For these older, heavily-eroded impact craters or **astroblemes** (fig. 10), confirmation that an impact event occurred can be challenging, especially when rock samples or exposures are limited. Impact craters are often confused with other circular landforms on Earth, such as **sinkholes**, **structural domes**, and circular **river bends**, making suspect the identification of an impact crater based on shape alone. In instances where the crater form has been completely eroded away, only remnants of target rock may remain. Quite often, only fragments or minute traces of the projectile

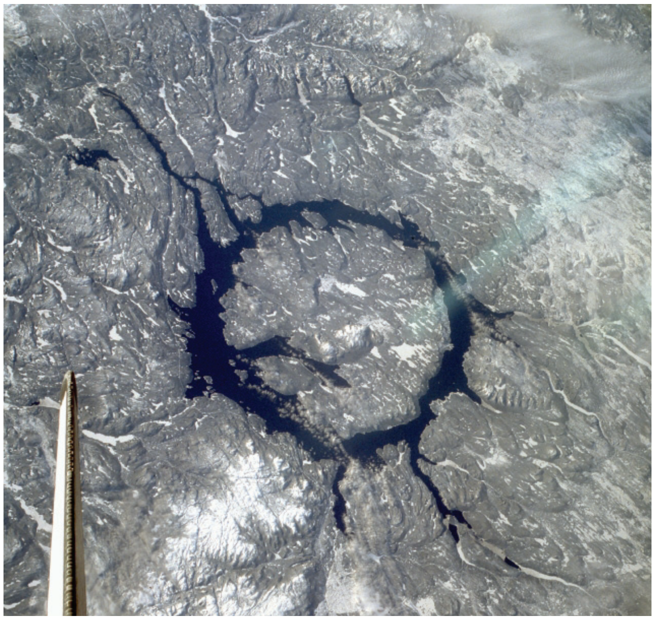


FIGURE 10.—The 62-mi (100-km) diameter Manicouagan impact crater in Québec, Canada. This Triassic-aged (214 Ma) astrobleme is home to the circular Manicouagan Reservoir, a prominent producer of hydroelectric power in the region. Photo: NASA.

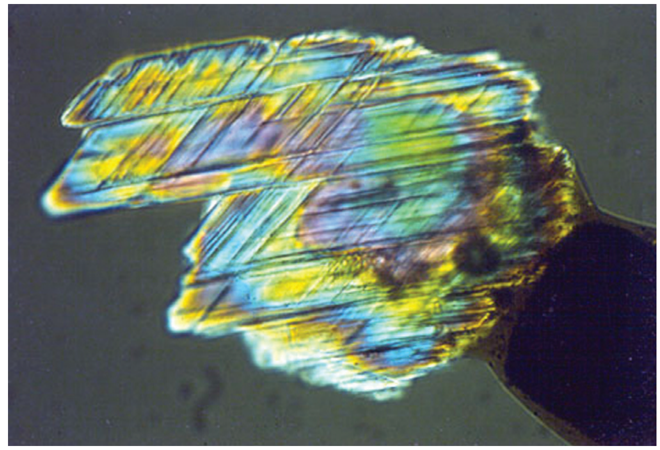


FIGURE 11.—Photomicrograph of a single shocked quartz grain from the Cretaceous-Tertiary boundary, Raton Basin, Colorado. Photo: Glenn A. Izett, USGS.

are preserved, and those that survive are subject to chemical and physical weathering. Therefore, the key to confirming the presence of an impact crater lies in the identification of actual remnants of impactor material or features in remaining target rock or ejecta produced by shock metamorphism (French, 1998; French and Koeberl, 2010).

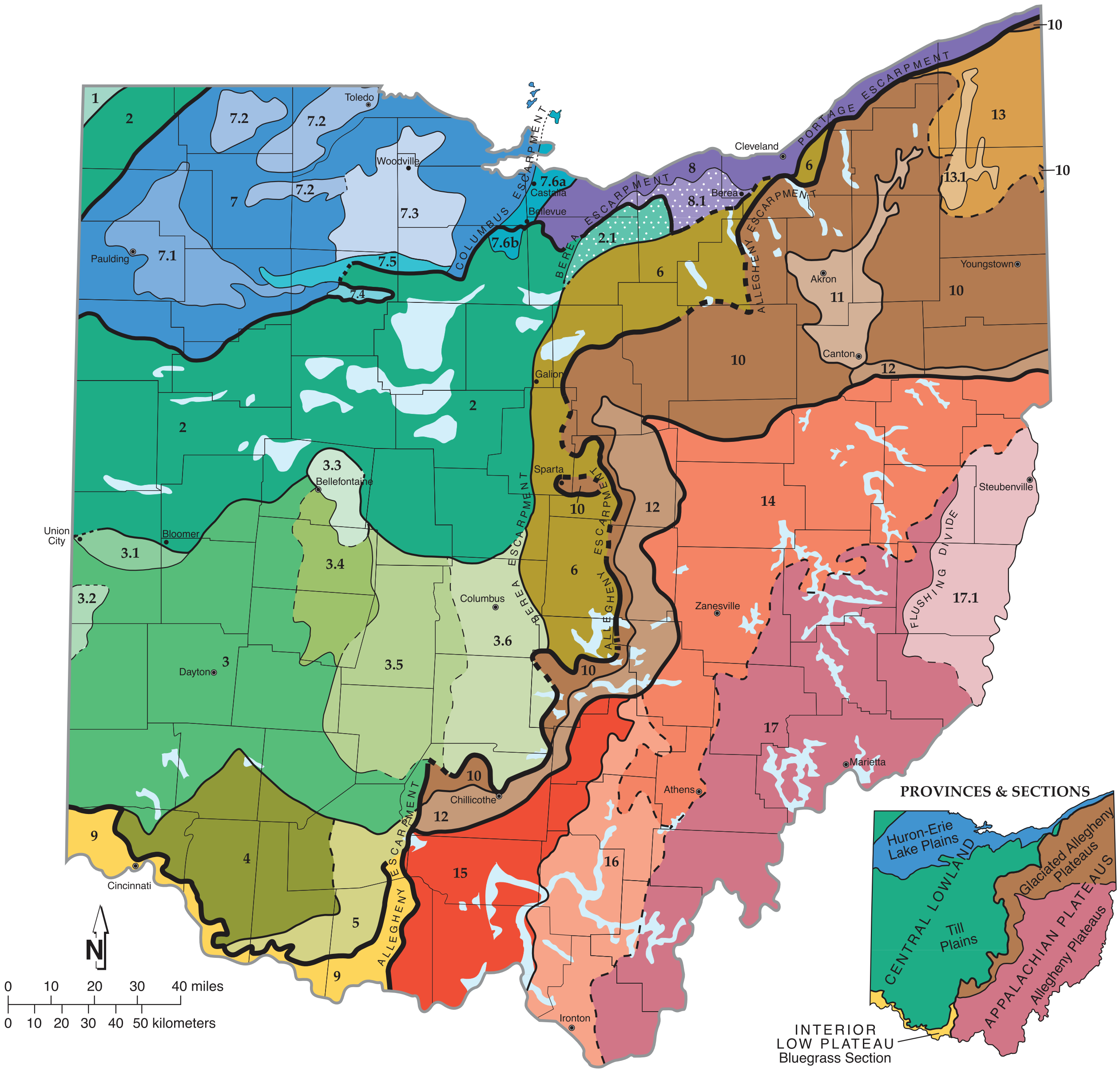
As shock waves permeate target rock during an impact event, the amount of force they impart can exceed the internal strength of the target rock, even down to the scale of a single grain. Changes that occur are characteristic of the high pressures experienced at the surface of a planet only during impact events. Shock metamorphism can certainly shatter, mix, and even melt target rock, but the products that result (fractures, faults, breccias, and glassy material) can all be produced by other geologic processes, such as tectonic activity or volcanism. So while these products occur at many impact craters, this evidence is circumstantial at best. Therefore, in the absence of preserved impactor fragments, the only macro scale indicators of shock metamorphism are shatter cones (Dietz, 1947, 1959, 1960; French, 1998; French and Koeberl, 2010). Shatter cones (see fig. 3) are unique conical fractures found only at the center of impact craters (floor or central peak) and as lithic fragments in crater ejecta. With some practice, they are easy to identify in the field, but they can be confused with similar features, such as **cone-in-cone** structures, **plumose joints**, and even **blast cones** produced by manmade explosive charges.

Other evidence for shock metamorphism can only be observed microscopically or measured using advanced geochemical techniques. Minerals such as quartz may contain **planar microstructures** that represent shock damage to the crystalline lattice (fig. 11). When subjected to the high pressure of a shock wave, the orderly internal crystalline lattice can be arranged in a fashion that is more stable at higher pressures, forming a polymorph of the original mineral. Coesite and **stishovite** are common polymorphs of quartz.

In order to familiarize participants with the local stratigraphy, the field trip commences by examining some of the rocks surrounding the Serpent Mound Impact Structure that have not been deformed or shock metamorphosed by the impact event. These rocks will be observed again once inside the crater.

PART II: EXPLORING THE REGIONAL GEOLOGY AND STRATIGRAPHY

Southern Ohio is home to some of the most revealing geology and **Paleozoic** stratigraphy in the state. Field trip stops are situated along the eastern edge of the **Cincinnati Arch**. You will spend most of your time in Adams, Highland, and Pike Counties in the Appalachian Plateaus, the Interior Low Plateau, and the Dissected Illinoian Till Plain physiographic provinces/districts (fig. 12). The two plateaus correspond to a major division between younger



Till Plains

- 1. Steuben Till Plain
- 2. Central Ohio Clayey Till Plain
  - 2.1. Berea Headlands of the Till Plain
- 3. Southern Ohio Loamy Till Plain
  - 3.1. Union City-Bloomer Transitional Terrain
  - 3.2. Whitewater Interlobate Plain
  - 3.3. Bellefontaine Upland
  - 3.4. Mad River Interlobate Plain
  - 3.5. Darby Plain
  - 3.6. Columbus Lowland
- 4. Illinoian Till Plain
- 5. Dissected Illinoian Till Plain
- 6. Galion Glaciated Low Plateau

Transitional boundary

Lake basin/deposits outside Huron-Erie Lake Plains

Huron-Erie Lake Plains

- 7. Maumee Lake Plains
  - 7.1. Paulding Clay Basin
  - 7.2. Maumee Sand Plains
  - 7.3. Woodville Lake-Plain Reefs
  - 7.4. Findlay Embayment
  - 7.5. Fostoria Lake-Plain Shoals
  - 7.6a and 7.6b. Bellevue-Castalia Karst Plain
- 8. Erie Lake Plain
  - 8.1. Berea Headlands of the Erie Lake Plain

Bluegrass Section

- 9. Outer Bluegrass Region

Glaciated Allegheny Plateaus

- 10. Killbuck-Glaciated Pittsburgh Plateau
- 11. Akron-Canton Interlobate Plateau
- 12. Illinoian Glaciated Allegheny Plateau
- 13. Grand River Low Plateau
  - 13.1 Grand River Finger-Lake Plain

Allegheny Plateaus

- 14. Muskingum-Pittsburgh Plateau
- 15. Shawnee-Mississippian Plateau
- 16. Ironton Plateau
- 17. Marietta Plateau
  - 17.1. Little Switzerland Plateau

FIGURE 12.—Physiographic map of Ohio (ODGS, 1998).

Period	Rock Unit	Thickness (m)	Range of Elevations of Base (m)
Early Mississippian	Cuyahoga Formation	15–98	329–366
	Sunbury Shale	3–15	341–366
Late Devonian	Berea Sandstone	3–15	366
	Bedford Shale	24–30	256–347
	Ohio Shale	76–152	280
	Olentangy Shale	6–17	189–287
Late Silurian	Tymochtee Formation	0–15	262
	Greenfield Dolomite	0–30	
Middle Silurian	Peebles Dolomite	12–21	247–277
	Lilley Formation	5.5–24	250–262
	Bisher Formation	6–26	219–256
	Rochester/Estill Shale	9–55	202–250
	Dayton Formation	0.6–2	201–238
Early Silurian	Noland Formation	0–30	
	Brassfield Limestone	1.5–3	
Late Ordovician	Drakes Formation	6–9	700
	Bull Fork/Waynesville Formation	27–37	61

FIGURE 13.—Simplified stratigraphic column of sedimentary rocks exposed in the Serpent Mound Impact Structure in south-central Ohio (modified from Milam and others, 2011, fig. 2). Data compiled from Rexroad and others (1965), Swinford (1985), Swinford (1991), Shrake and others (2007), Schumacher and Reidel (2002), Schumacher (2002b), and Baranoski and others (2003).

siliciclastic sedimentary rock and older, carbonate-dominated sedimentary rock. Devonian- and Mississippian-age detrital sedimentary rock is exposed in the high-relief (400–800 ft [122–244 m]) landscape of the Appalachian Plateaus; this physiographic region is further subdivided into four smaller plateaus (ODGS, 1998). We will begin our field trip in the westernmost of these, the Shawnee-Mississippian Plateau, 490–1,340 ft (149–408 m) above mean sea level [m.s.l.]). The Shawnee-Mississippian Plateau is dominated by relatively flat-lying **shales**, **siltstones**, and sandstones. These strata were formed from sediment shed from the Appalachian Mountains rising to the east during the Alleghenian **Orogeny**. After descending the Allegheny Escarpment, which defines the edge of the Shawnee-Mississippian Plateau, the next part of the trip will be spent in the Outer Bluegrass Region of the Interior Low Plateau. The Outer Bluegrass Region lies between 455 and 1,120 ft (139–341 m) above m.s.l. and displays moderately high relief (300 ft [91 m]). The Outer Bluegrass Region is home to Ordovician- and Silurian-age **dolostones**, limestones, and shales that are indicative of shallow marine environments. Subsequent erosion of overlying **glacial till** and exposure and dissolution of the underlying carbonates have resulted in these parts of Adams and Highland Counties exhibiting one of the densest concentration of **karst** areas in Ohio (ODGS, 1999). One stop in our trip will occur in the Dissected Illinoian Till Plain, a region that still preserves ground moraine from the Illinoian glacial advance, 130,000–

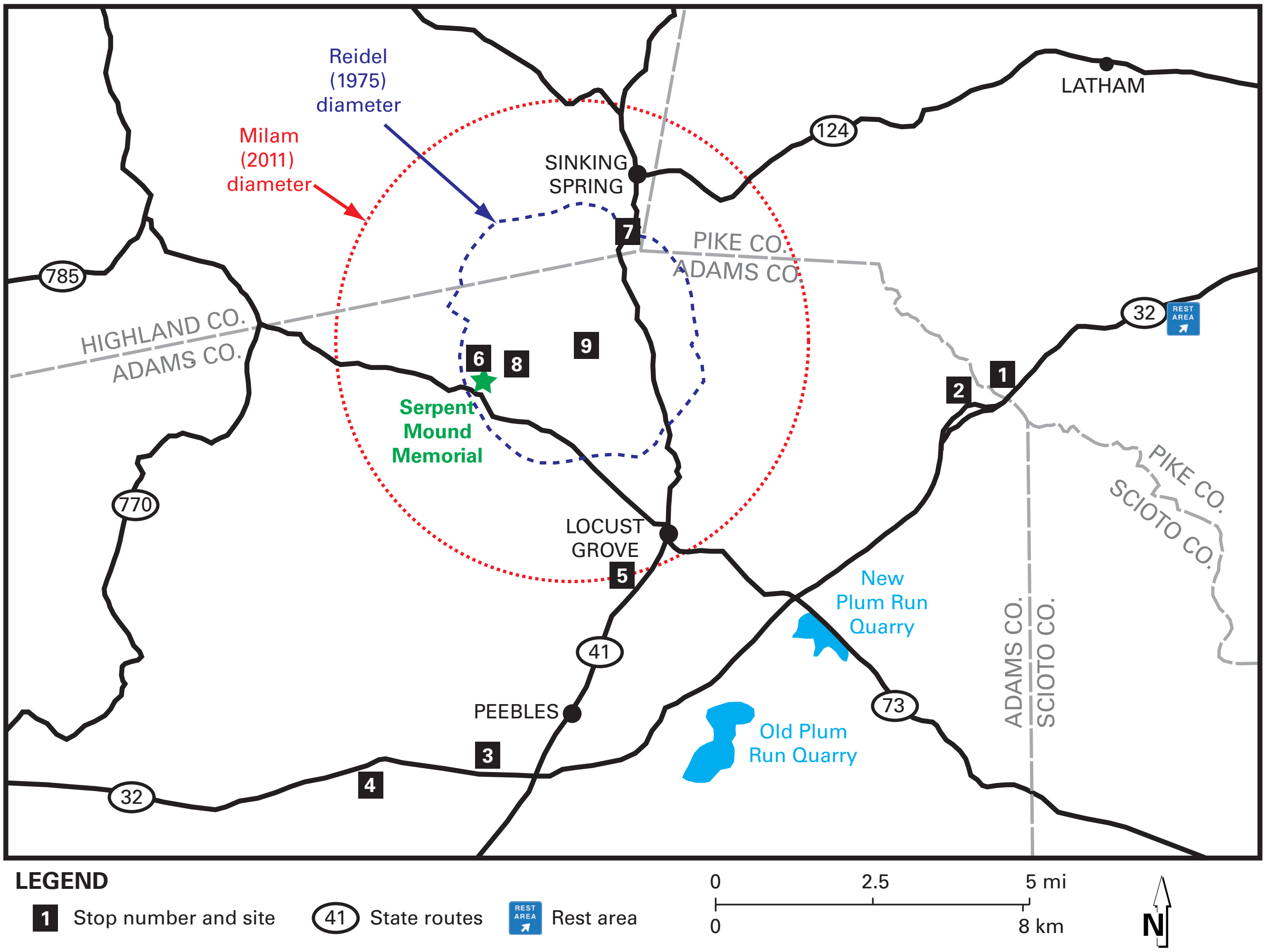


FIGURE 14.—Overview map of the Serpent Mound Impact Structure field trip area in south-central Ohio, showing major highways, towns, and county boundaries. Field trip stops are indicated as numbered boxes. More detailed topographic and geologic maps of field trip stops are provided in figures 15, 20, 27, 30, 31, and 34.

300,000 years ago, and underlying Late Ordovician strata. Bedrock in this region consists of **fossiliferous** limestones and shales typical of the Cincinnati Arch.

Our field area is home to some of the best exposures of Paleozoic strata in all of Ohio (fig. 13). A trip along Ohio State Route 32 (also known as the James A. Rhodes Appalachian Highway) reveals much of the geologic story of Ohio with roadside exposures ranging from Permian (286–245 **Ma**) to Late Ordovician (443–438 Ma) in age. For the first half of this field trip, State Route 32 will serve as a window into the local stratigraphy. You will examine sedimentary rocks ranging from Early Mississippian to Late Ordovician in age (fig. 13) and will be introduced to many of the geologic units that were present at the time of the Serpent Mound impact event. Upon completion of the first part of the field trip, you should be able to identify most of the formations that we will later see exposed within the crater itself.

A few words of caution are in order. Stops 1–4 occur along State Route 32 (fig. 14), which is a very busy thoroughfare. Please do not cross or stand in the highway at any of these stops. Please do not stand between vehicles or unload from vehicles on the highway side. If you have bright or reflective clothing, please wear it to improve your visibility to passing motorists. Please never stand in or cross the highway on foot.

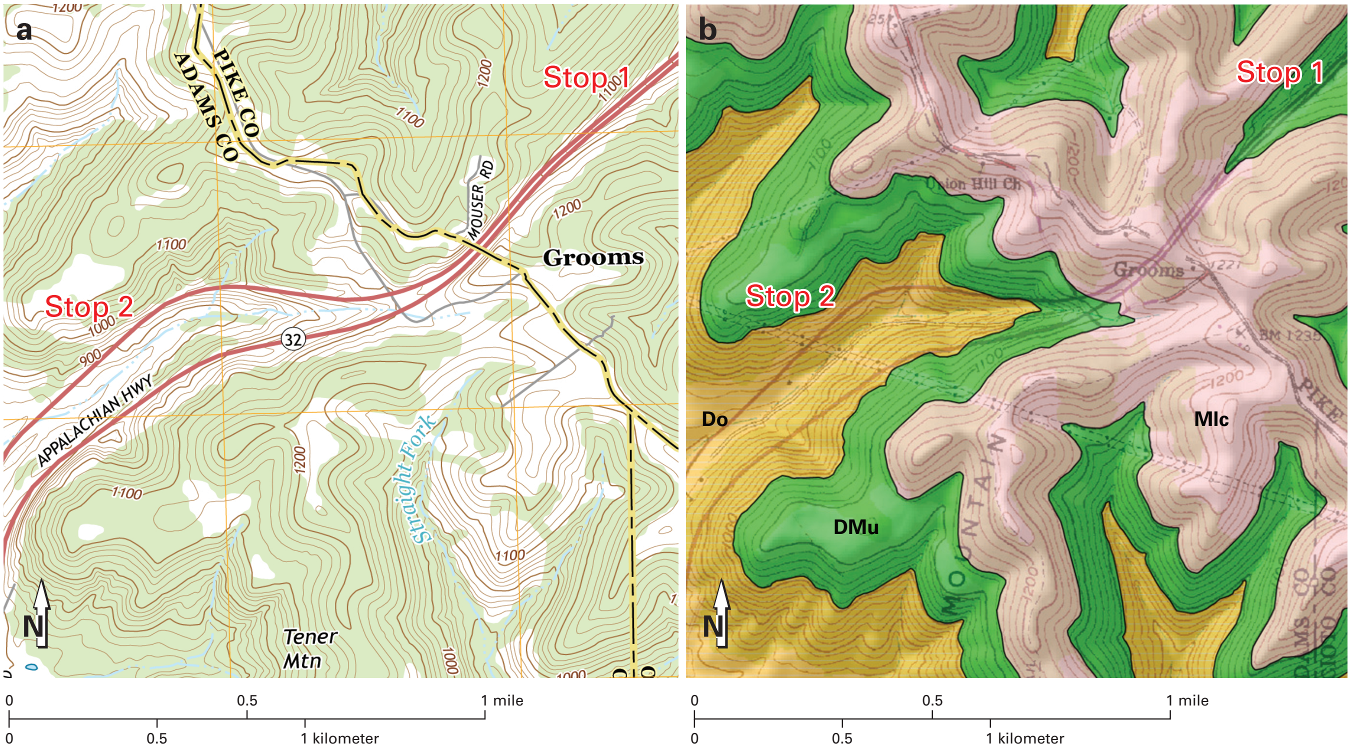


FIGURE 15.—(a) USGS 7.5-minute topographic map of the Byington quadrangle (20-ft contour interval) showing the locations of Stops 1 and 2 along State Route 32 on Tener Mountain, in Pike and Adams Counties, respectively. (b) Bedrock geologic map (Schumacher and Reidel, 2002) of the Byington quadrangle (20-ft contour interval) showing the locations of Stops 1 and 2 along State Route 32 on Tener Mountain, in Pike and Adams Counties, respectively. Legend: Mlc = Logan and Cuyahoga Formations undivided; DMu = Sunbury Shale, Berea Sandstone, and Bedford Shale undivided; Do = Ohio and Olentangy Shales undivided.

Stop 1 – Late Devonian-Early Mississippian Strata along Tener Mountain, Pike County, Ohio

Driving Directions: From the Rest Area south of State Route 32 (James A. Rhodes Appalachian Highway) in Pike County, turn left and travel for 2.6 mi (4.2 km) to an exposure along the north side of the highway (figs. 14, 15). Please park your vehicles well off of the north side of the highway. This is a very busy corridor, so caution should be used when viewing the exposure here.

Coordinates: lat 39°01'33.7"N., long 83°16'16.7"W.

The trip begins high atop the Shawnee-Mississippian Plateau, east of the Allegheny Escarpment, approximately 7.33 mi (11.8 km) ESE of the center of the Serpent Mound Impact Structure. Relatively flat-lying (minor southeast dip) sedimentary rocks that range from Late Devonian to Early Mississippian in age are exposed in the plateau. At this particular site, strata from the Bedford Shale, Berea Sandstone, and Sunbury Shale are visible.

The Late Devonian Bedford Shale (Newberry, 1870) is a 78–108 ft (24–33 m)-thick, greenish-gray shale interbedded with sandstone and siltstone (Baranoski and others, 2003; Shrake and others, 2007). The Bedford Shale contains some siltstone layers with symmetrical **ripple marks** (Swinford, 1985) and **tool marks** indicative of current movement. Sole marks, such as **load** and **flute casts**, and **burrows** are common in the Bedford Shale (Provo and others, 1977). The contact between the Bedford and the overlying Berea Sandstone lies where the sandstone content exceeds 50 percent (Baranoski and others, 2003).

The Berea Sandstone is a unit traditionally thought to be Early Mississippian in age (Swinford, 1985), but micropaleontology evidence suggests a Late Devonian age (Molyneux and others, 1984). The Berea Sandstone is exposed at the surface from Kentucky to Ohio to Pennsylvania and is approximately 46 ft (14 m) thick in this area (Provo and others, 1977; Swinford, 1985). Despite its name, this unit also contains gray siltstone and shale. Yellow-gray, fine-grained, quartz-rich sandstone dominates in the upper portion of this unit. The relatively high **porosity**, high **permeability**, and **compositional homogeneity** of the sandstone in this unit make it a commonly used rock standard for experimental analysis in the petroleum industry (Aldrich, 1969; Churcher and others, 1991). The Berea Sandstone has also been used extensively as a building stone for more than 150 years. Previous studies have shown that the Berea Sandstone represents deposition in marine and deltaic environments of the Appalachian Basin (DeWitt, 1951). This unit contains ripple marks (fig. 16) in the lower portion (Swinford, 1985) indicative of moving currents. To the north in central Ohio, tilting and folding in the Berea Sandstone provide evidence of **syndepositional mass movement** (Cooper, 1943). *Zoophycus*, an **ichnofossil** thought to be representative of deeper-water environments below wave base (Osgood, 1987; Kotake, 1989), can be found here in the sandstone. The Berea Sandstone is the youngest deformed geologic unit exposed in the Serpent Mound Impact Structure (Reidel, 1985).

A traverse farther up the hill brings an end to sandstone of the Berea Sandstone and the beginning of the black to brown carbonaceous shales of the Sunbury Shale (fig. 17). The Sunbury Shale is approximately 16 ft (4.9 m) thick along Tener Mountain in Pike County (Provo and others, 1977). It is a quartz- and clay-rich shale with *Lingula* fragments (Provo and others, 1977) that contains millimeter-thick couplets thought to represent **solar-modulated climatic cyclicity** during the Early Mississippian (Algeo and Woods, 1994).

After examining the strata at Stop 1, continue westward along State Route 32, traveling up section to the top of Tener Mountain, where the Cuyahoga Formation is exposed (fig. 15). As you cross the divide, continue downhill and down section back through the Sunbury-Berea-Bedford interval into the Ohio Shale. The best exposures of these geologic units along this route are on the right or north side of the road.

FIGURE 16.—Symmetrical ripple marks in a siltstone collected from the Berea Sandstone geologic unit. Photo: Keith A. Milam.

FIGURE 17.—Sandstone and shale exposed in the Sunbury Shale at Stop 1 along State Route 32 in Pike County, Ohio. Photo: Keith A. Milam.

FIGURE 18.—The Ohio Shale exposed along the north side of State Route 32 at Stop 2 in Adams County, Ohio. Photo: Keith A. Milam.

Stop 2 – The Late Devonian Ohio Shale, Tener Mountain, Adams County, Ohio

Driving Directions: From Stop 1, travel approximately 0.70 mi (1.1 km) to the southwest (crossing into Adams County) to an exposure along the north side of the highway, on the right (figs. 14, 15). Please park vehicles well off of the side of the highway. This is a very busy corridor, so caution should be used when viewing the exposure here.

Coordinates: lat 39°01'07.4"N., long 83°17'25.2"W.

Stop 2 provides field trip participants with an opportunity to examine the Ohio Shale (fig. 18). The Late Devonian Ohio Shale is a black shale present in southern, central, and northeastern Ohio and is stratigraphically equivalent (or partially so) to the Chattanooga Shale (Over, 2007) and New Albany Shale (Campbell, 1946), as well as other Late Devonian black shales in North America. The Ohio Shale is divided into three members (fig. 19) in ascending order: the Huron Shale, the Chagrin Shale/Three Lick Bed, and the Cleveland Shale (Lewis and Schwietering, 1971; Provo and others, 1997). The Stop 2 exposure is the Cleveland Member, which is dominated

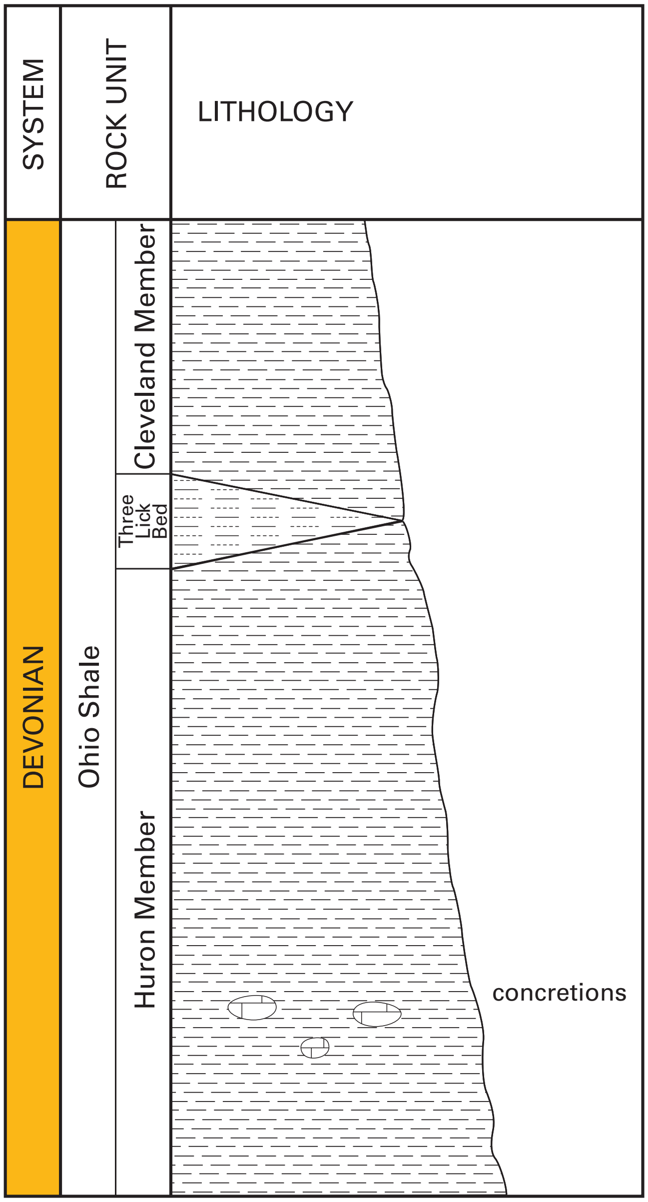


FIGURE 19.—Generalized stratigraphy of the Ohio Shale in southern Ohio.

by fissile black shales that have a yellow, orange, or gray appearance on their weathered surfaces. This organic- and quartz-rich shale contains some minimal amounts of **pyrite** and an occasional **carbonate concretion**. It is approximately 61 ft (19 m) thick along Tener Mountain. The depositional setting for the Cleveland Member was a restricted inland **epicontinental** sea where sediments from the **prograding** westward **Catskill Delta** were being deposited (Lewis and Schwietering, 1971). Mixed in with the eroded shale float are pieces of yellow-orange siltstone with symmetrical ripple marks, tool marks, and burrows (Provo and others, 1977). This material has fallen from exposures of the Bedford Shale just above this stop.

As the trip continues to the west, the elevation will continue to drop from the Shawnee-Mississippian Plateau onto the Bluegrass Section of the Interior Low Plateau. You will be traveling down the Allegheny Escarpment, a **geomorphic** feature that marks the boundary between the **glaciated** terrain to the west with underlying carbonate bedrock and the unglaciated siliciclastic-dominated rocks of the eastern Appalachian Plateau. The downhill journey moves through the Chagrin Member/Three Lick Bed and the Huron Member, crossing the unconformity between these Late Devonian black shales and the gray Middle Silurian dolostones.

Stop 3 – Middle Silurian Peebles Dolomite, Lilley and Bisher Formations, and Estill Shale

Driving Directions: From Stop 2, continue approximately 11.4 mi (18.3 km) west, crossing State Routes 73 and 41 (figs. 14, 20) and pull well off of the road onto a short gravel pull-off. Staying well off of the north side of the road, proceed east on foot and uphill to an exposure of the Peebles Dolomite.

Coordinates: lat 38°56'12.9"N., long 83°27'04.2"W.

The roadcuts along State Route 32 are among the best continuous exposures of Middle Silurian stratigraphy in the state (fig. 21). Begin at the highest part of the roadcut, and the youngest part of the section, with the Peebles Dolomite. The Peebles Dolomite is a 39–69 ft (12–21 m)-thick (Swinford, 1985), highly variable dolostone with well-developed horizontal bedding in some places, wavy or undulating bedding in places, and massive bedding in others. At some horizons, the Peebles Dolomite is locally brecciated with **clast**-supported, **monolithic breccias** dominating. In other beds, typical Silurian **fossils** and **fossil molds** are common (Swinford, 1985). Near the top of the Peebles Dolomite, single beds of fining-upward sequences have been observed that appear to be **tempestites**. Two particularly distinguishing features of the Peebles Dolomite are an overall vuggy appearance and asphalt (fig. 22) filling voids (Bowman, 1956; Baranoski and others, 2003). Asphalt can be observed at several locations at the base of the Peebles Dolomite.

Continue down the hill and transition across an **intertonguing** contact to the carbonate-rich, gray shales of the upper part of the Lilley Formation, then into the lower part of the Lilley Formation consisting of coarse-grained, crinoid-rich limestone (fig. 23). The crinoids visible in the lower Lilley Formation are mostly columnals, stems, and polygonal plates that disarticulated soon following the death of these ancient sea lilies. The Lilley Formation ranges from 18 to 66 ft (5.5–20 m) in thickness in the Peebles quadrangle (Swinford, 1985).

Below the Lilley Formation lies the Bisher Formation (fig. 24), an **argillaceous** dolostone that ranges from

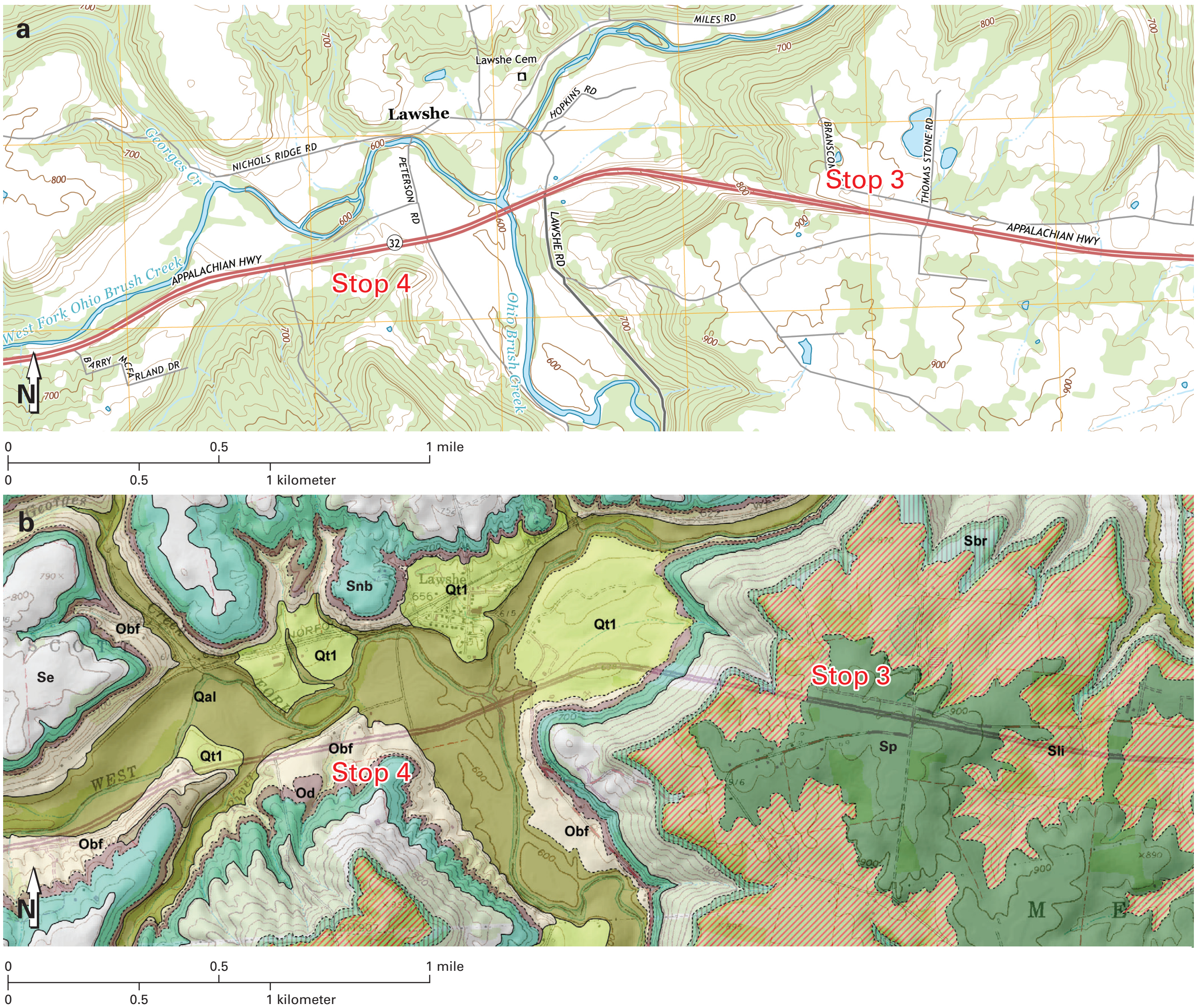


FIGURE 20.—(a) USGS 7.5-minute topographic map of the Peebles quadrangle (20-ft contour interval) showing the locations of Stops 3 and 4 along State Route 32 southwest of Peebles, Adams County, Ohio. (b) Bedrock geologic map (Swinford, 1991) of the Peebles quadrangle (20-ft contour interval) showing the locations of Stop 3 and 4 along State Route 32 southwest of Peebles, Adams County, Ohio. Legend: Qal = alluvium; Qt1 = first terrace deposits; Sp = Peebles Dolomite; Sli = Lilley Formation; Sbr = Bisher Dolomite; Se = Estill Shale; Snb = Noland and Brassfield Formations undivided; Od = Drakes Formation; Obf = Bull Fork Formation.

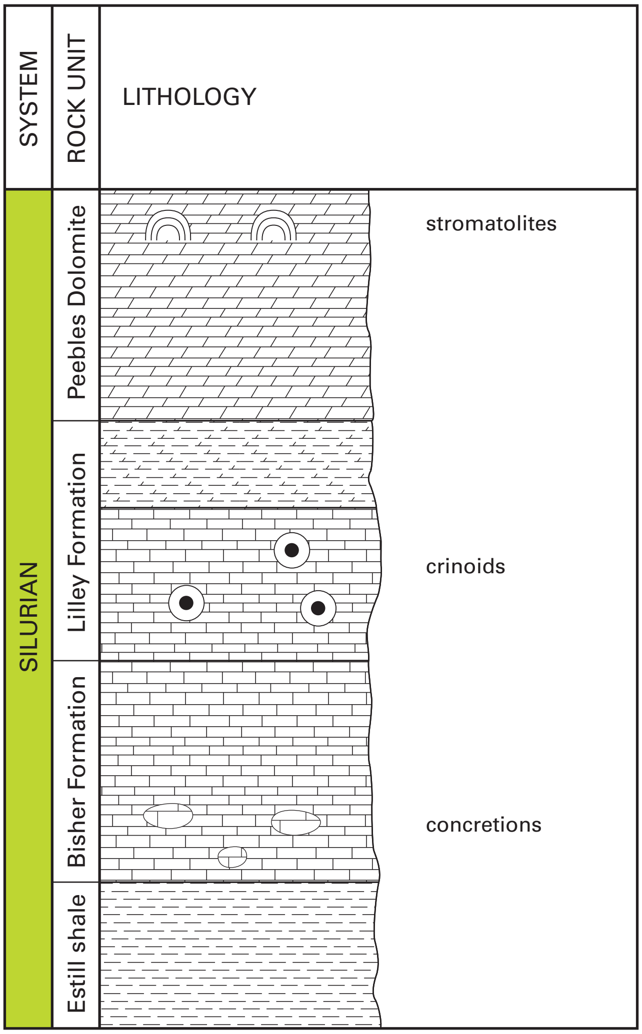


FIGURE 21.—Generalized stratigraphic column of the northern roadcut at Stop 3 along State Route 32, Adams County, Ohio.

FIGURE 22.—A hand specimen of the Peebles Dolomite with black asphalt filling vugs and pore spaces. Photo: Keith A. Milam.

FIGURE 23.—A hand specimen from the lower Lilley Formation, showing crinoid-rich limestone. Photo: Keith A. Milam.

approximately 20 to 85 ft (6.1–26 m) in thickness (Bowman, 1956; Swinford, 1985; Baranoski and others, 2003). The top of the Bisher Formation begins where the crinoidal facies of the Lilley Formation ends. The two units are very similar in appearance and exhibit intertonguing relationships in places, so the disappearance of crinoid fragments is a key indicator of where the Lilley Formation begins (Baranoski and others, 2003). The Bisher Formation ranges from coarse- to fine-grained dolostone with wavy or undulating bedding in places to cross-bedding in other locations in the section. Nodules and rip-up clasts have been observed at the base of the Bisher Formation in this area (Swinford, 1985).

Continuing downhill, beyond the gravel pull-off, small weathered exposures of the upper part of the Estill and Rochester Shales appear. The fissile shales and thinly-bedded siltstones of these units have a weathered reddish-brown to pink appearance. At this particular exposure, the Estill Shale contains abundant *Petroxestes pera* and *Trypanites* ichnofossils (fig. 25).

FIGURE 24.—Field image of the Bisher Formation at Stop 3 along State Route 32 in Adams County, southwest of Peebles, Ohio. The contact between the Lilley and Bisher Formations is difficult for the average observer to identify in the field. However, as Baranoski and others (2003) state: "The upper contact of the Bisher Formation is the top of the uppermost argillaceous dolomite bed underlying the medium- to coarse-grained crinoidal dolomite beds of the Lilley Formation." Photo: Keith A. Milam.

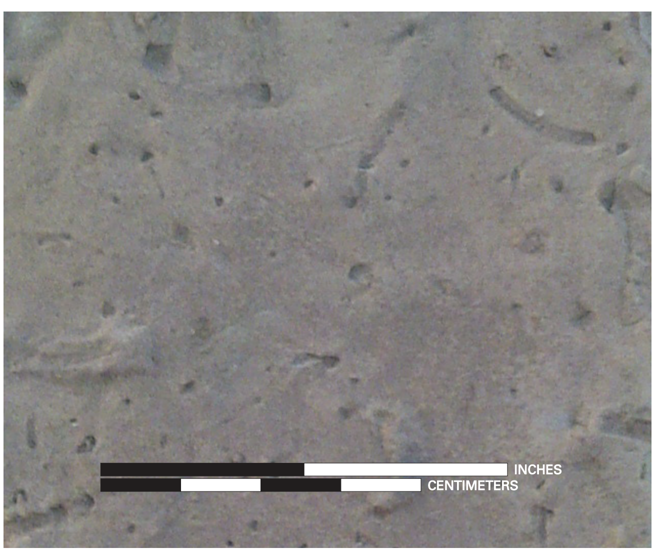


FIGURE 25.—A hand specimen of the Estill Shale showing the trace fossils *Petroxestes pera* and *Trypanites*. Photo: Keith A. Milam.

Stop 4 – Late Ordovician Bull Fork Formation

Driving Directions: From Stop 3, proceed westward along State Route 32 for approximately 1.7 mi (2.8 km) to the crossing with Tater Ridge Road. Carefully turn around and proceed east on State Route 32 for 0.2 mi (0.4 km). Pull well off of the south side of the road near a short roadcut of limestones and shale (figs. 14, 20).

Coordinates: lat 38°56'01.7"N., long 83°28'41.1"W.

Stop 4 offers an opportunity to examine Late Ordovician interbedded, fossiliferous limestones and shales of the Bull Fork Formation (Swinford, 1985). In a sequence stratigraphic framework, the Bull Fork Formation corresponds to the Richmondian age of the Late Ordovician (Katian) and more specifically to the C4–C6 sequences (Alycia Stigall, Ohio University, oral commun., 2011). The base of the Bull Fork Formation corresponds to the beginnings of a significant biological immigration event known as the Richmondian Invasion, where new or reintroduced species of marine

FIGURE 26.—A hand specimen from the Bull Fork Formation collected along the south side of State Route 32 in Adams County, Ohio. Photo: Keith A. Milam.

invertebrates migrated into the Cincinnati region (Holland and Patzkowsky, 2007; Dudei and Stigall, 2010). **Rugose corals** and **rhynchonellid brachiopods** first appear in the Cincinnatian Series in the C4 sequence (Dudei and Stigall, 2010). You may be able to find both types of fossils in this exposure along with numerous other species of brachiopods, corals, and **bryozoans** (fig. 26).

Now that you've been exposed to the stratigraphy of southern Ohio, you will turn your attention back to the Serpent Mound Impact Structure where you will see this same stratum but deformed and displaced by the impact event.

PART III: EXPLORING THE SERPENT MOUND IMPACT STRUCTURE

The Serpent Mound Impact Structure is a heavily-eroded impact structure nearly 9 mi (14 km) in diameter located at the junction of Adams, Highland, and Pike Counties in southern Ohio, just west of the Allegheny Escarpment and north of the town of Peebles (figs. 1, 14). The southwest quadrant of the crater is home to the Serpent Mound Paleo-Indian **effigy**, from whence the crater name is derived. The Serpent Mound Impact Structure is a complex crater by type, with a central peak surrounded by an eroded crater floor and the possible remnants of a crater rim to the east. As discussed in Part I, it was first discovered by John Locke in 1838 and later described as the first cryptovolcanic structure in North America (Locke, 1838; Bucher, 1936). Its identity as an impact crater was confirmed with the identification of shatter cones, coesite, and shocked quartz (Dietz, 1960; Cohen and others, 1961; Carlton and others, 1998; Milam and others, 2011). This portion of the field trip will begin in the outer regions of the Serpent Mound Impact Structure and work towards the center.

Stop 5 – On the Crater Rim

Driving Directions: From Stop 4, travel east along State Route 32 for 1.3 mi (2.1 km) to its intersection with State Route 41. Turn left and travel north along State Route 41 for 3.5 mi (5.7 km) through the town of Peebles, Ohio. At the intersection of State Route 41 and Cemetery Road, take a left and pull into the entrance of Locust Grove Cemetery (figs. 14, 27). (Important Note: The cemetery drive is not designed for large vehicles such as buses and passenger vans. Larger vehicles may have to be parked outside the cemetery.) Proceed by vehicle or on foot along the driveway to the highest point in the cemetery.

Coordinates: lat 38°58'41.7"N., long 83°23'13.7"W.

One of the best views (from the ground) of the Serpent Mound Impact Structure is from this hill (fig. 28). Approximately 4 mi (6 km) to the north-northwest (N. 13° W.) lies the central peak of the crater. Approximately

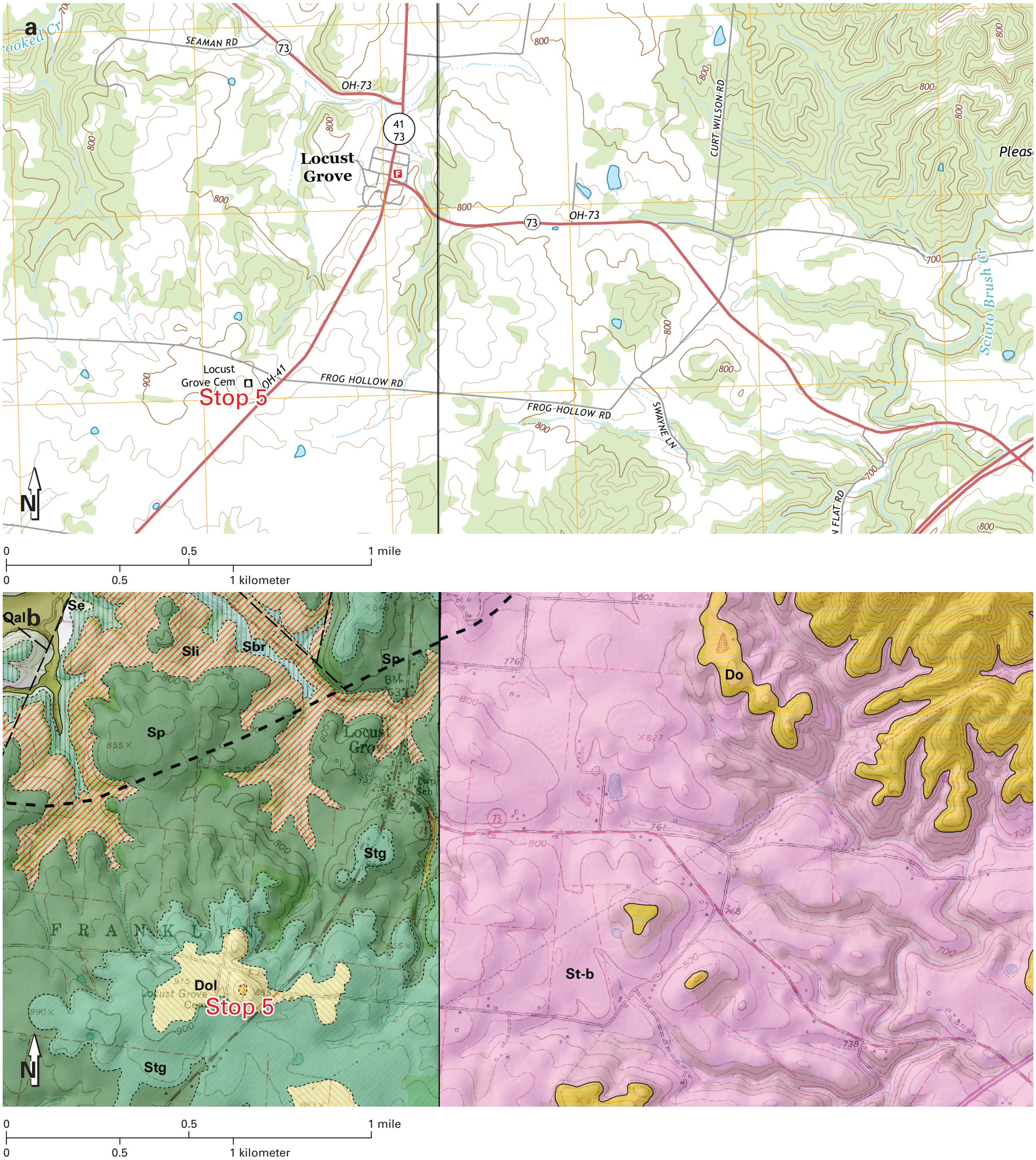


FIGURE 27.—(a) USGS 7.5-minute topographic map of portions of the Jaybird (right) and Peebles (left) quadrangles (20-ft contour interval) showing the location of Stop 5 along State Route 41 between the towns of Peebles and Locust Grove, Adams County, Ohio. (b) Bedrock geologic map of the Jaybird (Schumacher, 2002b) and Peebles (Swinford, 1991) quadrangles (20-ft contour interval) showing the location of Stop 5 along State Route 41 between the towns of Peebles and Locust Grove, Adams County, Ohio. Legend: *Left* (Peebles) Qal = alluvium; Dol = Olentangy Shale; Stg = Tymochtee and Greenfield Dolomite undivided; Sp = Peebles Dolomite; Sli = Lilley Formation; Sbr = Bisher Formation; and Se = Estill Shale. *Right* (Jaybird) Do = Ohio and Olentangy Shales undivided; St-b = Tymochtee, Greenfield, and Peebles Dolomites and Lilley and Bisher Formations undivided.

2.4 mi (3.8 km) to the northeast lies a suspiciously circular segment of the Allegheny Escarpment (figs. 28, 29). Initial estimates of the diameter of the so-called "disturbance" ranged from 7.5 to 8 km (Reidel, 1975); however, this range encompasses only the central peak and the surrounding **ring graben** (or crater floor equivalent) of the structure. Complex craters also contain a crater rim whose walls have collapsed inward along normal faults during the modification stage of impact (figs. 5, 8). Known **morphometric** relationships (Pike, 1985) were used by Milam (2010) to demonstrate that the rim-to-rim diameter of the crater must be somewhere between 6 and 15 mi (10–24 km). Milam (2010) also examined the morphology of the surrounding landscape using Shuttle Radar Topographic Mission (SRTM) data and noticed a circular ridge corresponding to the circular part of the Allegheny Escarpment and the hill on which the cemetery stands (fig. 29). This circular ridge conforms to the circular shape of the inner parts of the crater as defined by Reidel (1975) and lies within a 7–9-mi (11–14-km) diameter area. Well logs reveal that the downward structural displacement on the **unconformable** contact between Middle Silurian carbonates and the Late Devonian Ohio Shale is also confined to a 9-mi (14-km) diameter area that corresponds to the circular ridge (Milam, 2010). Therefore, morphometric modeling, the presence of a circular ridge conforming to the crater shape, and the lateral extent of structural deformation suggests that the Serpent Mound Impact Structure may be up to 9 mi (14 km) in diameter (Milam, 2010), placing Stop 5 right along the crater rim. Recent work by Trygstad (2014) has demonstrated deformation (in the form of faults) that extends well into this larger region.

The revised diameter of the Serpent Mound Impact Structure has implications for the size of the impact event itself. This new information can be used to model the impact and the resulting effects. Using a 9-mi [14-km] rim-to-rim diameter for the Serpent Mound Impact Structure and typical impact parameters, models can be produced using the Earth Impact Effects Program (Collins and others, 2004) to help place constraints on the impactor that produced the Serpent Mound Impact Structure and to visualize the impact event from the vantage point of Stop 5. For example, following are two plausible models for the Serpent Mound impact event. Please note that these are typical cases and do not represent an all-inclusive list of possibilities.

Scenario 1: An Asteroid from the Main Asteroid Belt

In this scenario, a 2,870-ft (875-m) diameter asteroid (density of 3,000 kg/m^3) traveling at 11 mi/s (17 km/s) and impacting at an angle of 45° encounters Earth. The asteroid begins to break up about 34 mi (54 km) above Earth's surface. The fragments hit Earth at 11 mi/s (16.9 km/s), releasing 3.58 x 10^4 megatons (MT) of energy or nearly 2.4 million times the amount of energy released by the Hiroshima nuclear bomb. The initial or transient crater that forms will be 5.9 mi (9.5 km) in diameter, but after rim collapse it will reach 8 mi (12.8 km) in diameter.

An observer at Stop 5 would not be in the most ideal location during the impact event. The thermal radiation from the consuming (6.6-mi [10.6-km] diameter) fireball alone would ignite clothing and give third degree burns only milliseconds after the event. Nearby vegetation would ignite as well. About 1.3 seconds after the event, the seismic waves—registering 7.6 on the Richter scale—would begin to shake the ground violently. Nineteen seconds following the event, the radiating air blast would knock the observer off of his feet, while 36 seconds after the impact, he will be buried under 912 ft (278 m) of continuous ejecta, with the average block size being 390 ft (119 m) in diameter. The ground inside of the crater at this point (and possibly including the area at Stop 5) would be collapsing downward and inward.

Scenario 2: A Comet from the Outer Solar System

A 2,526-ft (770-m) diameter comet (density of 1,000 kg/m^3) traveling at 32 mi/s (51 km/s) and impacting at an angle of 45° encounters Earth. The comet begins to break up about 322 ft (98 m) above Earth's surface. The cometary fragments hit Earth at 30 mi/s (49 km/s), releasing 6.84 x 10^4 MT of energy, even more energy than in Scenario 1. The fireball appears to be 8 mi (13 km) in diameter.

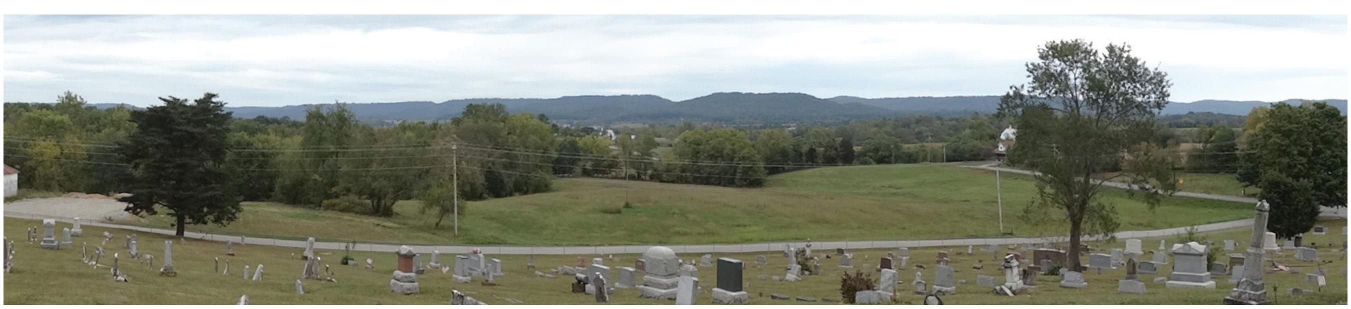


FIGURE 28.—Panoramic view northwest to northeast (left to right) from the Locust Grove Cemetery located along the postulated southeastern crater rim area (Milam, 2011) of the Serpent Mound Impact Structure. Photo: Charles R. Salmons.

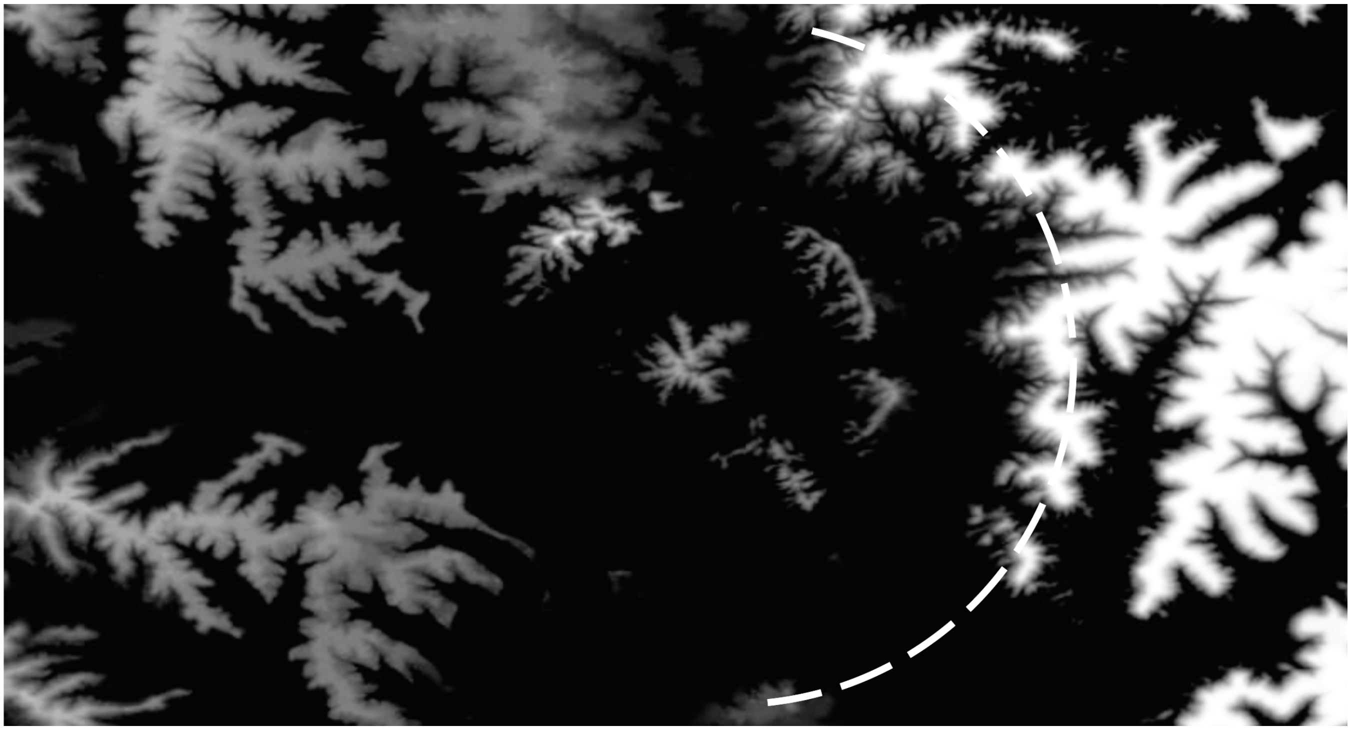


FIGURE 29.—Nadir view of a digital elevation model of the Serpent Mound Impact Structure showing the location of major crater landforms and the circular portion of the Allegheny Escarpment and its apparent equivalent to the Locust Grove Cemetery (at the lower end of the dashed line). Brighter colors indicate higher elevations, while darker colors indicate lower elevations.

The transient crater that forms will be 6 mi (10 km) in diameter, and after rim collapse, it will reach 8 mi (13 km) in diameter.

Only milliseconds after impact, the observer at this location would be consumed by the fireball, clothing would ignite, and third degree burns would occur. Nearby vegetation (if present) would ignite and be blown down. About 1.3 seconds after impact, the ground would begin shaking violently as 7.8 magnitude seismic waves travel beneath one's feet. About 19 seconds after impact, an air blast would knock down the observer, and 36 seconds after impact, he would be buried beneath a continuous blanket of ejecta about 922 ft (281 m) in thickness. The average size of the blocks raining from the sky would be 391 ft (119 m) in diameter. Rim collapse would be occurring here as in Scenario 1.

Stop 6 – The Serpent Mound Paleo-Indian Effigy

Driving Directions: From the intersection of Cemetery Road and State Route 41, continue north on State Route 41 for approximately 1.0 mi (1.6 km) and turn left onto State Route 73. Travel northwest along State Route 73 for 3.5 mi (5.7 km) until reaching the entrance of the Serpent Mound State Memorial (figs. 14, 30). Turn right into the entrance road and continue up the hill to the entrance station.

Coordinates: lat 39°01'24.7"N., long 83°25'48.2"W.

Logistics Note: Hours of admission vary and there is an entrance fee. The park features restrooms, picnic tables, and a covered pavilion. No collecting of any kind is allowed at this site. For more information, please call the Serpent Mound State Memorial visitors center at (937) 587-2796 or 800-752-2757 or visit the Ohio History Connection website at ohiohistory.org and search "Serpent Mound."

This stop affords field trip participants the opportunity to examine the Serpent Mound, a Paleo-Indian effigy in the shape of a serpent located in the southwestern portion of the crater. The mound is situated high on a bluff of Middle Silurian carbonate rock above Brush Creek (fig. 30). Construction of this 0.25-mi (0.40-km) long mound has been attributed to the Adena and Fort Ancient cultures. There is an observation tower for obtaining an elevated view of the mound and surrounding area. Walking and hiking trails, a visitor center, and a museum are great ways to round out a lunch-time visit.

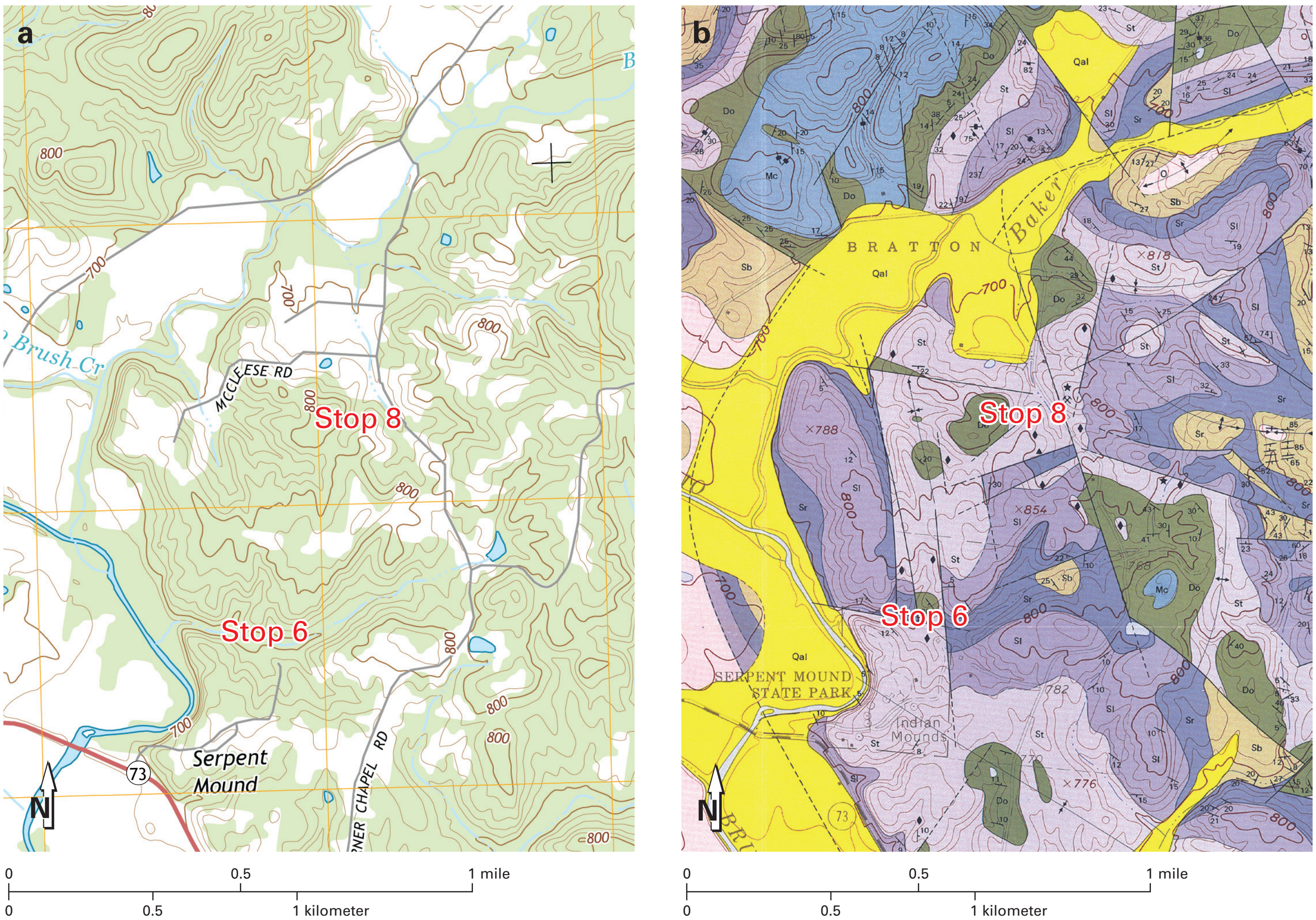


FIGURE 30.—(a) A portion of the USGS 7.5-minute topographic map of the Sinking Spring quadrangle (20-ft contour interval) showing the locations of Stops 6 and 8 along State Route 73 and Horner Chapel Road, respectively, in Adams County, Ohio. (b) Bedrock geologic map (Reidel,1975) of a portion of the Sinking Spring quadrangle (20-ft contour interval) showing the locations of Stops 6 and 8 along State Route 73 and Horner Chapel Road, respectively, in Adams County, Ohio. Legend: Qal = alluvium; Mc = Cuyahoga Formation, Sunbury Shale, Berea Sandstone, and Bedford Shale undivided; Do = Ohio Shale; St = Tymochtee Formation, Greenfield Dolomite, and Peebles Dolomite undivided; Sl = Lilley and Bisher Formations undivided; Sr = Rochester Shale; Sb = Brassfield Limestone; O = Ordovician undifferentiated.

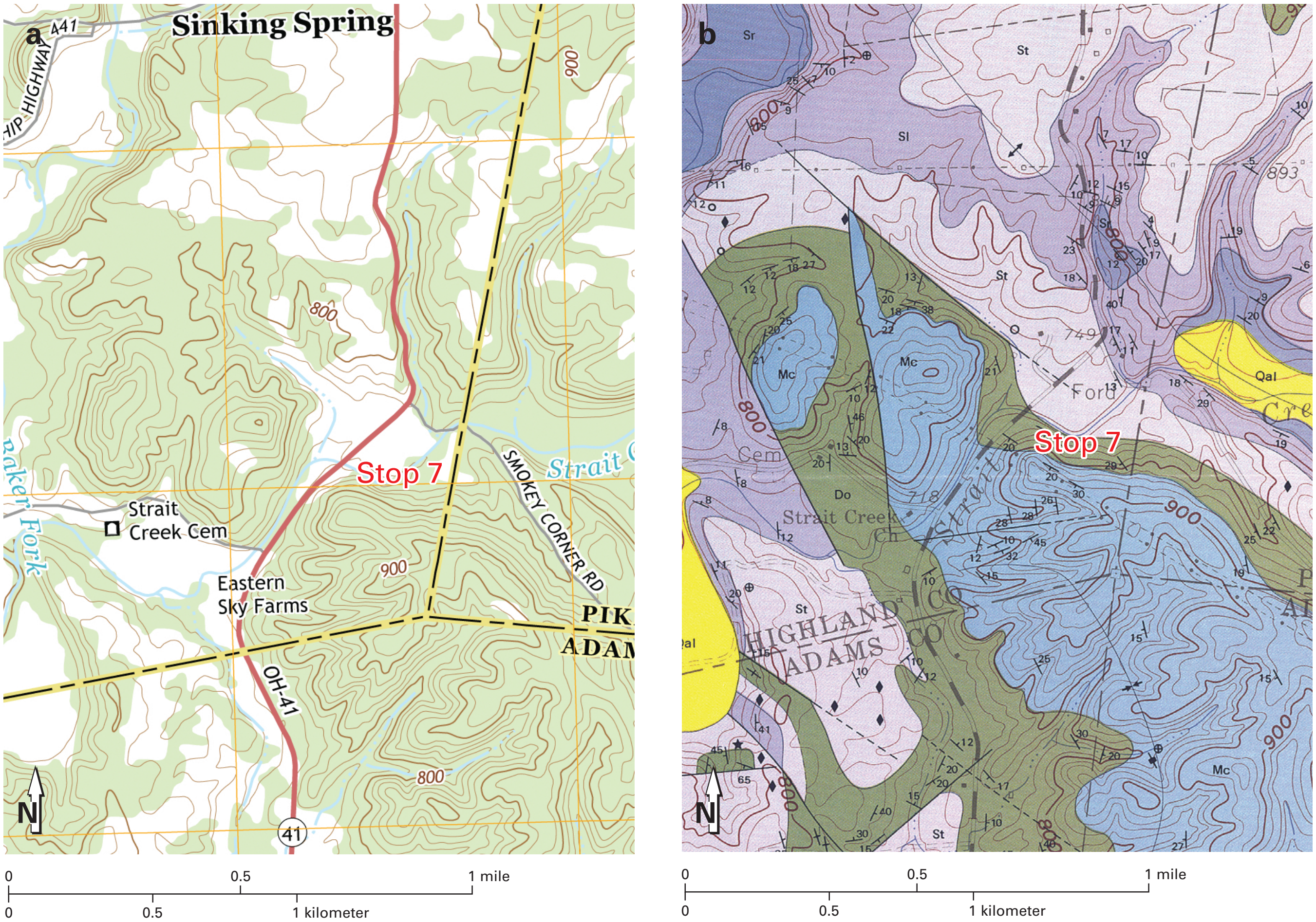


FIGURE 31.—(a) A portion of the USGS 7.5-minute topographic map of the Sinking Spring quadrangle (20-ft contour interval) showing the location of Stop 7 along State Route 41 in Highland County, south of the town of Sinking Spring, Ohio. (b) Bedrock geologic map (Reidel,1975) of a portion of the Sinking Spring quadrangle (20-ft contour interval) showing the location of Stop 7 along State Route 41 in Highland County, south of Sinking Spring, Ohio. Legend: Qal = alluvium; Mc = Cuyahoga Formation, Sunbury Shale, Berea Sandstone, and Bedford Shale undivided; Do = Ohio Shale; St = Tymochtee Formation, Greenfield Dolomite, and Peebles Dolomite undivided; Sl = Lilley and Bisher Formations undivided; Sr = Rochester Shale; Sb = Brassfield Limestone; O = Ordovician undivided.

Stop 7 – The Ring Graben along Strait Creek

Driving Directions: From the entrance to the Serpent Mound State Memorial, turn left and return southeast along State Route 73. Travel for 3.6 mi (5.8 km) to the intersection where State Route 73 ends at State Route 41. Turn left, heading north, and continue for approximately 5.4 mi (8.7 km), passing the Adams-Highland County line and Strait Creek Road. Park off of the road on the right, south of the bridge (figs. 14, 31). Hike down to and walk east along the creek to a large exposure of bedrock. Please note that this stop is on both a public right-of-way and private property.

Coordinates: lat 39°03'32.9"N., long 83°23'18.9"W.

Stop 7 provides access to some of the bedrock deformed during the Serpent Mound impact event. Deformed Sunbury Shale can be observed at this location. This black fissile shale dips approximately 20° to the southwest toward the center of the crater. The rock is fractured, and in places, prominent plumose joints are exposed. Reidel (1975) suggests that this stop is part of the so-called *ring graben* or a fault block that has been displaced downward from its normal position. This particular block seems to have experienced some rotation during displacement. On the hill above the shale lies the Late Devonian Berea Sandstone, exposed in a road cut to the south of the creek bed.

Stop 8 – A Breccia in the Transition Zone

Driving Directions: Continue north along State Route 41 to the community of Sinking Spring and conduct a safe turn-around. Return south along State Route 41 and travel for 1.2 mi (1.9 km). Turn right, heading west-southwest along Strait Creek Road (County Road 45), and continue for 2.2 mi (3.5 km). Turn left onto Horner Chapel Road (Township Highway 116) and continue for 0.6 mi (1 km) to the south (figs. 14, 30). Stop 8 is an exposure on the left, partially on both private property and the public right-of-way.

Coordinates: lat 39°02'02.2"N., long 83°25'22.7"W.

This stop shows a rather odd exposure of carbonate sedimentary breccia (fig. 32) that seems to occur only in the Serpent Mound Impact Structure (Milam and others, 2011). The only known exposures of this breccia are in Adams and Highland Counties within the confines of the Serpent Mound Impact Structure as defined by Reidel (1975), specifically within the so-called *transition zone*. Initial inspection of this exposure reveals a matrix-supported, (apparently) **polylithic breccia** (fig. 33) with some **clasts** as large as boulders. At this site, the best exposures are in the gullies. This breccia is exposed in more than 20 other locations in the crater (Milam and others, 2011). The breccia is often spatially adjacent to or overlying the Middle Silurian Peebles Dolomite and also lies below the Late Devonian Ohio Shale. In most places, this deposit is pure dolomite and is largely devoid of fossils.

Breccias are commonly associated with impact craters, representing ejecta from the impact event itself. Milam and others (2011) initially thought that this **intracrater** breccia could represent ejecta that either has fallen back into the crater or has been transported by resurge following a marine impact. Numerous other (non-impact related) processes, such as karst collapse and **mass wasting**, may have been responsible for the formation of this breccia. Extensive analysis of this breccia reveals it to be a previously unrecognized portion of the Middle Silurian Peebles Dolomite (Milam and others, 2011).

FIGURE 32.—Roadside exposure of the breccia at Stop 8 in the so-called *transition zone* of the Serpent Mound Impact Structure, Adams County, Ohio.

FIGURE 33.—Close-up view of the breccia exposed at Stop 8 in the Serpent Mound Impact Structure, Adams County, Ohio.

Stop 9 – The Central Peak

Driving Directions: From Stop 8, return north along Horner Chapel Road (Township Highway 116), traveling for 0.6 mi (1.0 km). Turn right on Strait Creek Road (County Road 45) and continue for 2.2 mi (3.5 km) to the intersection of Strait Creek Road with State Route 41. Turn right, heading south on State Route 41. Continue for 1.9 mi (3.1 km), turning right onto Purcell Road (Township Highway 196). Continue for 0.5 mi (0.9 km) to the southwest until you reach a three-way intersection.

Coordinates: lat 39°01'39.2"N., long 83°23'24.4"W.

After obtaining permission from the property owners, you may veer right onto a private gravel driveway. Continue for 0.4 mi (0.6 km) and park (figs. 14, 34). Depending upon recent local weather conditions, you may have to hike or drive from this point on a 0.7 mi (1.2 km) trip along a dirt road with some potholes and gullies. If granted permission to drive to the top of the central peak, your vehicle(s) must have a high ground clearance to avoid damage. Whether hiking or driving, travel until you reach the approximate geographic coordinates, lat 39°01'58.1"N., long 83°24'11.4"W. at an elevation of approximately 958 ft (292 m) above m.s.l. Warning: There are stumps, rocks, and a well casing protruding from the ground along this path.

This point stands high atop the central peak of the Serpent Mound Impact Structure. The central peak consists of a jumbled, faulted, and folded mass of Ordovician and Silurian rocks that have been uplifted well above their normal stratigraphic positions. Reidel (1975) estimates that there has been as much as 950 ft (290 m) of uplift, while Baranoski and others (2003) estimate 400–902 ft (122–275 m) of displacement. This site would have been the approximate center of the impact event that formed the crater. Following excavation, shock-damaged rocks would have risen from below to form an actual topographic peak. Over hundreds of millions of years, erosion has denuded the landscape, but the topographic expression of the central peak remains.

From this point, continue downhill to the north into a small ephemeral stream that continues to dissect the central peak. Along the banks of this west-to-east–flowing stream are sporadic outcrops of Late Ordovician to Middle Silurian sedimentary rocks. Strata here are no longer positioned horizontally; most are oriented in a vertical or subvertical fashion. These dipping layers are separated by

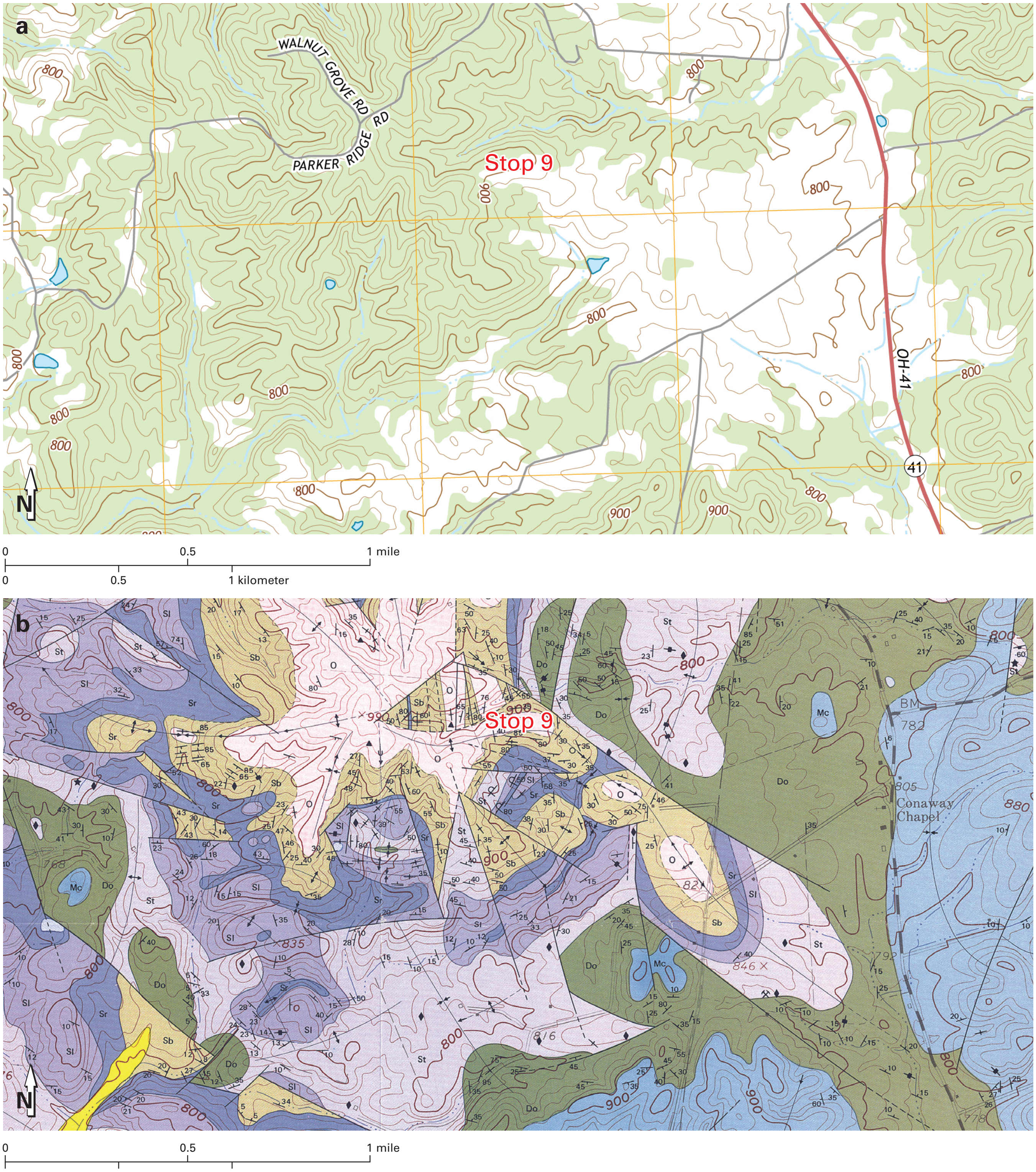


FIGURE 34.—(a) A portion of the USGS 7.5-minute topographic map of the Sinking Spring quadrangle (20-ft contour interval) showing the location of Stop 9 off of the intersection of Purcell and Parker Ridge Roads, Adams County, Ohio. (b) Bedrock geologic map (Reidel, 1975) of a portion of the Sinking Spring quadrangle (20-ft contour interval) showing the location of Stop 9 off of the intersection of Purcell and Parker Ridge Roads, Adams County, Ohio. Legend: Qal = alluvium; Mc = Cuyahoga Formation, Sunbury Shale, Berea Sandstone, and Bedford Shale undivided; Do = Ohio Shale; St = Tymochtee Formation, Greenfield Dolomite, and Peebles Dolomite undivided; Sl = Lilley and Bisher Formations undivided; Sr = Rochester Shale; Sb = Brassfield Limestone; O = Ordovician undifferentiated.

numerous faults, most of which are not visible, that cut across this small valley. In a few select locations, polylithic breccias are exposed along the stream bank. It is quite probable that most of these breccias were generated during the impact or are the product of more recent erosion and weathering or mass wasting processes.

Along the streambed, you will notice several loose cobbles of mostly carbonate sedimentary rock. These cobbles are chock-full of Ordovician- and Silurian-age fossils, such as brachiopods, bryozoans, and crinoids. Some of these cobbles contain the only macro scale indicator of an impact event at Serpent Mound—shatter cones. Shatter cones (fig. 3) are conical fractures that form in target rock when the strength of the material is exceeded by the transiting shock wave produced by an impact event. Although many of the rocks in the creek bed will not contain shatter cones, several still do. When examining a rock, hold the surface in question so that sunlight strikes it at a very low angle; this is the best lighting to observe shatter cones. Please only collect those shatter cones that are needed for teaching or research purposes. A hike farther downstream will reveal more deformed rock of increasingly younger age, ranging up to the Devonian black shale.

REFERENCES CITED

Aldrich, M.J., Jr., 1969, Pore pressure effects on Berea Sandstone subjected to experimental deformation: Geological Society of America Bulletin, v. 80, no. 8, p. 1577–1586.

Algeo, T.J., and Woods, A.D., 1994, Microstratigraphy of the Lower Mississippian Sunbury Shale—A record of solar-modulated climatic cyclicity: Geology, v. 22, no. 9, p. 795–798.

Baranoski, M.T., Schumacher, G.A., Watts, D.R., Carlton, R.W., and El-Saiti, B.M., 2003, Subsurface geology of the Serpent Mound Disturbance, Adams, Highland, and Pike Counties, Ohio: Columbus, Ohio Department of Natural Resources, Division of Geological Survey Report of Investigations No. 146, 60 p., 3 pls.

Bowman, R.S., 1956, Stratigraphy and paleontology of the Niagaran Series in Highland County, Ohio: Columbus, The Ohio State University, Ph.D. dissertation, 339 p.

Bucher, W.H., 1921, Cryptovolcanic structure in Ohio of the type of the Steinheim Basin: Geological Society of America Bulletin, v. 32, no. 1, p. 74–75.

Bucher, W.H., 1935, A crypto-volcano structure in southern Ohio: The Compass of Sigma Gamma Epsilon, v. 15, p. 157–162.

Bucher, W.H., 1936, Crytovolcanic structures in the United States: International Geologic Congress (1933), Report of the 16th Session, v. 2, p. 1055–1084.

Carlton, R.W., Koeberl, Christian, Baranoski, M.T., and Schumacher, G.A., 1998, Discovery of microscopic evidence for shock metamorphism at the Serpent Mound structure, south-central Ohio—Confirmation of an origin by impact: Earth and Planetary Science Letters, v. 162, no. 1–4, p. 177–185.

Campbell, Guy, 1946, New Albany Shale: Geological Society of America Bulletin, v. 57, no. 9, p. 829–908.

Churcher, P.L., French P.R., Shaw J.C., and Schramm, L.L., 1991, Rock properties of Berea Sandstone, Baker Dolomite, and Indiana Limestone, *in* International Symposium on Oilfield Chemistry, Feb. 20–22, Anaheim, Calif. [proceedings]: Society of Petroleum Engineers, doi: 10.2118/21044-MS, 19 p.

Chyba, C.F., Thomas, P.J., and Zahnle, K.J., 1993, The 1908 Tunguska explosion—Atmospheric disruption of a stony asteroid: Nature, v. 361, p. 40–44.

Cohen, A.J., Bunch, T.E., and Reid, A.M., 1961, Coesite discoveries establish cryptovolcanics as fossil meteorite craters: Science, v. 134, no. 3490, p. 1624–1625.

Collins, G.S., Melosh, H.J., and Ivanov, B.A., 2004, Modeling damage and deformation in impact simulations: Meteoritics and Planetary Science, v. 39, no. 2, p. 217–231.

Cooper, J.R., 1943, Flow structures in the Berea Sandstone and Bedford Shale of central Ohio: Journal of Geology, v. 51, no. 3, p. 190–203.

DeWitt, Wallace, Jr., 1951, Stratigraphy of the Berea Sandstone and associated rocks in northeastern Ohio and northwestern Pennsylvania: Geological Society of America Bulletin, v. 62, no. 11, p. 1347–1370.

Dietz, R.S., 1947, Meteorite impact suggested by the orientation of shatter-cones at the Kentland, Indiana disturbance: Science, v. 105, no. 2715, p. 42–43.

Dietz, R.S., 1959, Shatter cones in cryptoexplosion structures (meteorite impact?): Journal of Geology, v. 67, no. 5, p. 496–505.

Dietz, R.S., 1960, Meteorite impact suggested by shatter cones in rock: Science, v. 131, no. 3416, p. 1781–1784.

Dudei, N.L., and Stigall, A.L., 2010, Using ecological niche modeling to assess biogeographic and niche response of brachiopod species to the Richmondian Invasion (Late Ordovician) in the Cincinnati Arch: Palaeogeography, Palaeoclimatology, and Palaeoecology, v. 296, nos. 1–2, p. 28–43.

French, B.M., 1998, Traces of catastrophe—A handbook of shock-metamorphic effects in terrestrial meteorite impact structures: Houston, Lunar and Planetary Institute, LPI Contribution No. 954, 120 p.

French, B.M., and Koeberl, Christian, 2010, The convincing identification of terrestrial meteorite impact structures—What works, what doesn't, and why: Earth Science Reviews, v. 98, no. 1, p. 123–170.

Hartmann, W.K., and Davis, D.R., 1975, Satellite-sized planetesimals and lunar origin: Icarus, v. 24, p. 504–515.

Holland, S.M., and Patzkowsky, M.E., 2007, Gradient ecology of a biotic invasion—Biofacies of the type Cincinnatian series (Upper Ordovician), Cincinnati, Ohio region, USA: Palaios, v. 22, no. 4, p. 392–407.

Koeberl, Christian, Buchanan, P.C., and Carlton, R.W., 1998, Petrography and geochemistry of drill core samples from the Serpent Mound structure, Ohio—Confirmation of an impact origin [abs.]: Houston, Tex., Lunar and Planetary Science Institute, Abstracts from the Lunar and Planetary Science XXIX Conference, no. 1392.

Kotake, Nobuhiro, 1989, Paleoecology of the *Zoophycos* producers: Lethaia, v. 22, no. 3, p. 327–341.

Lewis, T.L., and Schwietering, J.F., 1971, Distribution of the Cleveland Black Shale in Ohio: Geological Society of America Bulletin, v. 82, no. 12, p. 3477–3482.

Locke, John, 1838, Prof. Locke's geological report, *in* Mather, W.W., 2nd Annual Report of the Geological Survey of the State of Ohio: Columbus, [State of Ohio Legislature], p. 201–286.

Mark, Kathleen, 1995, Meteorite craters: Tucson, University of Arizona Press, 288 p.

Milam, K.A., 2010, A revised diameter for the Serpent Mound Impact Crater in Southern Ohio: Ohio Journal of Science, v. 110, no. 3, p. 34–43.

Milam, K.A., Hester, Adam, and Malinski, Peter, 2011, An anomalous breccia associated with the Serpent Mound impact crater, southern Ohio: Ohio Journal of Science, v. 110, no. 2, p. 18–30.

Melosh, H.J., 1989, Impact cratering—A geologic process: Oxford University Press, 245 p.

Molyneux, S.G., Manger, W.L., and Owens, B., 1984, Preliminary account of Late Devonian palynomorph assemblages from the Bedford Shale and Berea Sandstone formations of central Ohio, U.S.A.: Journal of Micropaleontology, v. 3, no. 2, p. 41–51.

Newberry, J.S., 1870, Report on the progress of the Geological Survey of Ohio in 1869, pt. 1 *of* Report of the Geological Survey of Ohio, 1869: Columbus, [State of Ohio Legislature], p. 3–53.

Ohio Division of Geological Survey (ODGS), 1998, Physiographic regions of Ohio: Columbus, Ohio Department of Natural Resources, Division of Geological Survey, page-size map with text, 2 p., scale 1:2,100,00.

ODGS, 1999, Known and probable karst areas: Ohio Department of Natural Resources, Division of Geological Survey, 2 p., map with text.

Ormö, J.O., and Lindström, Maurits, 2000, When a cosmic impact strikes the sea bed: Geological Magazine, v. 137, no. 1, p. 67–80.

Osgood, R.G., Jr., 1987, Trace fossils, in Boardman, R.S., Cheetham, A.H., and Rowell, A.J., eds., Fossil invertebrates: Oxford, Blackwell Scientific Publications, p. 663–674.

Over, D.J., 2007, Conodont biostratigraphy of the Chattanooga Shale, Middle and Upper Devonian, southern Appalachian Basin, eastern United States: Journal of Paleontology, v. 81, no. 6, p. 1194–1217.

Pike, R.J., 1985, Some morphologic systematics of complex impact structures: Meteoritics, v. 20, no. 1, p. 49–68.

Provo, L.E., Kepferle, R.C., and Potter, P.E., 1977, Three Lick Bed—Useful stratigraphic marker in Upper Devonian shale in eastern Kentucky and adjacent areas of Ohio, West Virginia, and Tennessee: U.S. Energy Res. Dev. Admin., Morgantown Energy Resource Center, Rep. MERC/CR-77-2, 56 p.

Reidel, S.P., 1975, Bedrock geology of the Serpent Mound cryptoexplosion structure, Adams, Highland, and Pike Counties, Ohio: Columbus, Ohio Department of Natural Resources, Division of Geological Survey Report of Investigations No. 95, color map, scale 1:12,000.

Reidel, S.P., Koucky, F.L., and Stryker, J.R., 1982, The Serpent Mound disturbance, southwestern Ohio: American Journal of Science, v. 282, no. 9, p. 1343–1377.

Rexroad, C.B., Branson, E.R., Smith, M.O., Summerson, C., and Boucot, A.J., 1965, The Silurian formations of east-central Kentucky and adjacent Ohio: Kentucky Geological Survey Bulletin 2, Series X, 34 p.

Schumacher, G.A., 2002a, August F. Foerste's unpublished field notes for the area of the Serpent Mound disturbance: Columbus, Ohio Department of Natural Resources, Division of Geological Survey Open-File Report 2002-01, 19 p.

Schumacher, G.A., 2002b, Reconnaissance bedrock geology of the Jaybird, Ohio quadrangle: Columbus, Ohio Department of Natural Resources, Division of Geological Survey Digital Map Series BG-2, scale 1:24,000.

Schumacher, G.A., and Reidel, S.P., 2002, Reconnaissance bedrock geology of the Byington, Ohio quadrangle: Columbus, Ohio Department of Natural Resources, Division of Geological Survey Digital Map Series BG-2, scale 1:24,000.

Shrake, D.L., Swinford, E.M., Schumacher, G.A., Larsen, G.E., and Slucher, E.R., 2007, Descriptions of geologic map units—A compendium to accompany Division of Geological Survey open-file 7.5-minute bedrock-geology maps: Columbus, Ohio Department of Natural Resources, Division of Geological Survey open-file Report 98-1, 8 p. [Revised April 25, 2011.]

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

Swinford, E.M., 1991, Reconnaissance bedrock geology of the Peebles quadrangle, Adams County, Ohio: Columbus, Ohio Department of Natural Resources, Division of Geological Survey Digital Map Series BG-2, scale 1:24,000.

Trygstad, Paul, 2014, A constrained diameter for the Serpent Mound impact crater: Athens, Ohio University, Senior thesis, 36 p.

Widom, Elizabeth, and Gaddis, S.J., 2004, Re-Os isotope systematics in carbonates from Serpent Mound, Ohio—Implications for Re-Os dating of crustal rocks and the osmium isotopic composition of Ordovician seawater: Geochemistry, Geophysics, and Geosystems, v. 5, no. 3, doi: 10.1029/2002GC000444.

GLOSSARY

A.U. (astronomical unit) – a unit commonly used when referring to the distances between planets in our solar system; defined as the mean distance (approximately 150 million km) between Earth and the Sun

argillaceous – said of rock that has a significant amount of clay minerals

asteroids – small, irregularly-shaped rocky or metallic bodies, sometimes with lesser amounts of ice, that orbit the Sun; most asteroids reside in the Main Asteroid Belt between the orbits of Mars and Jupiter

astroblemes – heavily-eroded impact craters that have partially or almost completely lost much of the original crater form

ballistic – referring to something free falling as a result of gravity

blast cones – radiating fractures that emanated from a drill hole where an explosive charge was detonated

breccia – a type of sedimentary rock comprised of angular fragments of other rocks

bryozoans – invertebrate marine creatures that grow in colonies and secrete material commonly forming twig- or branch-like, lacy, or corkscrew skeletons

burrow – a remnant form in sedimentary rock produced when an animal hunts for food or escapes predation in soft sediment; burrows can take on many shapes

carbonate – usually referring to rock that contains a mineral with CO_{3-2} in its chemical formula; also used to describe a mineral containing CO_{3-2}

carbonate concretion – a small, usually rounded or subrounded zone in a rock rich in carbonate minerals and/or cements

Catskill Delta – a wedge or delta-shaped accumulation of sediments that formed from erosion of the northern Appalachian Mountains during the Devonian Acadian Orogeny

central peak – positive topographic relief feature at the center of a complex crater that forms as a result of uplift of the crater floor; in eroded form (when not a positive relief feature), central peaks are often referred to as *central uplifts*

Cincinnati Arch – a northeast-to-southwest–trending structural high area comprising mostly sedimentary rocks and situated between the Appalachian Basin to the southeast and the Illinois and Michigan Basins to the northwest; rocks on the eastern side of the arch dip to the east, and rocks on the western side dip to the west; this structure is situated in Ohio, Indiana, Kentucky, Tennessee, and northern Alabama

clast – a fragment of a larger rock

coesite – a high-pressure polymorph of the mineral quartz (SiO_2)

coma – the sheath of dust and gas surrounding the nucleus of a comet; it is formed by sublimation of ice as a comet approaches and is heated by the Sun

comets – small bodies comprised of ice and lesser amounts of rock that travel around the Sun in highly elliptical orbits; at approximately 3 A.U., these small bodies begin to sublimate, forming a coma and a tail

complex crater – an impact crater with a central peak surrounded by a crater floor and collapsed rim

compositional homogeneity – referring to a material whereby the composition or bulk chemistry is the same throughout

cone-in-cone – a type of structure with a series of nested cones that appears to be produced by solutioning under pressure

continuous ejecta blanket – the ejecta deposited nearby the crater rim that results in a total covering of the adjacent landscape

crater rays – discrete lineations comprised of ejecta that radiate from an impact crater

crater rim – the outermost edge of an excavated crater where target rock have been uplifted and sometimes overturned; ejecta may also be present

cryptovolcanic – referring to a structure or event produced by volcanic activity where no obvious volcanic edifice or related extrusive igneous rock remain

discontinuous ejecta – the farthest zone of crater ejecta where ejected material does not completely cover the landscape; the ejecta here is often deposited as crater rays

dolostone – a sedimentary rock, usually formed in marine environments, comprised of the mineral dolomite $CaMg(CO_3)_2$; sometimes geologists incorrectly use the term *dolomite*, a mineral name, when referring to the rock, dolostone

drill core – a cylindrical piece of rock extracted during drilling operations

effigy – a likeness of something, often a person or other living thing, such as an animal

ejecta – lithic fragments, melt, and impactor material that is excavated and redeposited by ballistic sedimentation during an impact event

ejecta flap – a slab of inverted or overturned rock at the rim of a crater

ejected – to be thrown from a forming impact crater in a ballistic fashion

epicontinental – a type of sea said to be on or within a continent; usually marine environments that are shallower than those of the ocean

escape velocity – the minimum velocity needed to exceed the gravitational pull of a body; the escape velocity of Earth is ≈11 km/s

excavation – the process of removing fragmented material from a newly-forming crater that results from the momentum imparted to crater ejecta

flute casts – scoop-shaped sedimentary features between sedimentary rocks of differing grain sizes, formed when turbulent currents scoured an ancient streambed

fossil – the preserved remains of a once-living or ancient organism; typically referring to the preserved hard body parts of that organism

fossil molds – an impression made in soft sediment by the exterior skeleton or soft parts of an organism; fossil molds are commonly exposed when a rock is cracked open or when the actual fossil itself has been dissolved away

fossiliferous – referring to a sedimentary rock that is particularly rich in fossils

geology – the study of Earth

geomorphic feature – a synonym for *landform*

glacial till – loose sediment deposited by a glacier; comprised of a variety of grain sizes, including boulders, cobbles, pebbles, sand, silt, and clay

glaciated – referring to terrain that has been affected by the actions of glaciers or moving sheets of ice; glaciers can erode and transport large amounts of material over great distances

ichnofossil – the preserved record of biologic activity in sedimentary rock that does not necessarily contain the preserved or fossilized body parts of the organism; a term used interchangeably with the term *trace fossil*

impact crater – the bowl-shaped hole excavated by the collision of an asteroid or comet with the surface of a planet, dwarf planet, moon, asteroid, or comet

impactor – the smaller of two objects involved in an impact event; usually refers to an asteroid or comet

in situ – Latin term describing something found in place

indurated – a way of describing how hard or lithified a rock is compared to its original form (e.g., sediment)

intertonguing – a synonym for *interweaving*; interlayered

intracrater – said to be within the boundaries of a crater rim

karst – a type of landscape or terrain where soluble rock has experienced dissolution such that sinkholes, sinking streams, caves, underground streams, and emergent springs have formed and comprise an interconnected hydrological system for surface and groundwater flow

kinetic energy – this is the energy of the motion of an object defined as one half the object's mass multiplied by the square of its velocity (KE = ½mv2)

limestone – typically gray to white-colored sedimentary rock consisting of the mineral calcite ($CaCO_3$); limestone can form in the absence of organisms but was often formed in ancient marine environments out of the shells of marine creatures

lithic – of or pertaining to rock

lithification – referring to the process or processes involved in forming a rock

lithosphere – the crust and upper mantle of a planet

load casts – knob-like sedimentary features formed when coarse-grained sediments are protruded into finer-grained sediments

Ma – mega annum; denotes age in millions of years

marl – a rather archaic term referring to poorly **indurated** carbonate and clay-rich rock

mass wasting – the downslope movement of material, such as rock or soil, under the influence of gravity

monolithic breccia – rock comprised of angular clasts and matrix of only one rock type

morphometric – referring to the quantitative relationships between landform dimensions

normal fault – a type of fault in which the overhanging block of rock (hanging wall) moves down relative to the opposing block (footwall)

orogeny – a mountain-building episode

Paleozoic – that eon in Earth's geologic time scale spanning from 251 to 542 Ma

parallel deformation lamellae – parallel planes formed by mechanical failure of the crystal lattice

permeability – the ability of a rock, soil, or other substance to transmit a fluid, such as water

planar microstructures – **parallel deformation lamellae** or defects in a crystalline lattice, visible at the microscopic scale, that are produced by shock metamorphism

plumose joints – a type of joint formed by extensional stresses that display a plume or feature-like pattern usually radiating from a point that seems to indicate where the fracture began

polylithic breccia – rock consisting of angular clasts and matrix of multiple rock types

polymorph – another form of a mineral with the same chemical composition, but different crystalline structure

porosity – the ability of a rock, soil, or other substance to store fluids, such as water

prograding – in the case of deltas, those that advance seaward

projectile – the smaller of two objects involved in an impact event; usually refers to an asteroid or comet

pyrite – an iron sulfide mineral with the chemical formula FeS_2; commonly referred to as "fool's gold"

quartz – a common mineral in Earth's crust with the chemical formula SiO_2

rarefaction wave – the immediate release of pressure or decompression following shock wave passage

rhynchonellid brachiopods – type of marine invertebrate that has two articulated "shells" or valves that appear to curve outward and have ridges on their shells; the beak of this brachiopod is pointed

ring graben – a circular set of blocks of rocks, faulted on both sides, that has been displaced downward relative to the adjacent rocks

ripple marks – wave-shaped bedding forms in sedimentary rock formed by wave action; there are two types: asymmetric and symmetric, the former produced by current moving in one direction, while the latter are produced by current moving in two or more directions

river bend – a curve formed in a floodplain as a river continues to erode a stream bank

rugose corals – a type of solitary or colonial coral belonging to the order of Rugosa, which come in a variety of forms including horn or mound shapes

sandstone – a type of sedimentary rock formed of sand-sized (0.625–2.0 mm) particles that can be made of one or several minerals, such as quartz, mica, feldspar, zircon, and apatite

sedimentary rock – rock formed from the **lithification** of sediment by compaction and cementation

shale – a sedimentary rock with a thinly-bedded or "platy" appearance comprised of clay-sized (<0.0039 mm) sediment

shatter cones – distinctive conical fractures produced in target rocks at the centers of large impact craters

shock metamorphism – refers to the type of metamorphism that results from a hypervelocity impact event at the surface of a planet; the pressures produced by such an impact event can alter the physical state or permanently deform the target rock or impactor itself

shock wave – a wave of energy produced by an impact event that can travel through target rock at speeds exceeding the speed of sound through that rock; shock waves have the ability to vaporize, melt, and permanently deform (in the solid state) target rock

shocked quartz – the variety of the mineral quartz (SiO_2) that has been permanently deformed by the passage of a shock wave generated as a result of an impact event

siderophile elements – "iron-loving" elements or substances that have an affinity for (occur with) iron-rich substances
siliciclastic – said of sedimentary rocks comprised of pieces of other silicate-dominated rocks
siltstone – a type of sedimentary rock comprised of sediment (silt) ranging from 0.0039 to 0.0625 mm in diameter
simple crater – a bowl-shaped crater produced by an impact event; in comparison to a complex crater, a simple crater does not have a central peak or uplift nor a rim that has experienced as much collapse
sinkholes – holes at the surface of a planet formed from collapse when underlying rock has been removed by dissolution
solar-modulated climatic cyclicity – the repeated climate cycles as influenced by the Sun
stishovite – a high-pressure polymorph of the mineral quartz (SiO_2) that forms at even higher pressures than coesite
strata – layers of rock
stratum – a single layer of rock
structural domes – formed when layered rocks are folded upward in a dome-like fashion
sublimate – the changing in physical state of a material from solid to gas
syndepositional mass movement – the gravitational collapse of sediment during deposition
tail – the dust, gas, and ions that emanate from the nucleus and coma of a comet
target rocks – rocks existing on a planet or moon at the time of impact; these rocks can be igneous, sedimentary, or metamorphic by type
tempestite – a particular bed in sedimentary rock interpreted to have been deposited during the waning stages of a high-energy storm event; tempestites are indicative of shallow marine conditions where wave action has the ability to transport sediment
terraced – in this instance, referring to the "stair-stepped" profile or cross section (view from the side) that results from collapse of a crater rim along normal faults
tool marks – line-shaped sedimentary features formed when water currents dragged an object (such as a pebble or shell fragment) along the bottom of an ancient stream or other body of water
transient crater – the initial, gravitationally unstable crater that forms during impact
unconformable – referring to a surface, in a sequence of sedimentary rocks, where deposition was not continuous and erosion may have occurred
X-ray diffraction – a technique whereby a geologic specimen (often in powdered form) is exposed to X-rays, which interact with minerals present; scientists use the resultant X-ray pattern to determine the mineral composition of a sample

Milam • Guide to the Serpent Mound Impact Structure, South-Central Ohio • Guidebook 22