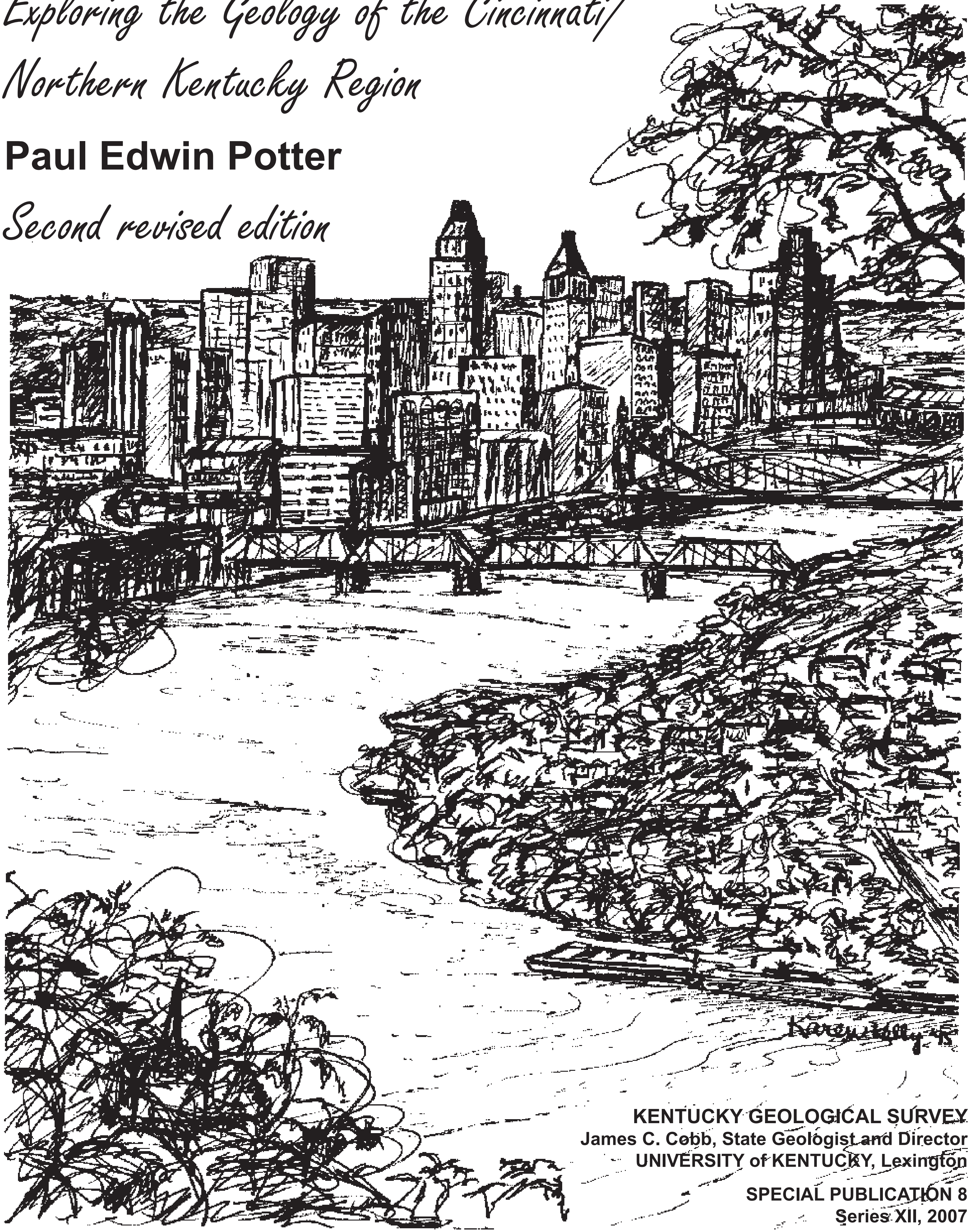
# *Exploring the Geology of the Cincinnati/ Northern Kentucky Region*

**Paul Edwin Potter**

*Second revised edition*



**KENTUCKY GEOLOGICAL SURVEY**
**James C. Cobb, State Geologist and Director**
**UNIVERSITY of KENTUCKY, Lexington**

**SPECIAL PUBLICATION 8**
**Series XII, 2007**

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**Front cover:** Downtown Cincinnati, the northern Kentucky city of Ludlow, and the Ohio River, looking east and upstream from the overlook at Mount Echo Park in Price Hill. The topographic basin occupied by Cincinnati's business district and Covington was formerly a course of the north-flowing Licking River, and the steep hill below the overlook is the result of erosion by the Ohio River as it flows west toward Anderson Ferry.

Special Publication 8 Series XII, 2007

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# Preface

As a graduate student in the late 1940's, I heard one of my professors say "Every geologist should do something for his local community." Although this idea has stayed with me ever since, it was not until the mid-1980's that I decided now was the time and the Cincinnati region of Ohio, Kentucky, and Indiana was the place to fulfill my obligation. "Exploring the Geology of the Cincinnati/Northern Kentucky Region" is the result.

This overview is intended for amateurs, civil engineers, geographers, geologists, planners, architects, and teachers from grade school through university—a broad, diverse audience. As a result, I have placed few references in the text, but included many annotated references in the "Digging Deeper" sections for all those who wish to pursue in more detail the diverse geology of the region. Excluding paleontological references, several hundred technical papers that bear on the geology of the region, many in hard-to-find technical journals, are references in this overview.

An overview of the geology of the Cincinnati/northern Kentucky region is timely, because over 75 years have passed since the Ohio Division of Geological Survey published N.M. Fenneman's "Geology of Cincinnati," a landmark study. The present overview is also timely because of the recent discovery of a large Precambrian basin underlying much of the Cincinnati/northern Kentucky region. This previously hidden sedimentary basin adds still another reason to learn about the geology of the Cincinnati/northern Kentucky region.

# Preface to the Second Edition

The second edition of "Exploring" has two parts: it begins with the geologic evolution of our metropolitan region, incorporating much new research since 1996, and follows with a section on living and working with this geologic inheritance. During the 11 years since 1996, the population of the 11-county metropolitan area has increased from 1.7 to 2.0 million, faithfully reflecting the increasing urbanization of the world. This means we need to make the *very best use* of our natural resources, both at the surface and below the earth's surface as well. With this in mind, "Living and Working with Our Inheritance" makes special effort to provide the initial background needed to make better decisions for ourselves today—and for the many generations to come—about how to best live, work, and enjoy ourselves on the geologic inheritance of the Greater Cincinnati region.

# Dedication

In preparing this second edition, I have frequently thought with admiration of Fenneman's pioneering "The Geology of Cincinnati and Vicinity," published by the Ohio Division of Geological Survey in 1916—one of the very early studies of urban geology in North America. Most remarkable to me is that Fenneman arrived at the University of Cincinnati as its first professor of geology in 1907 to establish the Department of Geology and Geography, and during these early busy years he still found time to prepare this fine study. Hence, it is a pleasure to acknowledge his energy, discipline, knowledge, and vision and dedicate this second edition to him on the first centennial of the founding of these two departments.

## Acknowledgments

Since coming to the University of Cincinnati in 1971, I have learned much about the geology of the Cincinnati region from personnel of the geological surveys and highway departments of Ohio, Kentucky, and Indiana; the U.S. Army Corps of Engineers; technical personnel of the city of Cincinnati; professionals in local consulting firms; and finally, from colleagues and the students in the Departments of Geology and Civil and Environmental Engineering at the University of Cincinnati. The three state geological surveys, which have long stressed the importance of geology in their metropolitan areas, deserve special thanks, because of their sustained encouragement and aid. In addition, I have benefited greatly from the help of both the staff of the Geology/Mathematics/Physics Library and the Department of Geology at the University of Cincinnati, and by the typing of Alice McDade and Sandi Cannell. Thomas Lowell helped greatly with glacial geology, and Carl Brett, Arnie Miller, and David Meyer provided important paleontological insights and help with Cincinnatian stratigraphy, especially Carl Brett. Atilla Kilinic reviewed the section on earthquakes, Mark Bowers of the College of Civil and Environmental Engineering read all of "Living and Working with Our Inheritance," and David Nash helped with groundwater and Figure 2. Timothy Phillips, departmental designer, ably worked on all the illustrations with generous and understanding patience. And finally, Meg Smath of the Kentucky Geological Survey did so much to improve the manuscript.

Outside readers include George Cummings of the Natural Resources Conservation Service and Greg Hand of the University of Cincinnati. Karen Kelly graciously prepared the original cover drawing. My sincere appreciation to everyone and to all the supporting organizations.

## Funding Acknowledgments

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H.C. Nutting
Kentucky Geological Survey
Ohio Division of Geological Survey
University of Cincinnati Geology Department

# Thank You

This second edition of *Exploring the Geology of Cincinnati/Northern Kentucky* was Dr. Potter's brainchild from beginning to end. He conceived, researched, photographed, illustrated, wrote, and organized it. He also raised money from various agencies to help cover printing costs. The first edition was published in 1996, sold out, and was reprinted. It was one of our most popular publications of all time. This new and expanded edition will be even more popular and brings our geologic heritage to geologists and nongeologists alike.

Dr. Potter has worked with the Kentucky Geological Survey for more than 50 years. He is sometimes referred to as our best unpaid employee because he has done so much for the Survey. Although never officially employed by KGS, he has contributed enormously to the geology of Kentucky. The KGS List of Publications shows that he authored or co-authored 16 publications from 1958 to 2007. Of these, eight are reports, four are guidebooks, and four are geologic maps or cross sections. These contributions are impressive in their own right, but are only a sidelight to his career as professor, researcher, and author. His work on Kentucky geology spans four Kentucky state geologists: Dan Jones, Wally Hagan, Don Haney, and me.

He knows the KGS staff well, most of us by name, from the Well Sample and Core Library to the director's office. As a frequent visitor he is well known for his gifts of apples, cookies, and doughnuts that he shares freely, and always with a big smile and handshake. Dr. Potter is a regular attendee at KGS seminars, lectures, and workshops. In 1992, he was the KGS distinguished lecturer.

As an example of his dedication to geology, there have been a number of news reports recently about the low water level in Lake Cumberland. Here at the Survey we have been discussing what to do about examining exposures only made possible by this temporary low water. While we were discussing this, Dr. Potter was already giving us feedback about where he had been and what he had seen at Lake Cumberland—We were talking, and he was doing. Doing geology typifies his career and his dedication.

Dr. Potter is our teacher, researcher, encourager, leader, and contributor. Most of all, he is our friend and reminds us how wonderful geology is.

James C. Cobb, State Geologist and Director, March 2007

# Exploring the Geology of the Cincinnati/Northern Kentucky Region

## Paul Edwin Potter

## Abstract

The 11 counties of the Cincinnati/northern Kentucky/southeastern Indiana region in adjacent parts of Ohio, Kentucky, and Indiana have a rich, diverse geology that has strongly influenced its inhabitants from initial settlement to the present time. The region has also produced an amazing number of talented amateur and professional geologists. Fortunately, much of the geology of the region is easily observed in hundreds of outcrops at the surface, and completely buried units can be studied using wells and seismic images.

Ten major events occurring at a subcontinental or continental or even global scale have shaped the geology of the region over the last billion years. Among these events were distant continental collisions, a major glaciation in the southern hemisphere about 470 million years ago, repeated flooding by the world ocean, the formation of the Cincinnati Arch, and the repeated global climate changes in the last million years. The last part of "Exploring" discusses living and working with our geologic inheritance and how to do it best for ourselves and the future.

A glossary of technical terms, a list of sources for more information, suggestions for field trips, and an extended, annotated bibliography provide additional useful material for added study of this fascinating urban area.

## Introduction

Greater metropolitan Cincinnati includes adjacent parts of Ohio, Kentucky, and Indiana and is composed of Butler, Clermont, Hamilton, and Warren Counties in Ohio; Boone, Campbell, Kenton, and Gallatin Counties in Kentucky; and Dearborn, Ohio, and Switzerland Counties in Indiana. It is locally called the Tri-State. The region has a population of almost 2 million and a combined area of 3,051 square miles. Another way to appreciate the size of the region is to be aware of its dimensions—its longest dimension from far northeastern Warren County to the southwestern corner of Gallatin County is 81 airline miles. The region is dominated by the Ohio River, and all but two of its counties, Butler and Warren, border the river (Fig. 1).

The Ohio River opened the American West by providing easy transportation to early settlers, and later connecting it to the world, either upriver to Pittsburgh or downriver to Louisville and New Orleans or to St. Louis and the Upper Mississippi Valley. Since pioneer days, the Ohio River has been an important transportation link, and even today the volume of its river traffic exceeds that of the Panama Canal. In a broader sense, Cincinnati and the Ohio River Basin belong to a larger "Ohiotown" (The Economist, 1988, 1990), which includes the entire length of the Ohio River and is a key part of America's heartland. This Ohiotown includes only 7 percent of the area of the conterminous United States, but has a population of 23 million people, is rich in natural resources and agriculture, and has a widely diversified industrial base plus a very significant commerce far outside of North America. Greater metropolitan Cincinnati is almost in the center of Ohiotown.

The first settlement in the Cincinnati region was in 1788, just below the mouth of the Little Miami River at Columbia, and a little later at Losantiville at what is now the foot of Sycamore Street in Cincinnati. Fort Washington was erected early the following year. Covington was settled in 1790. Topography was the essential factor in determining the growth of Cincinnati, Covington, Newport, and other satellite towns clustered together along the Ohio River (Fig. 2). The Ohio and Licking Rivers plus Mill Creek combined to produce a wide basin, most of which is above flood level and flat, because it has a significant fill of

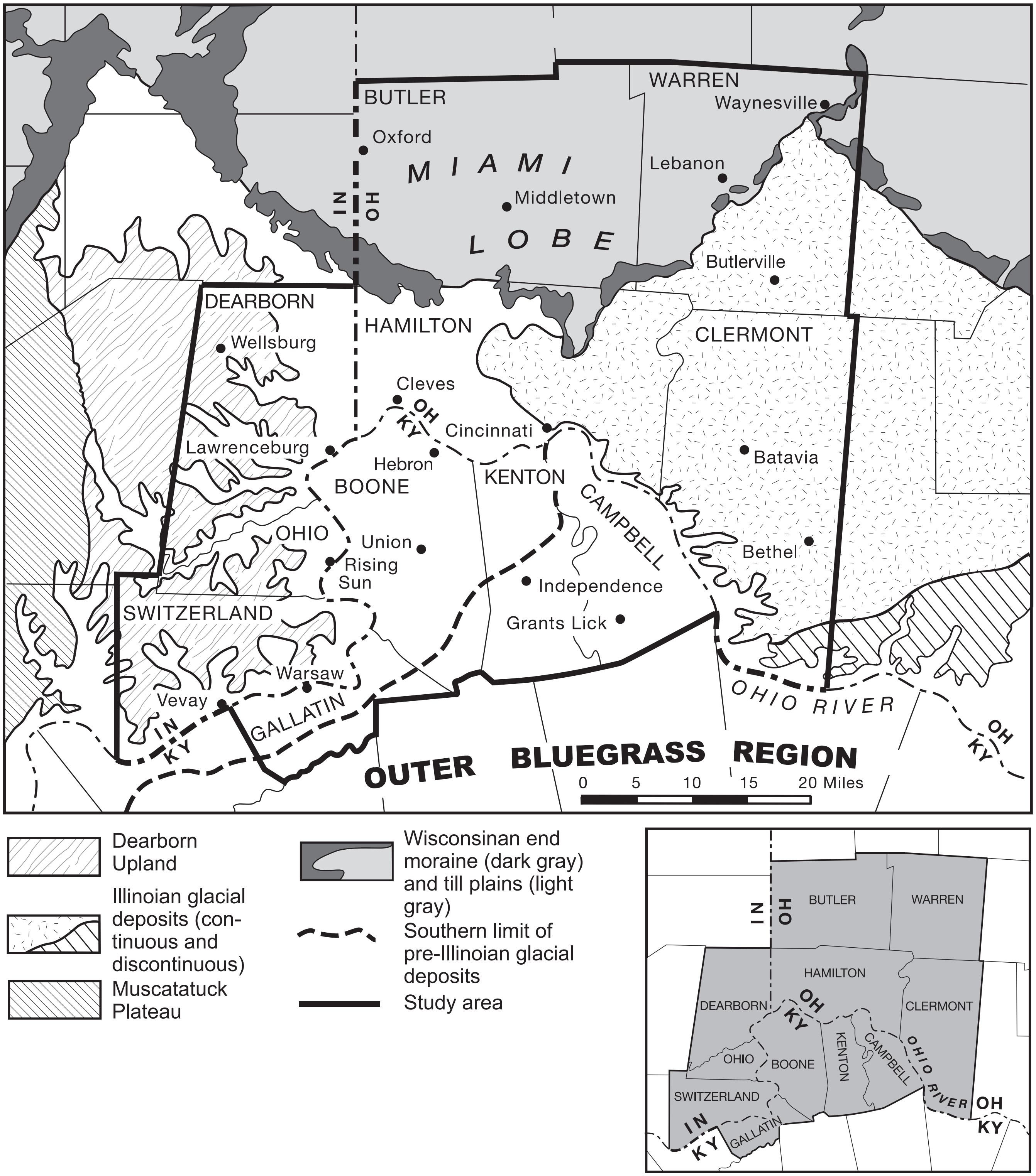


Figure 1. Study area includes 11 counties of adjacent Ohio, Kentucky, and Indiana. These counties extend over four different landscapes: youngest glacial till plains on the north, old glacial till plains in much of Clermont and parts of Hamilton Counties, the dissected topography of Kentucky's Outer Bluegrass, and the uplands of the Dearborn Upland Plateau in parts of Dearborn, Ohio, and Switzerland Counties of Indiana.

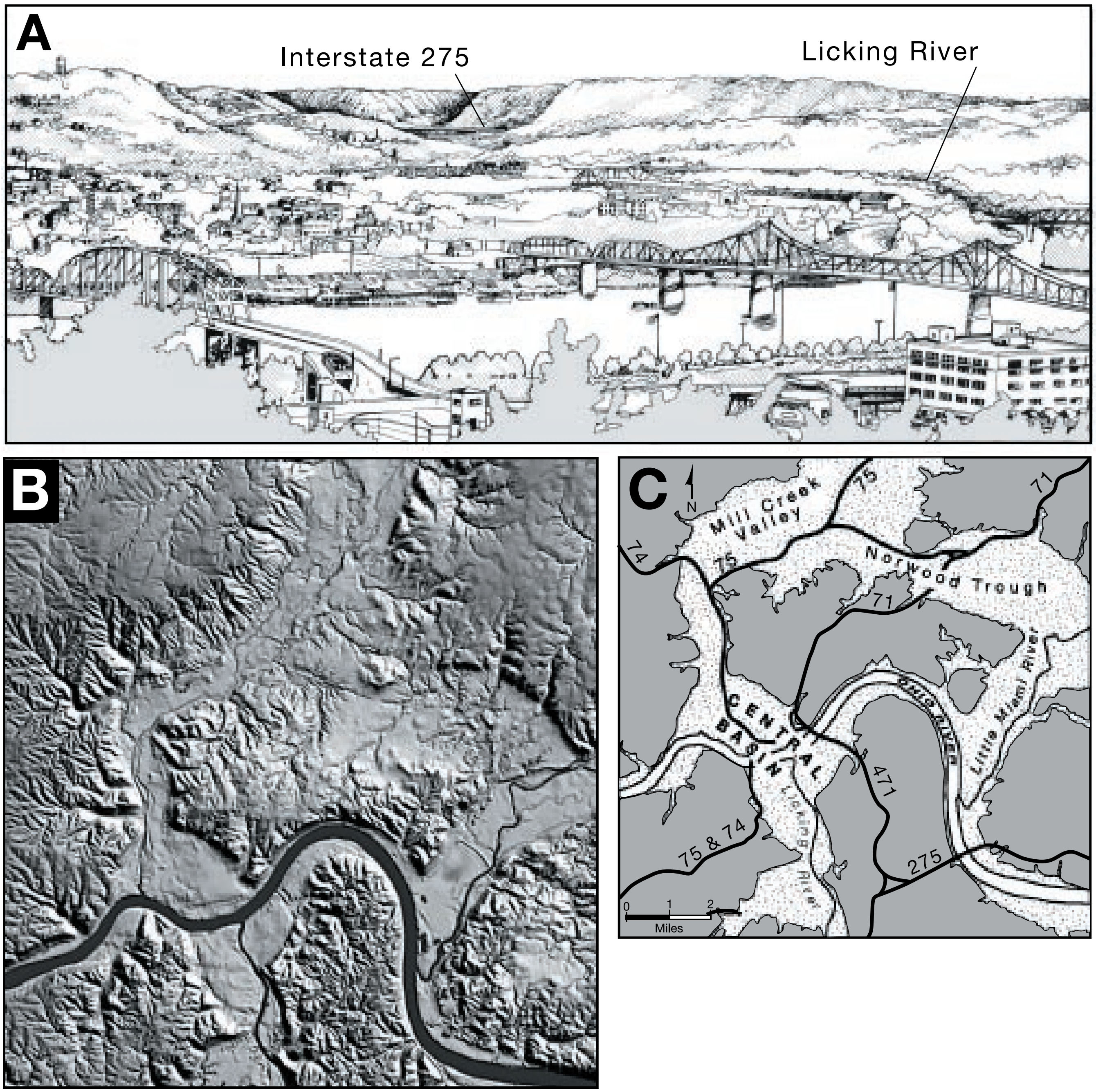


Figure 2. The inner core of the 11-county Greater Cincinnati area. (A) Looking south from Mount Adams in Cincinnati into Kentucky, as seen in 1992 (drawn from a photograph by Lila Messick). (B) Digital image of the inner core (taken from the National Elevation Dataset, resolution 1/3 arc second; courtesy of David Nash). (C) Simplified map of bedrock, alluvial fills, and Interstate highways.

glacial outwash, mostly of Illinoian and Wisconsinan age. Mill Creek Valley also provided easy access northward to Hamilton and Dayton and hence to northern Ohio and eastern Indiana. In 1829 the Miami and Erie Canal started, and later railroads also used Mill Creek Valley for easy access to the north. Railroads and the Norwood Lateral Highway were later built in the Norwood Trough, an abandoned preglacial valley, connecting the transportation links of Mill Creek with the eastern suburbs and beyond. Thus, geologic history—the preglacial drainage of the Teays and its later modification by ice sheets—was all-important for the settlement and development of the Cincinnati region.

Today most of its major transportation links are in secondary tributaries of the Ohio River.

After cable cars, inclines, streetcars, and roads were introduced, the population spread to the surrounding hills for a cleaner, more open environment. Thus, the metropolitan areas of the Cincinnati/northern Kentucky region grew on both sides of the river from a central basin and subsequently expanded to streetcar-railroad-automobile suburbs and to outlying communities and into the southeastern Indiana counties of Dearborn, Ohio, and Switzerland. See Giglierano and Overmeyer (1988) for overviews of the many different neighborhoods of northern Kentucky and Cincinnati. Topography continues to play an important role in the Cincinnati region: its hills provide a unique setting in the Midwest, with many wooded vistas and overlooks from many parks and backyards. Many tributary valleys to the Ohio favored small, self-contained neighborhoods. In a larger sense, as pointed out by Smale (1988), our wooded hillsides keep us in touch with nature. On the other hand, the same topography and hills (plus the shales of the Kope Formation) provide most of the colluvium that creates the many landslides so common in and around Cincinnati.

These are but a few of the many fascinating connections between bedrock, its unconsolidated cover, landscape, and the uses and demands that local inhabitants ask of our region. A pioneering study of the geology of the Greater Cincinnati region was published in 1916 by Fenneman and followed 90 years later by a study of its natural history (Hedeen, 2006).

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Hedeen, S., 2006, Natural history of the Cincinnati region: Cincinnati Museum Center, Scientific Contribution 1, 151 p.

Smale, J.G., 1988, What our hillsides do for us, and what we must do for them: The Outlook, v. 6, p. 1–3.

## Digging Deeper

Banta, R.E., 1949, The Ohio: New York, Rinehart and Co., 592 p.

Twenty-two readable chapters from “La Belle Riviere” to “Colored Waters” focus chiefly on the 16th century and later. It contains a detailed index.

Cauffield, J.V.B., and Banfield, C.E., eds., 1981, The river book: Cincinnati and the Ohio: Program for Cincinnati, 227 p.

This book contains many illustrations, old and new, plus 31 short articles, all of which include additional references. Notable for a very wide span of topics on the middle course of the Ohio, it is highly recommended as an entertaining and informative source book.

Clubbe, J., 1992, Cincinnati observed: Architecture and history: Columbus, Ohio State University Press, 531 p.

This extended account of the buildings in Cincinnati and nearby contains many photographs and descriptions of walking tours. It is rich in history and insight and a necessary companion to every building-stone tour.

Fenneman, N.M., 1916, Geology of Cincinnati and vicinity: Ohio Geological Survey Bulletin 19, 207 p.

Fenneman was a nationally distinguished professor of geology at the University of Cincinnati, where his prime interest was landscape. Hence, it is natural that this bulletin, one of the first urban geology publications in the United States, stresses the geologic processes that formed the Cincinnatian landscape. It contains many fascinating photographs.

Giglierano, G.J., and Overmeyer, D.A., 1988, The bicentennial guide to Greater Cincinnati: A portrait of two hundred years: Cincinnati Historical Society, 656 p.

This complete, well-illustrated coverage of Greater Cincinnati/northern Kentucky neighborhoods and history has a very detailed index of people and places. It cites field trips and over 100 references to additional literature.

Hansen, D., ed., 1987, 1988, 1990, Ojo, an Ohio River anthology: Yellow Springs, Ohio, Ojo Press, 3 v.

The three volumes are entitled “Movement and Place,” “River Journeys,” and “River Lives,” and together they provide an in-depth and fascinating insight into the settlement and people of the Ohio River. It is illustrated with beautiful river scenes by Harlan Hubbard.

Hedeen, S., 2006, Natural history of the Cincinnati region: Cincinnati Museum Center, Scientific Contribution 1, 151 p.

This well-written and -illustrated book provides a readily accessible introduction to the geology, woodlands, and inhabitants (the people, animals, and plants) of our region, plus an overview of its pollution. Color plates, ample references, good price, and format make this a fine companion.

Hubbard, H., 1977, Shantyboat: Lexington, University Press of Kentucky, 352 p.

Subtitled "A River Way of Life," this is a charmingly written account of a 7-year float down the Ohio and Mississippi Rivers, with much about the journey's start in Campbell County, Ky. Together with Hansen's anthology, these two books capture much of what the Ohio River means to the Cincinnati region.

Lafferty, M.B., ed., 1979, Ohio's natural heritage: Columbus, Ohio Academy of Science and Ohio Department of Natural Resources, 324 p.

This work consists of 19 chapters, of which "Written in the Rocks," "Ice Over Ohio," "Today's Landscape," "Hill Country," "Till Plains," and "The Bluegrass" are of the most interest.

National Geographic Society, 1985, Ohio Valley (10th map in the series "The Making of America"): National Geographic Magazine, v. 168, p. 812, supplementary map, scale 1:1,551,000.

Well-displayed history of all the Ohio River Valley from 1,000 B.C. to today is delivered in seven annotated colored maps plus brief text.

Regina, K., Giglierano, G.J., Hagedorn, N.L., Howells, B.M., Overmeyer, D.A., and Rhodes, G.L., 1989, Cincinnati: An urban history: Cincinnati Historical Society, 278 p.

This illustrated history was prepared for the public schools.

Ulack, R., ed., 1998, Atlas of Kentucky [2d ed.]: Lexington, University of Kentucky, 316 p.

The atlas comprises 12 parts; "The Natural Environment," "Minerals, Energy and Timber," "The Agricultural Landscape," and "The Urban Landscape" are most relevant. It contains many colored plates.

White D., Johnston, K., and Miller, M., 2005, Ohio River Basin, *in* Benke, A.C., and Cushing, C.E., eds., Rivers of North America: Amsterdam, Elsevier Academic Press, p. 375–384.

This good overview includes physiography and climate, basin landscape and use, description of the main stem, hydrology and chemistry, plus riverine biodiversity and ecology, ecosystems, and human impacts. An interesting fact is that the Ohio River is the third largest by discharge in the United States.

Williams, C., 1968, Cincinnati scenes: Garden City, N.Y., Doubleday, 174 p.

This book consists of over 70 beautiful pen and ink sketches of Greater Cincinnati in the 1920's and 1930's, each accompanied by several paragraphs of informative text.

Writers Program (Ohio), 1943, Cincinnati; a guide to the Queen City and its neighbors: Cincinnati, Wiesen-Hart Press, 570 p.

Truly a classic, this fine book provides information on history, buildings, parks, industry, the arts, and recreation, plus an extended collection of illustrations. It is the last of the WPA's American Guide Series.

# Yesterday's Pioneers

The Ohio River and its engulfing hills with their many outcrops make the geology of the greater metropolitan region easily accessible for study and thus provide many rich glimpses of local earth history. The earliest visitors and inhabitants recognized this advantage.

Fossils, unconsolidated deposits, and landscape attracted the interest of many early and later inhabitants of the region, with fossils foremost. The bulk of this interest was and is today focused on the abundant invertebrate fossils of the Ordovician outcrops of our region, but the very first scientific papers were about the mastodons, mammoths, and other Ice Age animals found at what is now Big Bone Lick State Park in Boone County, Ky. These fossils were first collected by a Frenchman, Baron de Longuevil, and taken back to Paris in 1739. They are mentioned in an early report on Kentucky by Filson (1784, p. 33–36) and were of such fame that Thomas Jefferson authorized an expedition to collect and study them in 1807—the first federally financed scientific paleontologic expedition in U.S. history. See Davis (1981) for full details.

But it was the great abundance and splendid preservation of the local invertebrate fossils that attracted serious amateurs, many of whom were physicians. This great abundance has ever since powered a sustained interest in paleontology and local bedrock geology. These invertebrate fossils were so famous that Sir Charles Lyell, the premier natural scientist of the 19th century, came to Cincinnati to study and write about them ("Travels in North America," 1845, p. 62–68). Subsequently, a "Cincinnati school" of paleontology was started by U.P. James (1811–1889) and his son J.F. James (1857–1897). Today, an active local group of serious amateurs, the Dry Dredgers (drydredgers.org), successfully continues this tradition.

The deep valley of the Ohio River near Cincinnati has broad terraces that attracted the attention of early naturalists and travelers (Fig. 3). Volney (1803, p. 69, Plate 1) saw and illustrated these terraces in 1796. He also recognized that the gravels underlying these terraces were transported by the Ohio River from the northeast. In 1815, Drake, an early physician, was the first in North America to suggest a glacial origin for the crystalline debris transported from Canada, and later, in 1825, he was the first to recognize glacial till in North America. Thus, the Tri-State area gave birth to two important scientific concepts of glacial geology. Much later, Frank Leverett (1902) published an impor-

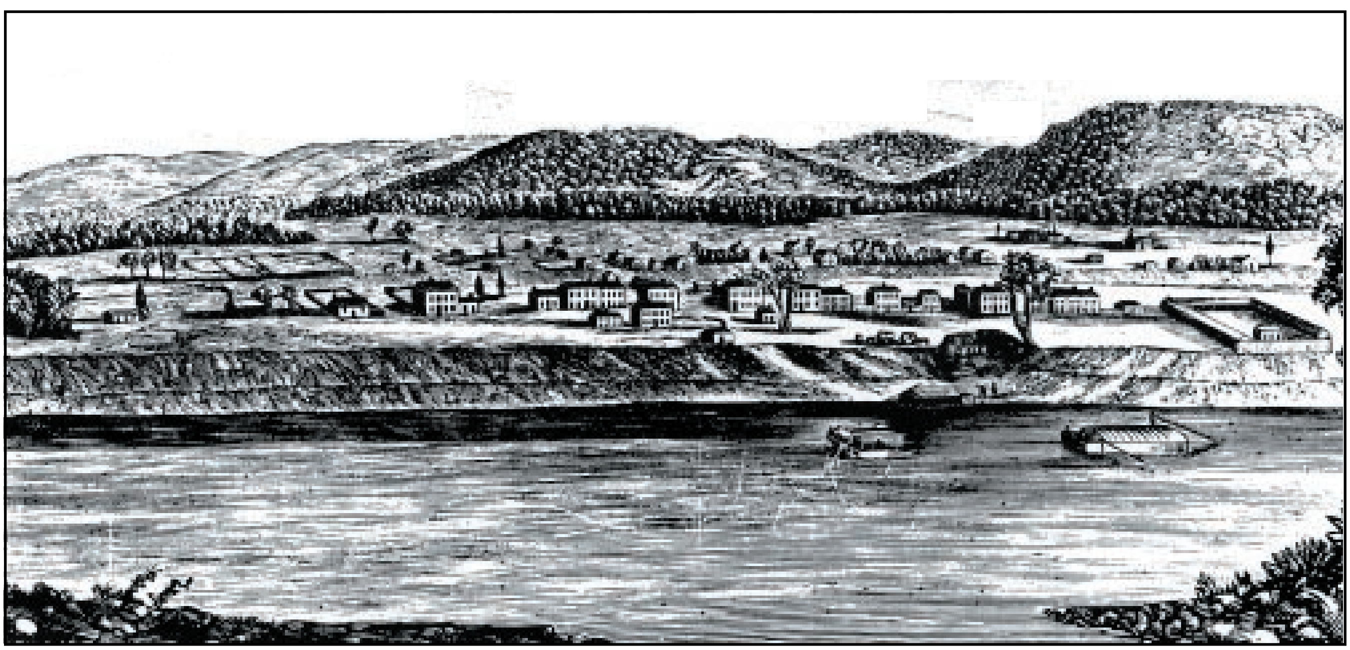

Figure 3. Looking into Ohio and Cincinnati from Kentucky in the very early 19th century. This drawing, reproduced in Booraem (1987), shows flat, flood-free terrace surfaces underlain by Wisconsinan and older sands and gravels, with distant bedrock hills. The two partially forested hills in the distance are present-day Fairview (center) and Bellevue (left). Illustration courtesy of the Cincinnati Historical Society.

tant monograph on the glacial deposits and drainage of the Erie and Ohio Basins.

In 1838, John Locke, professor of chemistry at the Cincinnati Medical School, illustrated the outcropping bedrock formations in a cross section extending from Keys Hill (Mount Auburn) across the Ohio River to Bullocks or Botany Hill (Devou Park). From this cross section it is easy to recognize the geologic formations of today (Fig. 4). Locke's work was later greatly amplified by Edward Orton (1873) during the Second Geological Survey of Ohio. Locke and David Dale Owen (the second State Geologist of Kentucky) seem to have been the first to recognize the existence of the Cincinnati Arch.

In the early 20th century, two geological reports on Cincinnati were published. The first was by J.M. Nickles in 1902 and the other by N.M. Fenneman in 1916. Fenneman's study, with its wide scope, beautiful literary style, and many illustrations of old Cincinnati, is surely a landmark in the literature of urban geology, one from which we can all still learn much. Subsequently, Twenhofel's (1931) "The Building of Kentucky," McFarlan's (1943) "The Geology of Kentucky," the popular account by McGrain (1983), and the text by McDowell (1986) to accompany the "Geologic Map of Kentucky" all touched on the general geology of the Tri-State region.

The many readily accessible outcrops of richly fossiliferous limestones and shales in the Cincinnati/northern Kentucky/southeastern Indiana region made the study of their fauna ideal for local amateurs—laborers, ministers, physicians, lawyers, businessmen, and high-school principals and teachers. Many were of German ancestry, a good example being Carl Ludwig Rominger, who came to Cincinnati after the German Revolution of 1848; he was a physician for 25 years in the city and then spent 13 years as director of the Geological Survey of Michigan. Becker (1938) and Caster (1981) summarized the activities of these and other paleontological workers. Evidently, weekend fossil collecting rated far up the entertainment scale. Two early amateur paleontologists were David Christy (1802–1867), a newspaperman, and F.B. Meek (1817–

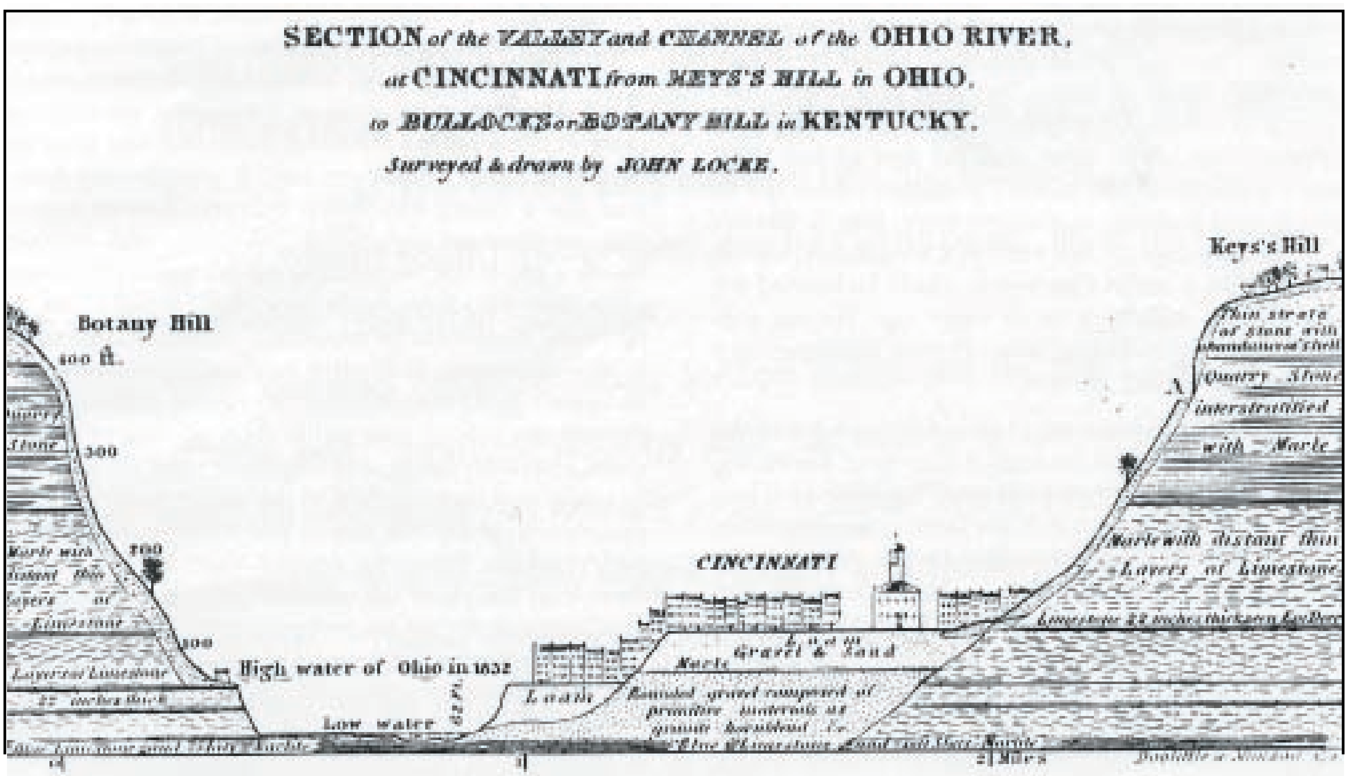


Figure 4. The first detailed geologic cross section published for the Cincinnati region shows both bedrock geology and its overlying unconsolidated glacial outwash much as we know it today (Locke, 1838, Plate 2). Keys Hill in Cincinnati is now called Mount Auburn and Botany Hill is Devou Park in Covington. Today, different names are used for these rock units, but Locke, a professor of chemistry, correctly saw their essential features much as geologists see them some 170 years later. The Quarry Stone Beds, today's Fairview and Bellevue Formations, were the principal material for stone walls, foundations, and piers, and the blue limestone is today's Point Pleasant Formation. Notice Locke's early recognition of colluvium (light stipple) mantling the bedrock. Reprinted with the permission of the Ohio Division of Geological Survey.

1876), who lived in Hamilton, Ohio. Other prominent amateurs were the James father and son, who had a bookstore; S.A. Miller (1836–1897), who published many papers; and E.O. Ulrich (1857–1944), who was born of Alsatian parents in Cincinnati, but early moved to Covington, Ky., where he had a laboratory. Ulrich published many papers and inspired many others to study the local fauna prior to his move to Washington, D.C., where he worked for the U.S. Geological Survey. Ulrich had no formal education in paleontology or geology, but was very influential in American stratigraphy.

August F. Foerste (1862–1936) deserves special mention. Born of German parents in Dayton, Ohio, he learned about fossils from Professor Orton of Ohio State University, studied at Denison and Harvard Universities, and studied postdoctorally in Europe with some of the most famous petrologists of his day: Rosenbusch and Osann at Heidelberg and Fouque and Lacroix at the College de France in Paris. He returned to Dayton in 1893 with a Ph.D., where he taught physics in a high school, but still found time to publish 135 papers on paleontology and stratigraphy and spend his summers on geological research—surely a model for all of us today. Another prominent Covington paleontologist inspired by Ulrich was John M. Nickels (1859–1945), who was the last of the well-known paleontologists of the Cincinnati school not to have formal training in paleontology. Ray S. Bassler (1878–1961), although not born in Cincinnati, spent all his formative years there, where he learned the joys of fossil collecting at an early age. He too was inspired by Ulrich. Bassler was a prolific publisher on a range of major fossil groups. N.S. Shaler (1841–1906), a prominent Harvard professor and the director of the Second Geological Survey of Kentucky, was born in Newport, Ky. Perhaps even better known was W.H. Twenhofel (1875–1957). He too had a strong interest in paleontology, but is better known for his early studies of sedimentation, both in North America and Europe, and for his pioneering books on this developing subject, which provided the standards of his time. Twenhofel was born on a farm near Covington, Ky., a property he later donated to the Kenton County School District, on which was located Twenhofel Junior High School.

Another prominent geologist from the Cincinnati region was Charles Schuchert (1858–1942), who was born in Cincinnati of German immigrants. He achieved worldwide recognition in the fields of paleontology, stratigraphy, and paleogeography and became a famous professor at Yale University. His formal education was only through the sixth grade, but his exposure to Cincinnati fossils and E.O. Ulrich were key elements in determining a most successful professional career. William H. Shidler (1886–1958), who was born in West Middletown in Butler County, Ohio, was also a successful geologist and teacher. He entered Miami University in 1904, founded its geology department in 1920, and retired from it in 1957. He was a great teacher and a great student of the Upper Ordovician, whose works include geologic maps of northern Kentucky plus several papers on the Cincinnati Arch and Cincinnatian paleogeography. Covington was also the birthplace of Charles F. Deiss (1903–1959), who, as a child, moved to Middletown, Ohio, and studied first at Miami University under Professor Shidler, and later at the University of Michigan. His early interest was paleontology, especially trilobites, which later expanded to the lower Paleozoic stratigraphy and mineral resources of the central and northern Rocky Mountains. In 1945 he returned to the Midwest and was head of the Department of Geology and State Geologist at Indiana University.

Clearly, the Greater Cincinnati region has produced an amazing number of American paleontologists. This is primarily because of its location astride a rich, diverse storehouse of interesting geology, all close at hand for the weekend naturalist and local geologist to study and appreciate. A contributing factor was also a strong 19th century German culture (Faust, 1927) that emphasized education, learning, and science, surely a key factor responsible for the many prominent geologists who have come from the region. In addition, there were far fewer entertainment alternatives in the 19th and early 20th centuries than there are today—no television, no videos, and much less printed matter—so that rather than passive entertainment, active diversion was necessary. And what would be easier and more natural to the intellectually inquisitive than to study the fossils and rocks of our region? And what was true more than 100 years ago remains true today: all of us in the Cincinnati region are fortunate to live in the Tri-State area with such a fascinating and accessible window to the past.

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# Geologic Evolution

The objective of "Geologic Evolution" is to set forth the geology of the three-state Cincinnati region, a region rich in fascinating geology, for all to see. Consider but a few questions. Why is the skyline, as seen from the region's many hills overlooking the Ohio River, so level? Why is Mill Creek Valley so wide, yet Mill Creek itself so small? Even better, how old is the Ohio River? Why does the Great Miami Valley have so many gravel pits and the Licking Valley so few? What is the origin of our famous hills? Why are there so many landslides on our hillsides? Or consider now the region's many outcrops: How did the interbeds of thin limestones and shales form? From where did the mud come to form these shales? Why are these limestones so rich in beautiful fossils? How old are the deepest known rocks under the Cincinnati region? And the large exotic boulders that we see at the junction of driveways and access roads—are these local? Why are the soils of Clermont County so different from those of Butler County? And finally, have far-distant events affected our region? At first glance, all these questions might seem to be totally academic. But in reality, many of the answers to these questions also have practical significance, which we will explore later in "Living and Working with Our Inheritance."

The geology of every city is easy to learn, and the geology of our Greater Cincinnati region—from its building stones to its fossils and bedrock to its landscape—is an easily accessible intellectual resource that provides great pleasure and stimulation for all to enjoy.

## Continental Position and Overview

The Cincinnati region lies within the Interior Arch and Basin Region of North America, a region of interior cratonic basins separated by broad regional arches, all of which are underlain by the Precambrian rocks of the North American craton (Fig. 5). Gentle regional tectonic stresses produced regional arches that separate the sedimentary basins of the craton from one another across most of North America east of the Rocky Mountains (Sanford, 1993, Fig. 10). In the Greater Cincinnati region, these Precambrian rocks are concealed by a thin sedimentary cover only 3,400 to 3,700 feet below the surface. The passive behavior of this craton for millions of years—subdued subsidence occasionally interrupted by gentle uplift along regional arches—is the key to understanding local geology. Such passive behavior is characteristic of a craton, a large old nucleus that forms the core of a continent. This Precambrian core of North America is called *Laurentia.* The larger unit, of which the craton is the core, is called the North American Plate.

Three arches (Fig. 6) occur in and near the Cincinnati/northern Kentucky/southeastern Indiana region—the Cincinnati, Findlay, and Kankakee—all of which are broad, have gentle dips, and were formed in the early Paleozoic, starting in the Late Ordovician or earliest Silurian. Ancient continental collisions along the eastern margin of the continent caused these arches. Along these arches, depth to bedrock is much less than in neighboring basins. The Cincinnati Arch separates the Appalachian Basin from the Illinois Basin, the Findlay Arch separates the Michigan Basin from the Appalachian Basin, and farther to the northwest the Kankakee Arch separates the Illinois Basin from the Michigan Basin. These arches, easy to drive over and miss, nonetheless all have great regional significance, mostly because they bring rocks of different ages and characteristics to the surface and because they influence the circulation of deep fluids.

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## Landscape

The Ohio River and its tributaries are the dominant factors responsible for the relief of the Greater Cincinnati region along with two important glacial events—the Wisconsinan and Illinoian ice sheets (Fig. 1). Collectively, these three factors have had more influence on our lives—economically, politically, and culturally—than any other aspect of the region's geology. To see this better, think how important topography is for land use: locations of roads, canals, railroads, and airports; flat areas for factories; parks and homes with a view; farming; and how the central basin of Cincinnati and Covington, with its Wisconsinan terraces above floodwaters, facilitated high ground safe for urban

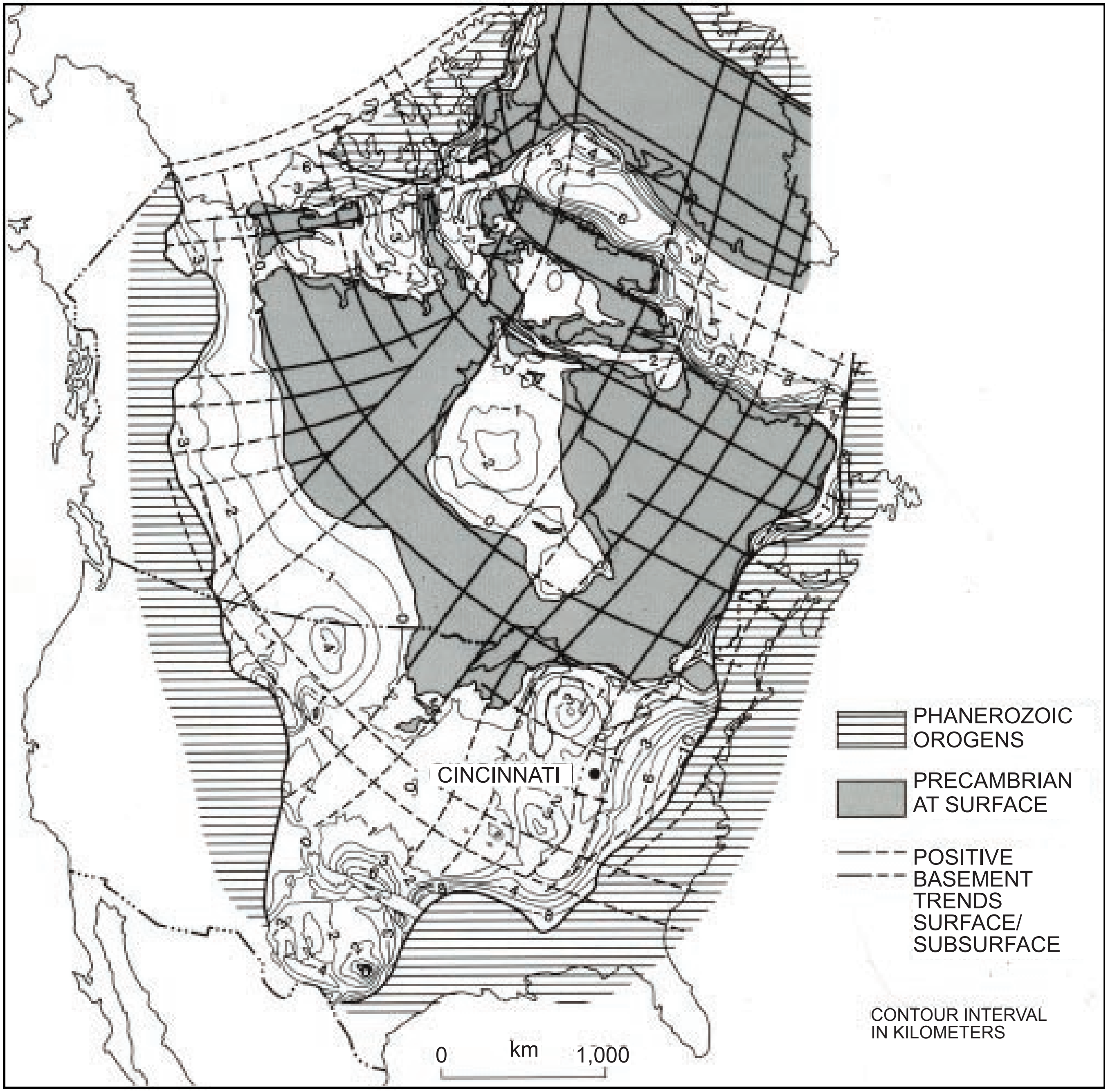


Figure 5. Cincinnati and its relation to the major units of the North American continent: the Precambrian Shield, the old core of the continent with its partial cover of Paleozoic sedimentary rocks, and two bounding orogenic belts. These orogenic belts are mountain chains caused by continental collisions during the last half billion years. The black trend lines (northeast–southwest and northwest–southeast) enclose interior basins such as the nearby Illinois and Appalachian Basins, which are separated by arches such as the Cincinnati and Findlay Arches. Collectively, this entire region is called the North American Plate. From Sanford and others (1985, Fig. 3). Reprinted with the permission of the Canadian Society of Petroleum Geologists.

growth, yet was still near the Ohio River. Thus, since the earliest times, the hills of the Greater Cincinnati region have affected us in many ways—mostly for the best, although there are some negatives too (Table 1). Among the positives is one that is all too easy to forget. During the early part of the Civil War, it was necessary to protect northern Kentucky and Cincinnati from Confederate armies—the dissected topography

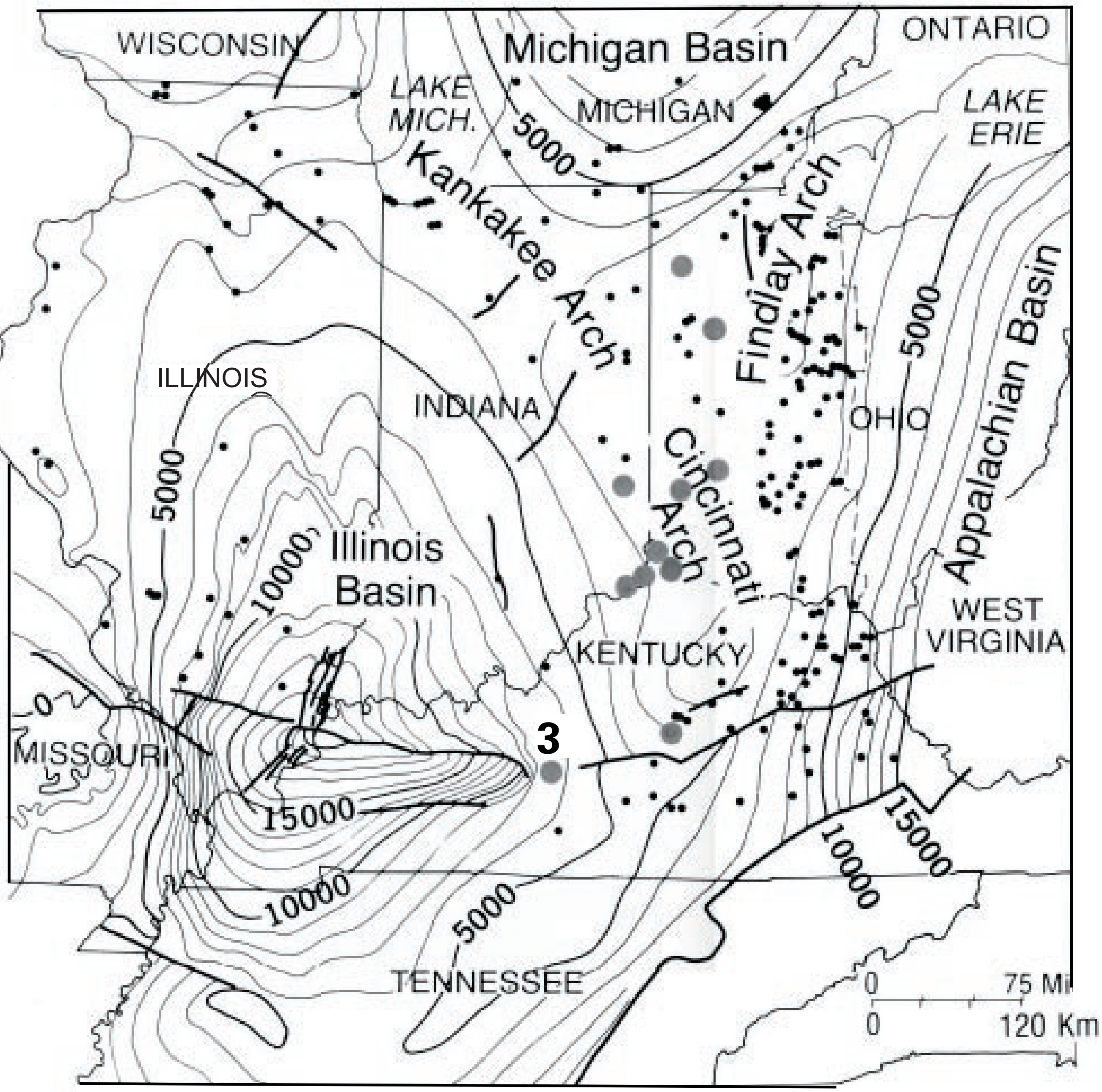


Figure 6. Elevation of the top of the Precambrian basement. Notice the shallower depths to basement along the axes of the two regional arches—the Cincinnati and Findlay—which separate the Illinois Basin from the Appalachian Basin. Large circles represent wells that encountered the newly discovered Middle Run Formation of Precambrian age. The “3” above the well symbol in west-central Kentucky indicates three closely spaced Precambrian wells. After Rudman and Rupp (1993, Fig. 1); reprinted with the permission of the Indiana Geological Survey.

of Campbell and Kenton Counties greatly facilitated the defense of our region (Fig. 7).

First, let’s begin our study of the landscape of the Greater Cincinnati area by recognizing its four distinct subregions beginning in the north (Table 2).

### *Four Principal Landscape Regions*

In Warren and Butler Counties, Ohio, Wisconsinan glacial deposits of the Wisconsinan till plain make the most fertile soils—loamy and calcareous—and wider areas of subdued relief for two reasons. First, with the exception of the southeastern part of Warren County, both counties have been exposed to weathering for only 19,000 years or less, and second, both are farthest in the Tri-State area from the Ohio River. And only in these two counties are there clearly defined, easy-to-see glacial end moraines and a few kames. Here, Wisconsinan glaciation diverted both the Great and Little Miami Rivers and part of Caesar Creek to form narrow valleys—one 8 miles long near Fort Ancient in Warren County and the other some 10 miles long from New Baltimore to Cleves in western Hamilton County, Ohio (Fig. 8A).

**Table 1.** Positives and negatives of our hills (adapted from Smale, 1988). Reprinted with the permission of the Hillside Trust.

*Positives*

- Wooded hills keep us in touch with nature.
- They provide many beautiful parks and homes with a view.
- They shelter wildlife (but see below).
- They help avoid the monotony of a uniformly gridded, “flatland” city.
- They favor small government enclaves, each with local character and institutions.
- They facilitated the defense of Cincinnati during the Civil War.
- Formerly, the many deep gullies and ravines of these hills provided a convenient place for household trash.

*Negatives*

- They make construction of all kinds more expensive.
- They cause most of our landslides.
- They favor many small municipalities rather than county-city governments.
- They lead to too many deer (which destroy vegetation and collide with cars and trucks).
- The roads require extra attention on icy days.
- The irregular road grid makes giving directions to strangers difficult.

In Clermont and parts of Hamilton and Warren Counties is another, older glacial landscape, the Illinoian till plain, formed by the Illinoian ice sheet. This is flatter, more deeply leached, less well drained, and less fertile than the Wisconsinan till plain, because it has been exposed to weathering about six times longer—since the beginning of the Sangamonian interglacial about 125,000 years ago.

In parts of Switzerland, Ohio, and Dearborn Counties in Indiana, the Dearborn Upland is broadly similar to the landscape of the Illinoian glacial deposits of Clermont County, Ohio—flat, leached, and poorly drained, although here glacial deposits are thinner and scattered and thus may even be pre-Illinoian in age. Thus, we can think of both regions as pre-Wisconsinan drift plains that have markedly lower fertility and more waterlogged soils than the loamy, calcareous soils of the Wisconsinan glacial deposits to the north. Together the Wisconsinan and Illinoian landscapes and the Dearborn Upland belong to the Interior Lowland Physiographic Province that extends across much of the Midwest.

The Outer Bluegrass landscape is part of the Interior Low Plateaus Province, which everywhere bor-

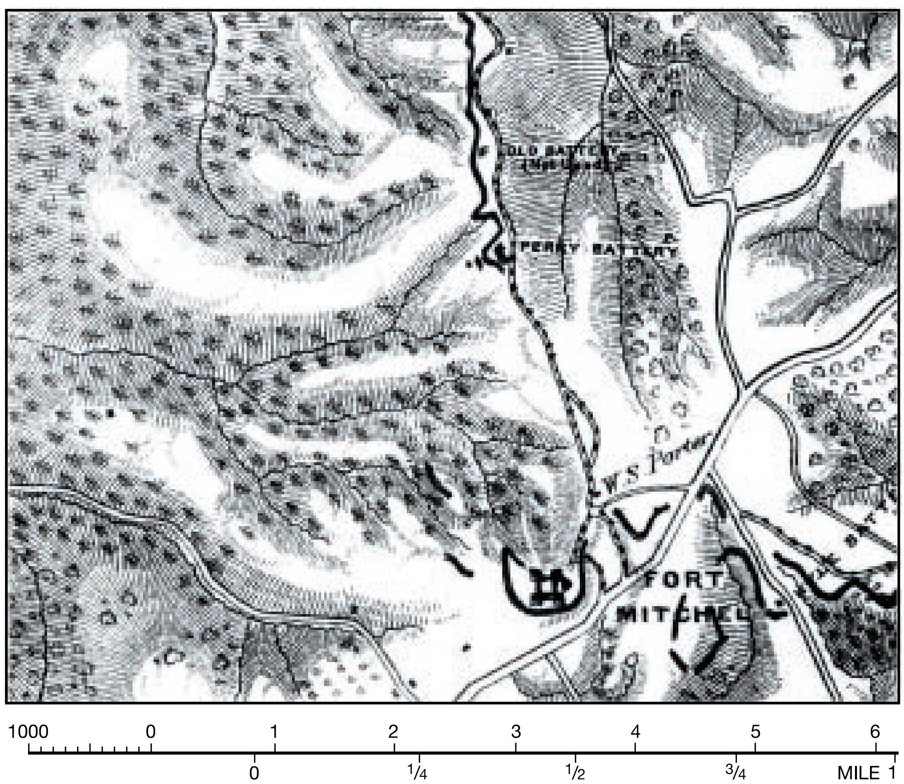


Figure 7. Defense of Cincinnati and northern Kentucky in 1861–62 (Simpson, 1864). Because of threatened attacks by Confederate armies in central Kentucky, a fortified line was constructed by Union troops looping across parts of Campbell and Kenton Counties. This line consisted of strong points (forts and batteries) located on high ground overlooking steep valleys with trees felled downslope (abatis) to slow enemy infantry advance. The Civil War Fort Mitchell is near present-day exit 191 of I-75 and I-71 in Fort Mitchell, Kenton County. Notice how these fortifications make full use of local topography and imagine how much easier the defense of Cincinnati was compared to a flatland city such as Columbus.

**Table 2.** Four different landscapes of the Greater Cincinnati region (adapted from Brockman, 1998; Woods and others, 1998, 2002; Gray, 2001). Reprinted with the permission of the Ohio Division of Geological Survey and the Indiana Geological Survey.

| | |
|---|---|
| *Wisconsinan till plain* | Level to weakly rolling till plain and end moraines plus glacial outwash in shallow to moderately entrenched valleys of the Great Miami, Little Miami, and Whitewater Rivers. Glacial till, thin to moderately thick, has loamy calcareous soils with good tilth and internal drainage. Water supply is best in present and buried valleys, some up to 260 feet deep. Typical soils are Russell-Miamian-Xenia-Wynn developed on gently sloping to flat surface. Landscape is 19,000 years old and younger. Part of Central Lowland Province. |
| *Illinoian till plain (Sangamonian landscape)* | Flat, deeply leached till plain with thick fragipan that impedes tree roots and downward flow of water. Few entrenched valleys except for East Fork and tributaries to the Ohio River. Groundwater restricted to household needs except for East Fork valley. Typical upland soils are Clermont and Rossmoyen Series. Locally known as the Pin-Oaks-Crawfish Flats region; there are many similarities to the Muscatatuck Plateau of Indiana. Landscape dates from the beginning of the Sangamonian interglacial about 125,000 years ago. Part of Central Lowlands Province. |
| *Dearborn Upland* | Flat, poorly drained landscape with thin, deeply leached soils plus minor loess and some thin tills. Well-developed fragipans restrict soil drainage (many crawfish castles). Groundwater resources sufficient only for single homes. Locally known as the Muscatatuck Flats. Typical upland soil series is Avonburg, much like Clermont Series. Initial landscape dates from Miocene with minor modification by pre-Illinoian glaciation. Part of Central Lowland Province. |
| *Outer Bluegrass* | Moderate to steep slopes except along narrow divides and valley bottoms of Ohio, Licking, and Whitewater Rivers. Northern limits have some glacial deposits: pre-Illinoian in northern parts of Boone, Campbell, and Kenton Counties; Illinoian till in tributaries to the Ohio in Clermont and Hamilton Counties; and thick glacial outwash along Ohio, Miami, and Whitewater Rivers with backwater fill along the Licking River. Entrenched rivers and some sinkholes. Ample groundwater only in larger valleys. Typical soils on slopes are Eden Series and Huntington Series in large valleys. Initial landscape dates from Middle to Late Miocene, 5 to 15 million years ago, with significant and repeated Pleistocene modifications. Part of Interior Low Plateaus Province. |

ders the Greater Cincinnati area on the south and is present in all counties except Warren and Butler. Its landscape is all in slopes except for the floodplains of the Ohio, Miami, Licking, and Whitewater Rivers and some narrow divides in northern Kentucky (Fig. 8C). This landscape occurs north of the Ohio River in parts of Clermont, Hamilton, Dearborn, Ohio, and Switzerland Counties, because of the deep entrenchment of the Ohio River, called the Deep Stage. This entrenchment occurred before Illinoian glaciation (as shown by Illinoian glacial deposits in these valleys). The steepest slopes of the region—some up to 36 percent—occur on the hillsides bordering the Ohio, Licking, and Great Miami Rivers at the outside of meander bends in the Outer Bluegrass subregion.

Elevations throughout the area (Table 3) range between 420 feet (pool stage of the Ohio River in Gallatin and Switzerland Counties) to as high as 1,102 feet in Butler County (high bedrock capped by glacial till). Elevations of most of the upland range between 870 and 930 feet, except for narrow tributary divides close to the Ohio River, which are somewhat lower. The level skyline of this upland truncates gently dipping geologic formations across the Cincinnati Arch, and many years ago was termed the *Lexington Peneplain* by Fenneman (1938, p. 441).

### Landscape Evolution

The origins of the landscape of the Greater Cincinnati region take us far outside the 11 counties of the region and far back in time, as much as 15 to 20 million years or more. Two University of Cincinnati geologists pioneered the study of our landscape—Nevin M. Fenneman (1865–1945) and Richard Durrell (1914–1994). Fenneman was a nationally recognized professor who studied landscape (physiography) and its evolution across all the United States and published in 1916 the first study of the geology of Cincinnati. Durrell was also a dedicated teacher who studied landscape and in addition was a pioneer in the local conservation of both our landscape and nature. Both trained many students who contributed much to the following discussion.

Our landscape story begins at the end of the Paleozoic Era when the Alleghany Orogeny formed the Appalachian Mountains and tilted most of Ohio, Kentucky, and parts of Indiana to the northwest about 250 million years ago (Judson, 1975). This initial drainage system is long vanished, of course, but there is good evidence for it in the old Teays drainage of late

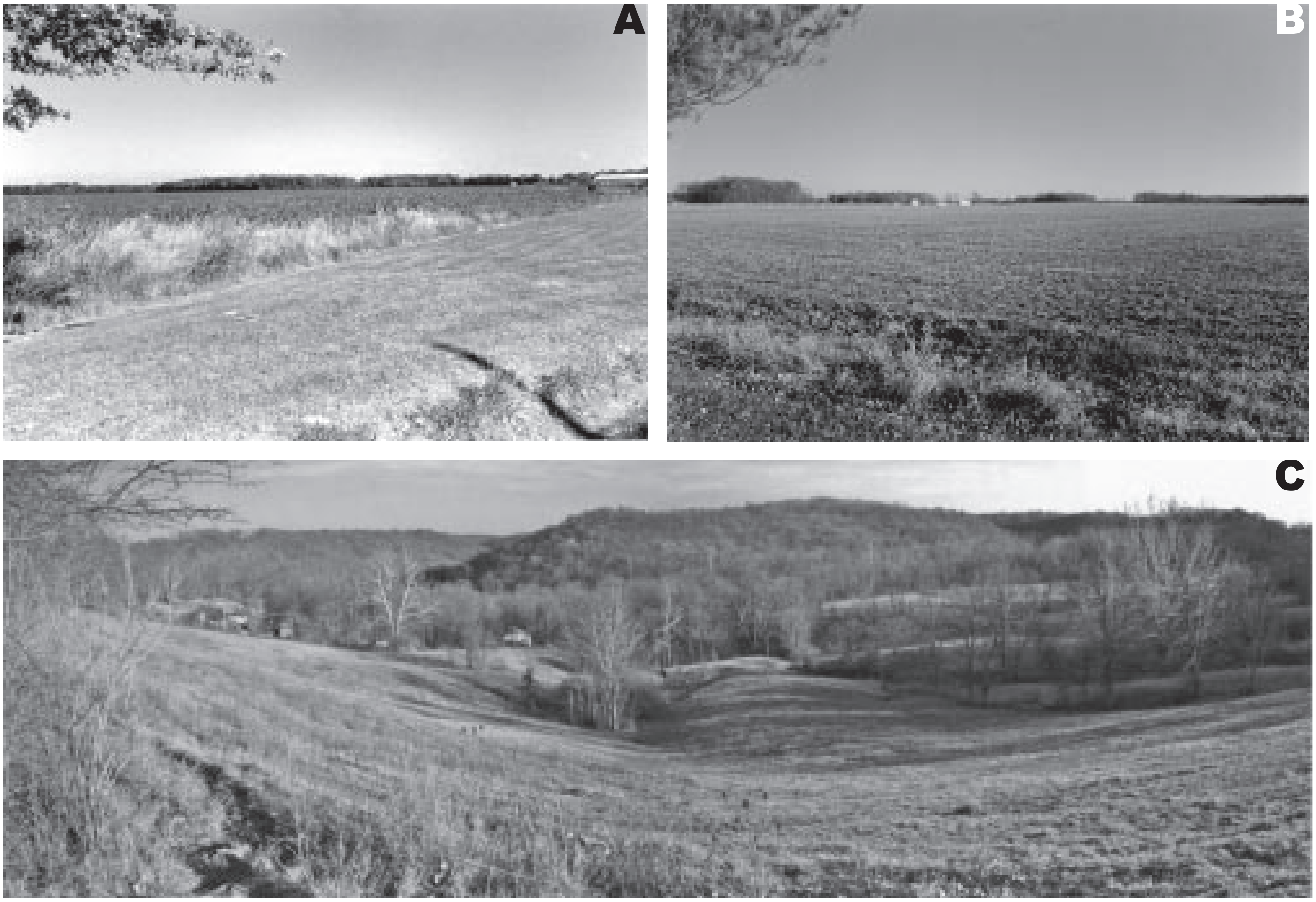


Figure 8. Three representative landscapes of the Greater Cincinnati region. (A) Flat landscape with high water table developed on Illinoian till in northern Clermont County. (B) Similar landscape of the Dearborn Upland near Avonburg in northern Switzerland County. (C) Slopes of the Outer Bluegrass along Banklick Creek, as seen from Ky. 1829 in Kenton County.

**Table 3.** Maximum and minimum surface elevations of counties in southwestern Ohio, northern Kentucky, and southeastern Indiana.*

| | Highest | Lowest |
|---|---|---|
| Boone | *964 | **455 |
| Butler | 1,102 | 532 |
| Campbell | 920 | **455 |
| Clermont | 973 | **455 |
| Dearborn | 1,041 | **455 |
| Gallatin | 920 | ***420 |
| Kenton | 960 | **455 |
| Hamilton | *962 | **455 |
| Ohio | 911 | **455 |
| Warren | 1,065 | 538 |
| Switzerland | 983 | ***420 |

*The Rumpke landfill in Hamilton County reached 1,064 feet and the Bavarian landfill in Boone County reached 920 feet in 2007.

**Pool stage of McAlpine Dam near Vevay, Switzerland County, Ind.

***Pool stage of dam at Louisville, Jefferson County, Ky.

Tertiary age (Hansen, 1987; Teller and Goldthwait, 1991) in West Virginia, Ohio, Indiana, and westward into Illinois (Fig. 9). Although Pleistocene glacial deposits now bury most of this drainage system, top-of-rock maps made from well records drilled for both groundwater resources and engineering geology can easily delineate its valleys. Beyond the limits of glaciation, Teays drainage can be reconstructed by study of landscape, as was done by Fenneman (1916, 1938), Barbour (1957), and Durrell (1977). See “Digging Deeper” for the long history of these studies. The summary of drainage evolution that follows is chiefly based on the work of Schneider (1966), Durrell (1977), Luft (1980), and Swadley (1971).

Our starting point in time is early middle Miocene time, about 15 million years ago. At this time, an old erosion surface, the Lexington Peneplain, had slow, low-gradient streams (ancestral Kentucky and Licking Rivers) flowing to the north in shallow, wide valleys. Worldwide, late Miocene uplift rejuvenated these streams and their tributaries, eroded the old weath-

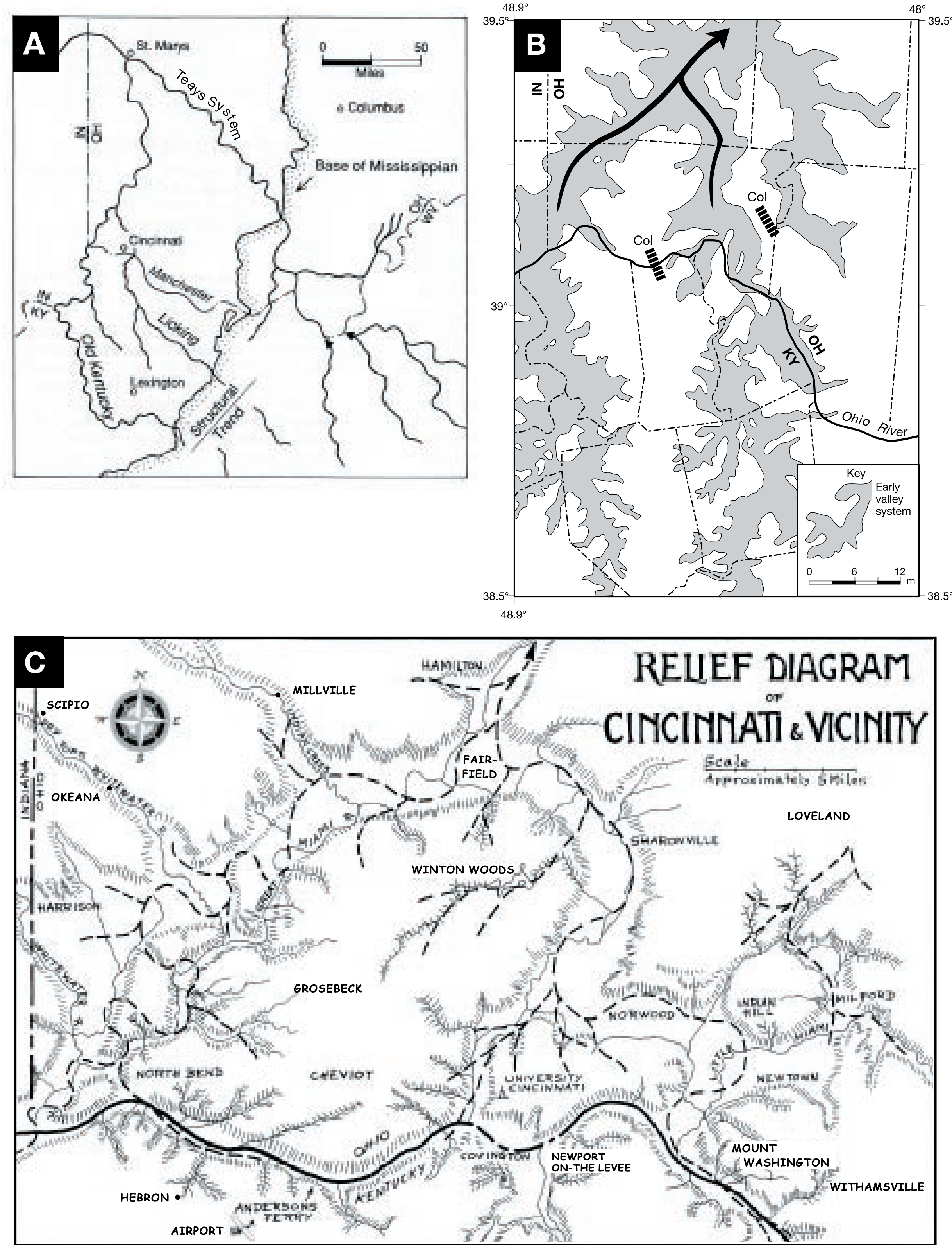


Figure 9. Preglacial Teays drainage. (A) Regional network. (B) Professor Durrell's (1961) drainage interpretation for southwestern Ohio, northern Kentucky, and southeastern Indiana. After Durrell (1961, Fig. 2). Reprinted with the permission of the Geological Society of America. A col is an abandoned divide. (C) Barbour's (1957) physiographic map. Reprinted with the permission of the University of Cincinnati Department of Geology.

ered deposits of regolith that mantled the peneplain, and redeposited them as quartz-rich sands and gravels along major streams, as shown by a few surviving deposits (Claryville Clay and the more distant Irvine and Lafayette Gravels of Kentucky). At this time the ancestral Licking and Kentucky Rivers joined near Hamilton, and a segment of the present Ohio, now called the Manchester River, had its headwaters not too far upstream from Maysville, Ky. All three were tributaries to the Teays system (Figs. 10–11). The first Pleistocene ice in our area blocked the north-flowing Kentucky and Licking Rivers and diverted them southwestward via Harrison, Cleves, and Carrollton to form a new single river, the present Ohio. Thus, early Pleistocene glaciers began the process of disassembling the preglacial Teays system and forming the ice-margin Ohio River, with its different segments of different ages. The Illinoian ice sheet completed most of this process when it blocked the ancestral Ohio in the Norwood Trough and Mill Creek Valley, causing the ancestral Ohio and Licking to flow westward through the narrows of Anderson Ferry instead of looping around to the north (Fig. 9B). As noted above, later smaller diversions by Wisconsinan ice formed a narrow valley below New Baltimore in western Hamilton County, the narrow valley of the Little Miami near Fort Ancient, and nearby in Caesar Creek in Warren County. Both large and small north-flowing rivers and tributaries to the Teays became lakes as they were dammed by ice and lake clays accumulated in slack water (see "Surface Processes," p. 74, for the significance of these clays for construction).

Now that we have an insight into the regional evolution of drainage in the Greater Cincinnati region, let's look more closely at cross sections of the Ohio River as it flows 118 miles from eastern Clermont County to far western Switzerland County (Fig. 12). The contrasting cross sections of Figure 12 illustrate many key points about the Ohio River and its valley. Valley widths in our region vary from less than a mile at Anderson Ferry to more than 1.5 miles at Rising Sun. At Anderson Ferry (Fig. 13) there are almost no floodplains and both valley walls are steep, whereas the Ohio's valley at Melbourne, Rising Sun, Upper East Bend, and Warsaw is much wider and terrace deposits are present. These four cross sections illustrate well the differences between the cut and aggrading sides of a meandering stream. At the cutbank, the river flows against the valley wall and erodes it, whereas on the opposite aggrading bank currents are weaker, deposition occurs, and a floodplain is bounded by higher terraces that do not flood. The outside cutbank results from erosion at flood stage, a process that easily trims back and removes colluvium and slump deposits that slide into the river, especially during wet weather (see "Surface Processes," p. 74). Note too that where the river impinges the valley wall, slopes are steeper than slopes on the opposite inside of the valley; it is here too, as you drive along Ky. 8, Ind. 56, or U.S. 52 and U.S. 42, that you see highway departments constantly fighting the Ohio River.

We also observe that below Anderson Ferry the valley of the Ohio River is wider than above Anderson Ferry. Three factors seem to be involved here. Possibly the most important factor was Wisconsinan and Illinoian meltwater (the Great Miami River delivered more than the Little Miami River, and Illinoian meltwater flooded downstream through Anderson Ferry). A second factor is the ancestral Kentucky River—the wide valley of the Ohio below Anderson Ferry is partially inherited from the ancestral north-flowing Kentucky River. In contrast, the cross sections at Melbourne and Fort Thomas are both from a short segment of the ancestral Ohio, the Manchester River, which had its headwaters near Manchester, Ohio, above Maysville, Ky.

What can be said about the large floodplains and terraces (locally called *bottoms)* of Cincinnati and Covington-Newport-Dayton and at the mouths of the Great and Little Miami Rivers (Fig. 2)? All three streams in those valleys formerly had greater discharge when Illinoian and Wisconsinan ice melted, and all three occur at river junctions—the Licking-Ohio, the Ohio–Great Miami, and the Ohio–Little Miami. Quite possibly these valley junctions are wide because valley spurs near a junction can be eroded and trimmed from both sides. Think of the narrow remnant peninsula that forms Shawnee Lookout County Park in southwestern Hamilton County.

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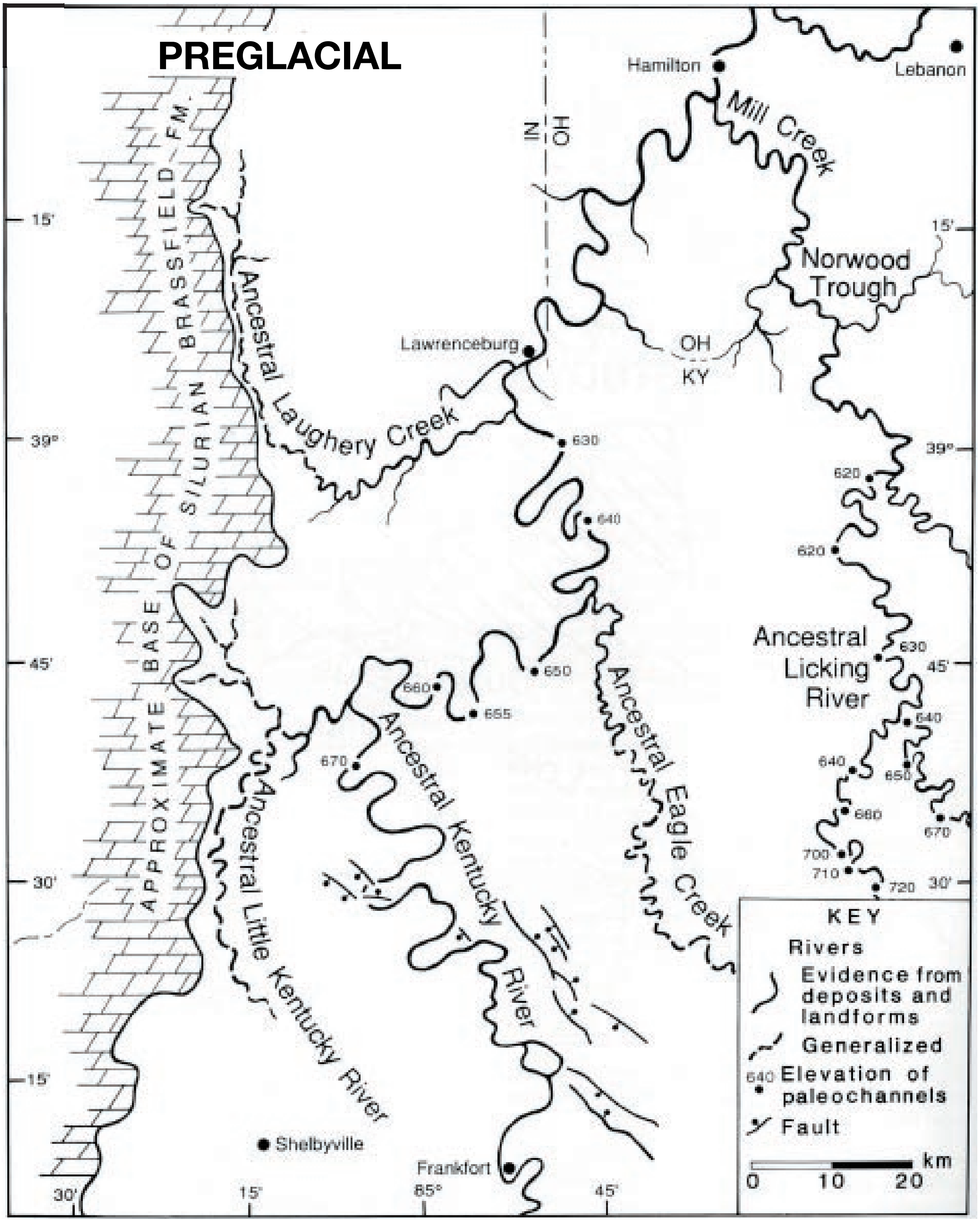


Figure 10. Preglacial drainage, looking south across our region from Hamilton (after Swadley, 1971; Luft, 1980). Note cols below Madison, Ind. (Madison was the headwaters of the lower preglacial Ohio River), at Anderson Ferry (diversion by Illinoian ice), and just adjacent to Cincinnati (also Illinoian ice?).

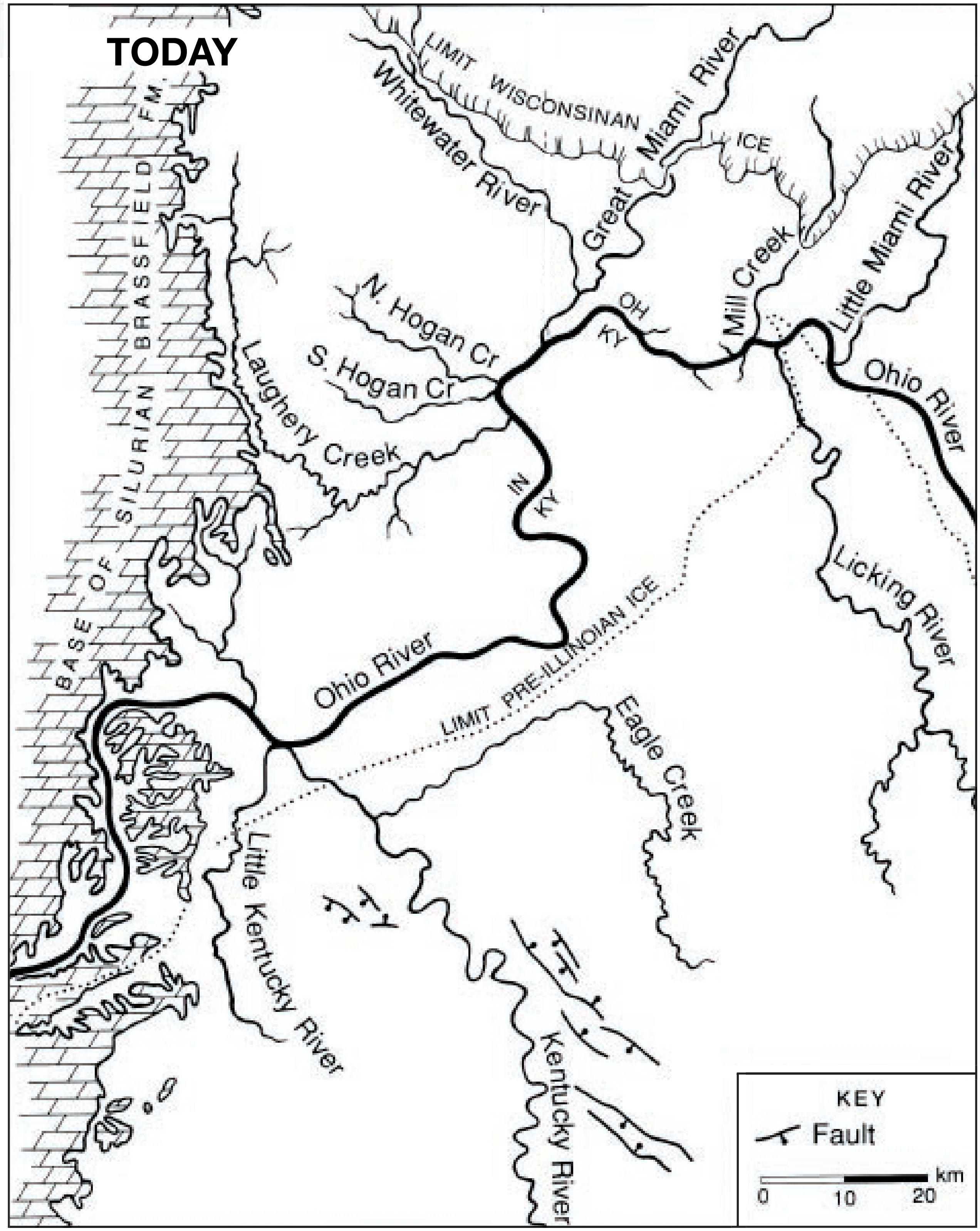


Figure 11. Today's drainage, looking south across our region from Hamilton.

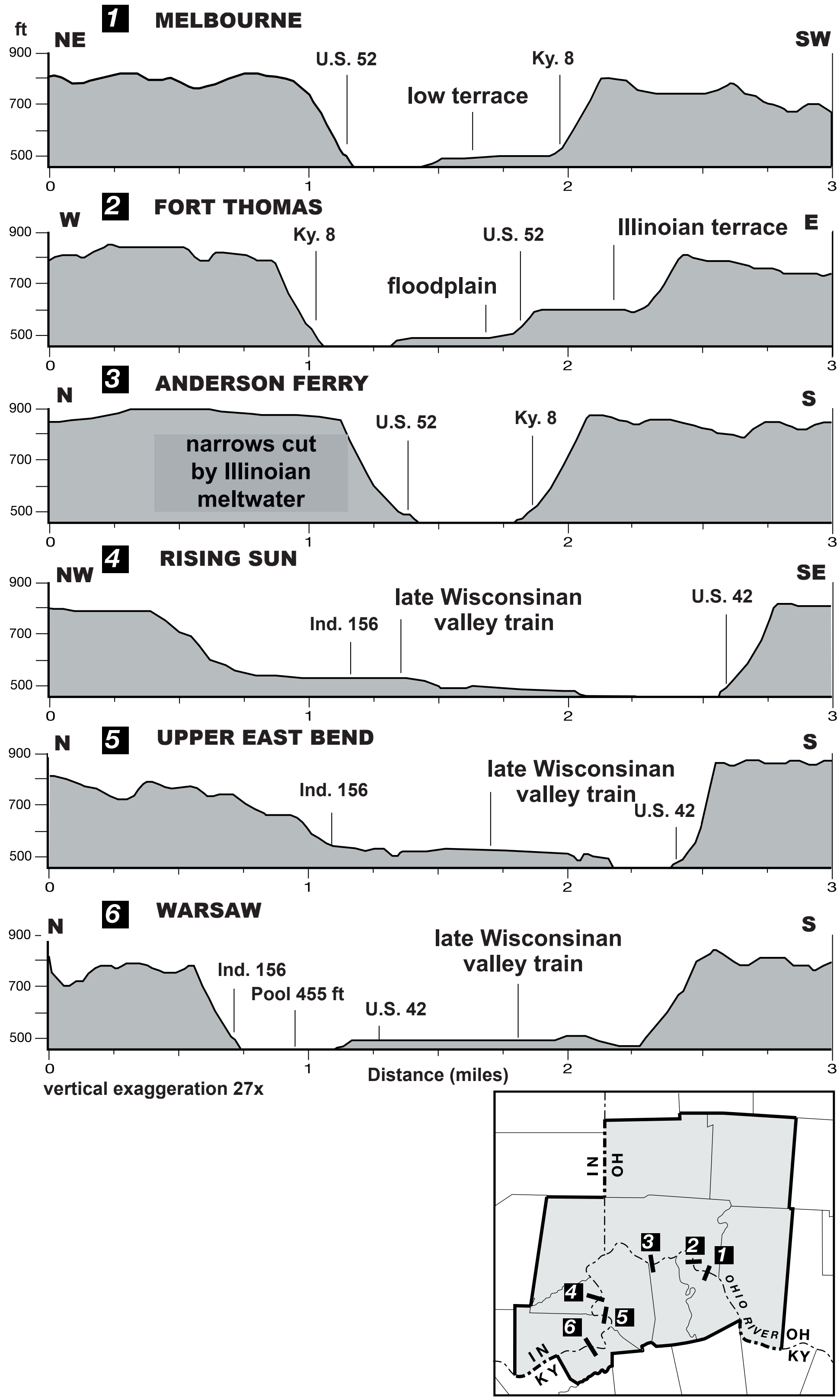


Figure 12. Cross sections of the Ohio River vary greatly from the steep, symmetrical narrows at Anderson Ferry (Illinoian diversion) to asymmetrical valleys with wide floodplains and terraces at Vevay, Upper East Bend, and Rising Sun, Ind.

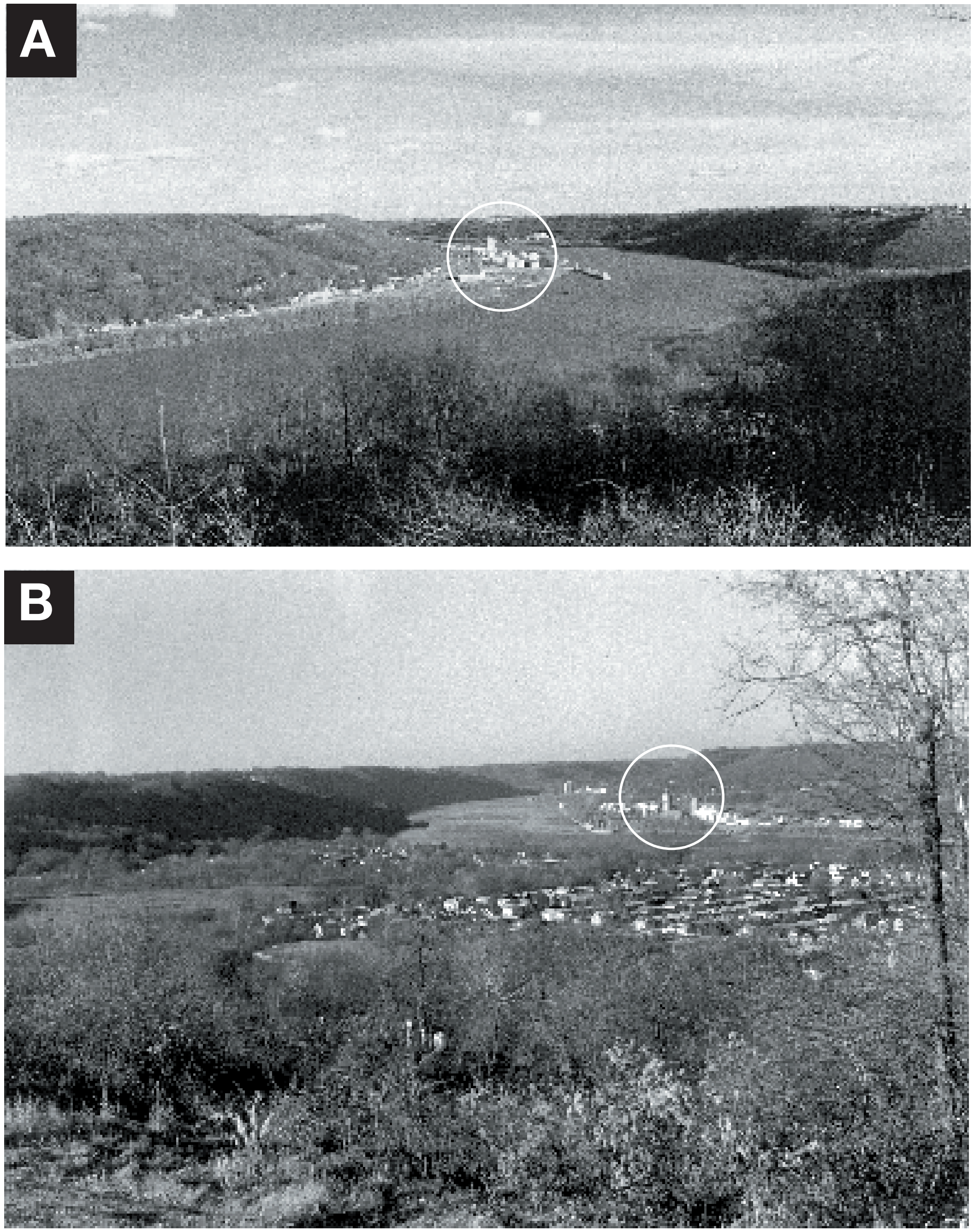


Figure 13. Narrows at Anderson Ferry. (A) Looking upstream and east. (B) Looking downstream and west from River's Breeze condominium in Ludlow, Kenton County, Ky. Circled silo is common point on both photographs.

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### *Digging Deeper*

Brockman, C.S., Larsen, G.E., Pavey, R.P., Schumacher, G.A., Shrake, D.L., Slucher, E.R., Swinford, E.M., and Vorbau, K.E., 2003, Shaded bedrock topography map of Ohio: Ohio Division of Geological Survey Map BG-3, scale 1:500,000.

This brilliantly colored, detailed map of the bedrock surface of Ohio has brief text and four colored supplementary maps.

Bunner, D.W., Jr., 1993, Bedrock surface altitude in the Midwestern Basins and Arches Region of Indiana, Ohio, and Michigan: U.S. Geological Survey Water-Resources Investigation Report 93-4050, scale 1:750,000.

This map covering west-central Ohio and east-central Indiana shows that the Teays drainage connects across the two states.

Durrell, R.H., 1977, A recycled landscape: Cincinnati Museum of Natural History Quarterly, v. 14, p. 8–15.

This well-illustrated, easy-to-read account by a longtime Cincinnati professor, world traveler, and lover of nature says it all in a few pages.

Dusablon, M.A., 1998, Walking the steps of Cincinnati: Athens, Ohio University Press, 165 p.

Subtitled "A Guide to the Queen City's Scenic and Historic Secrets," this guide details 35 walks with stairs, each with a brief description and map.

Fowke, G., 1933, The evolution of the Ohio River: Indianapolis, Hollenbeck Press, 284 p.

Late in his long life (1855–1933), Gerard Fowke took up residence in Madison, Ind., and wrote this book, which was later published by a friend. It is a fascinating, easy-to-read book that describes the topography, rivers, and creeks of much of the Ohio River Valley, and provides the reader with an integrated account of the river's present drainage. See Fowke's Figure 30 for his concept of preglacial drainage in the Cincinnati region.

Jackson, M.T., ed., 1997, The natural heritage of Indiana: Bloomington, Indiana University Press, 482 p.

This beautiful volume has six parts—a discussion of Indiana's terrain and its origins (15 papers) and the natural regions of Indiana (southeastern Indiana lies in both the Outer Bluegrass Region of Kentucky and the Muscatatuck Plateau).

Malott, C.A., 1922, The physiography of Indiana, *in* Logan, W.N., Cumings, E.R., Malott, C.A., Visher, S.S., Tucker, W.M., and Reeves, J.R., Handbook of Indiana geology: Indiana Department of Conservation, Division of Geology, Publication 21, pt. II, p. 59–256.

Interesting discussions of streams includes Laughery Creek between Ohio and Dearborn Counties.

McFarlan, A.C., 1958, Behind the scenery in Kentucky: Kentucky Geological Survey, ser. 9, Special Publication 10, 144 p.

This classic, popular, abundantly illustrated account is by a well-known professor at the University of Kentucky who devoted much of his professional life to the geology of Kentucky.

McGrain, P., and Currens, J.C., 1978, Topography of Kentucky: Kentucky Geological Survey, ser. 10, Special Publication 25, 76 p.

This unique report summarizes the topography of each country in Kentucky, its highest and lowest points, and provides the agriculturist, engineer, planner, sportsman, and tourist with a great wealth of information. For example, Boone, Campbell, and Kenton Counties all have the same lowest point, 455 feet, but the highest point of the three is in Boone County, at 964 feet.

Ohio, Kentucky, Indiana Regional Council of Governments, undated, Drainage patterns, OKI region: OKI, scale 1:120,000.

This map denotes major and minor divides and floodprone areas plus streams and their watersheds, many of which are named.

Schiff, T.R., 2005, Panoramic parks: Cincinnati, Lighthouse Publishing, 122 p.

Cincinnati is a city of parks, most of which are located on hills with a view—all the result of old Teays, north-flowing drainage. Over 100 panoramic colored pictures capture the contribution of more that 70 parks administered by the Cincinnati Park Board to our city's well-being.

Teller, J.T., and Goldthwait, R.P., 1991, The old Kentucky River; a major tributary to the Teays River, *in* Melhorn, W.N., and Kempton, J.P., eds., Geology and hydrology of the Teays-Mahomet bedrock valley system: Geological Society of America Special Paper 258, p. 29–41.

This thoughtful analysis is well worth reading.

Woods, A.J., Omernik, J.M., Brockman, C.S., Gerber, T.D., Hosteter, W.D., and Azevedo, S.H., 1998, Ecoregions of Indiana and Ohio: U.S. Geological Survey, scale 1:1,500,000.

The Greater Cincinnati region lies in national ecoregions 55 (Eastern Corn Belt Plains; six subdivisions) and 71 (Interior Plateau; four subdivisions). Well-illustrated, short descriptions of the surface environment are a great reference for planners, teachers, naturalists, and the general public.

Woods, A.J., Omernik, J.M., Martin, W.H., Pond, G.J., Andrews, W.M., Call, S.M., Comstock, J.A., and Taylor, D.D., 2002, Ecoregions of Kentucky: U.S. Geological Survey, scale 1:1,000,000.

Six major ecoregions are recognized with more than 20 subdivisions, each with a short, illustrated summary. It contains over 80 references and a summary table. Compare it with Woods and others (1998) for Indiana and Ohio. Both are outstanding.

## Bedrock

The consolidated rocks of the Cincinnati region, known as the *bedrock*, consist of formations that are exposed in creeks and roadcuts and others that are totally buried and known only from deep wells, most of which were drilled for petroleum (Figs. 14–15). More recently, seismic cross sections or images have added greatly to our knowledge. Knowledge of the bedrock is useful for many reasons: Foundation engineers need to know how rock properties vary from one formation to another and how soils developed from some geological formations differ with respect to slumping, sliding, and drainage compared to others, so we need to identify and map their distribution before construction (or perhaps avoid building upon them entirely). In addition, water quality and yield vary from one bedrock formation to another, as does the chemical composition of limestones, some of which are used by industry and for construction. For most of the 19th century, bedrock used for building stone was largely obtained locally, some rock formations being more desirable than others.

When both the buried and outcropping units are considered, the span of the geologic history of the Cincinnati region extends backwards—with many gaps—more than a billion years.

### *Subsurface Formations*

In many ways the buried rocks of any area are much more important than those seen in outcrop. Buried rock formations always represent a far greater volume; they nearly always contain important economic resources, especially when groundwater is included; and our understanding of them always leads us to a greatly expanded view of the geologic history. Thus, knowledge of subsurface geology is an important part of the study of every urban area, especially for the Cincinnati region. The first comprehensive subsurface study of the region was made by Fuller and Clapp in 1912.

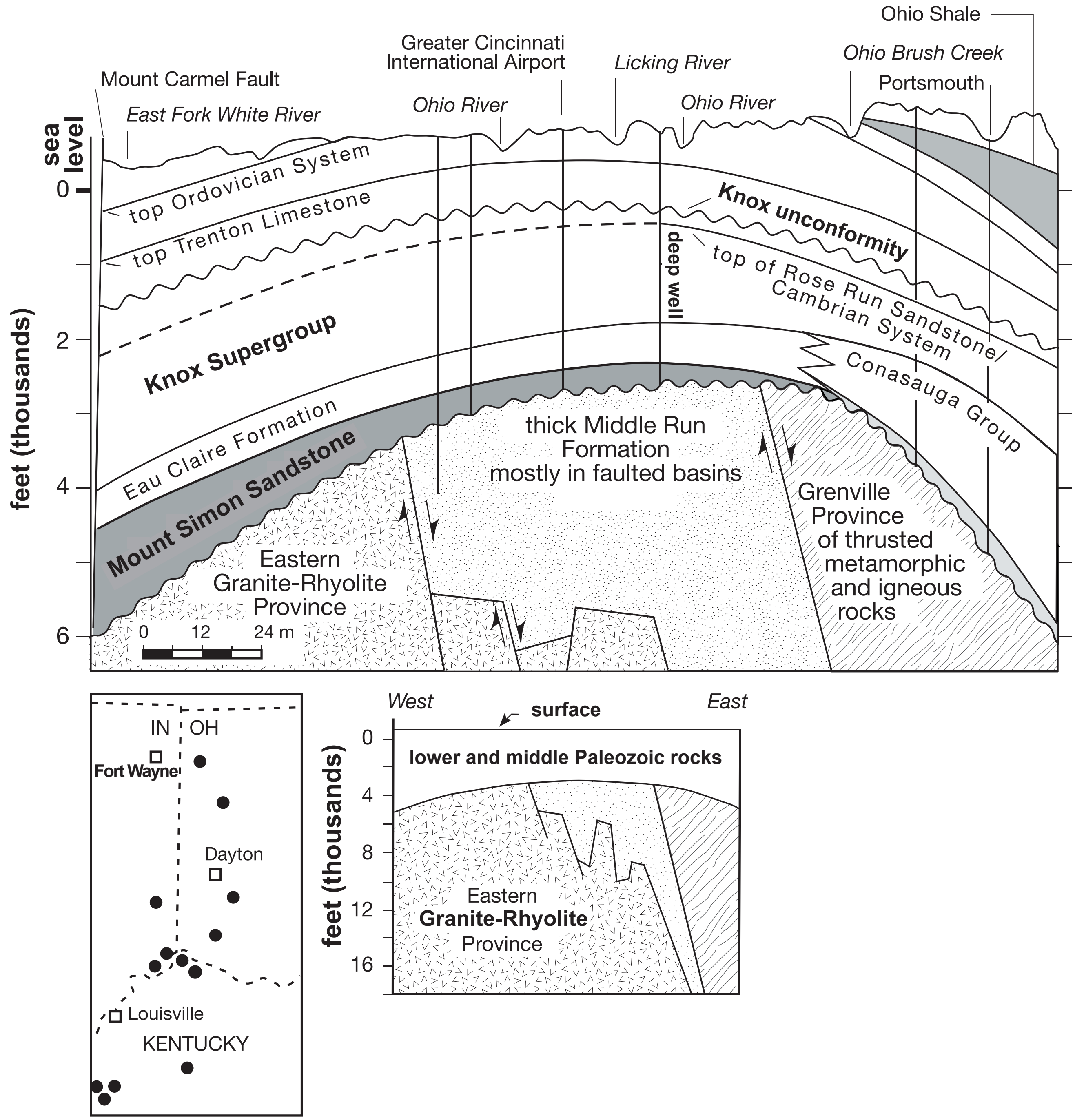


Figure 14. Cross section of the Paleozoic and Precambrian rocks of the Cincinnati Arch region. After Hansen (1996). Reprinted with the permission of the Ohio Division of Geological Survey.

### *Precambrian*

The Precambrian represents all the geologic time before 570 million years ago, or about 80 to 90 percent of all geologic time. Here in the Cincinnati region, Precambrian rocks seem to come from the latest part of this vast time span, called the Proterozoic Eon. The deep basement geology of Ohio, Indiana, and Kentucky has been studied using knowledge gained from deep wells plus that gained from regional geophysical studies: gravity and magnetic surveying and seismic reflection (Fig. 16). This last technique provides seismic images, which are particularly valuable for studying the deeply buried geology, because they show more details of its layering. Seismic studies since 1985 have revolutionized knowledge of the deep basement rocks of the Cincinnati region. Although our knowledge is

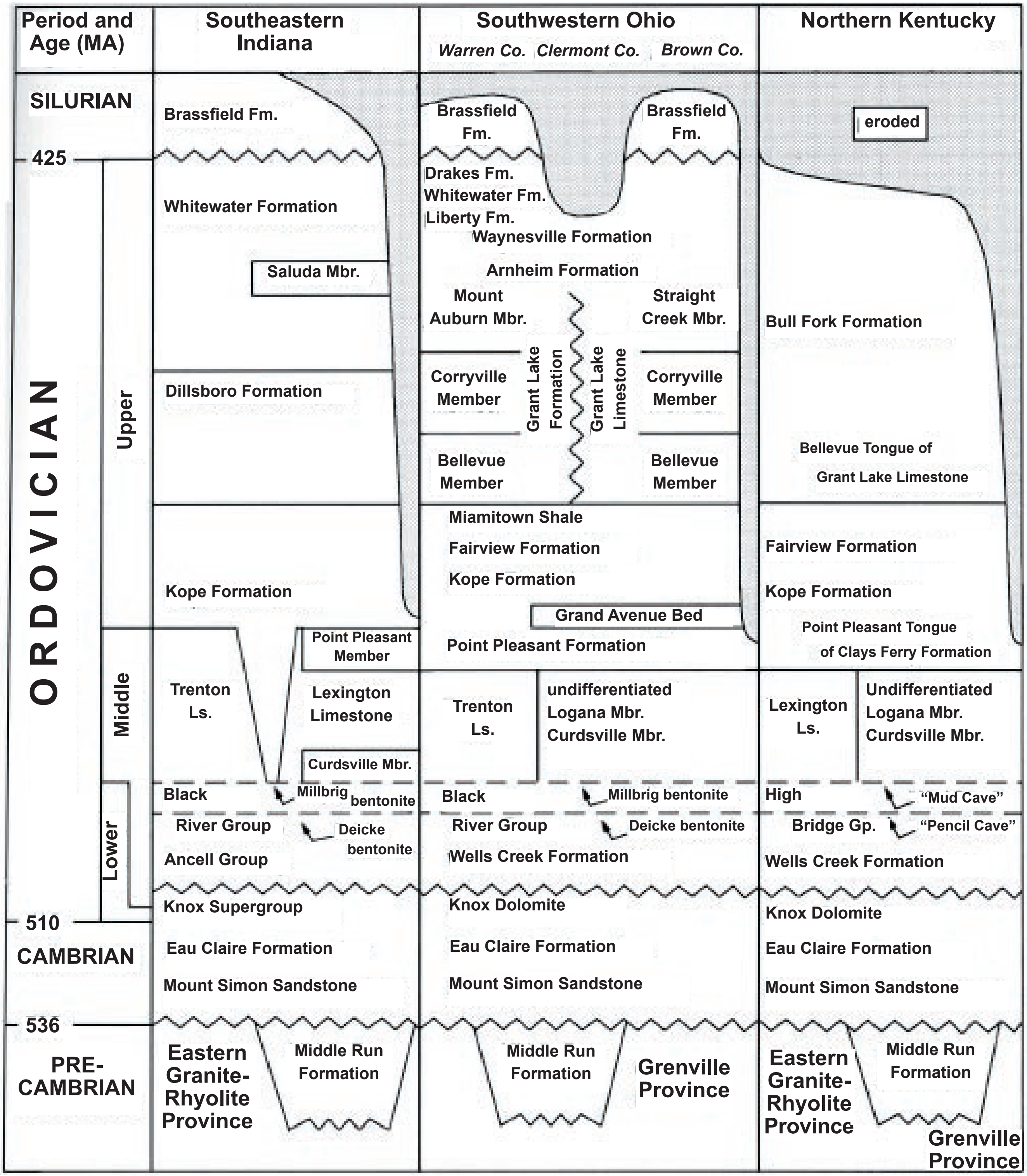


Figure 15. Outcrop and subsurface stratigraphic nomenclature of the Cincinnati/northern Kentucky region. Zigzag lines represent unconformities. Compiled by P.E. Potter (University of Cincinnati), Gregory Schumacher (Ohio Division of Geological Survey), Brian Keith (Indiana Geological Survey), and M.C. Noger (Kentucky Geological Survey). For a slightly different composite section, see Figure 26.

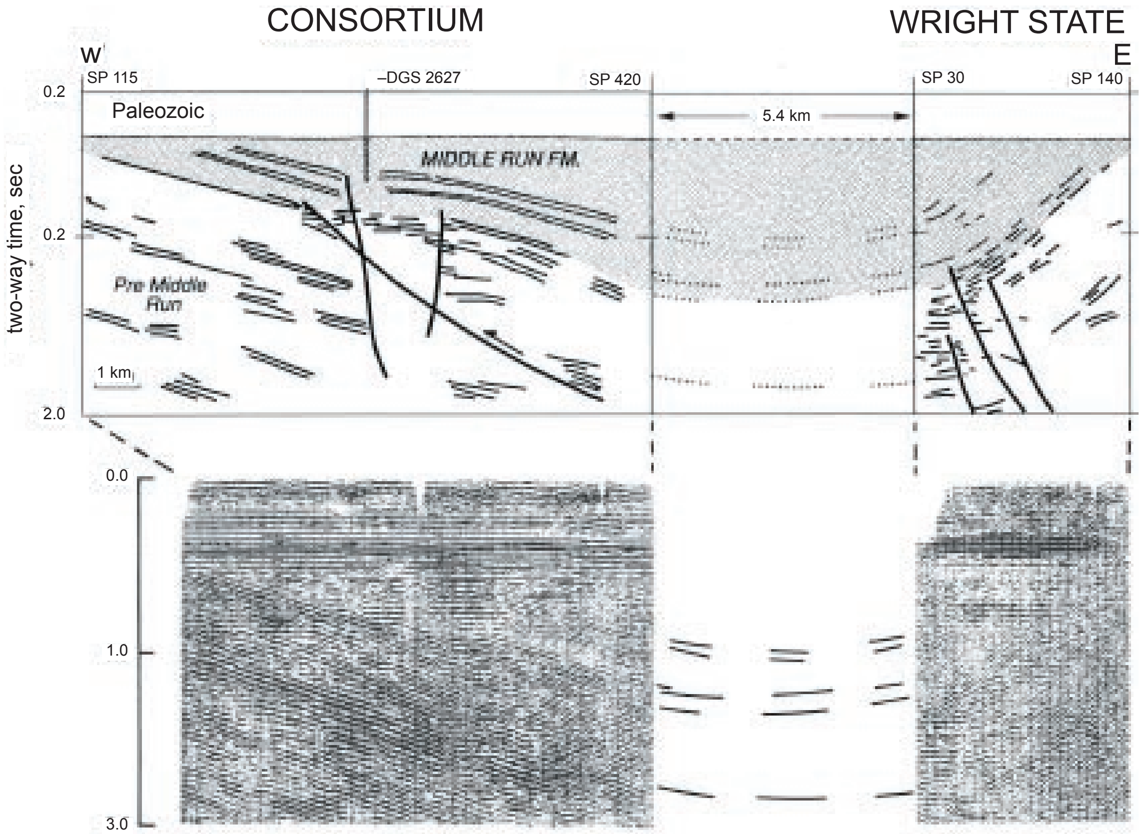


Figure 16. Interpreted seismic image of the Paleozoic and underlying Precambrian rocks of part of northern Warren and Green Counties (Wolfe and others, 1993). Solid line represents deep corehole of Figure 17. The dark, discontinuous lines on the seismic section are reflections from the contacts of rock units with contrasting sonic velocities. Reprinted with the permission of the Oil and Gas Journal. Geologic section encountered by the deep continuous core (DGS 2726) drilled in 1988 in northern Warren County by the Ohio Division of Geological Survey (Wolfe and others, 1989). Reprinted with the permission of the Society of Exploration Geophysicists.

still incomplete, we do know that the deepest formation is a widespread, layered sedimentary unit that begins in the western part of the Cincinnati region and extends over much of the Midwest (Hauser and Byrer, 1992; Pratt and others, 1992). It is informally known as the Precambrian Layered Province. These oldest rocks are Proterozoic in age, and are part of the buried North American craton. Just as the Cincinnati region spans two physiographic provinces, it also includes two buried Precambrian provinces: the Eastern Granite-Rhyolite Province, which underlies most of the Cincinnati region, and the Grenville Province, which lies to the east. In western Ohio, the Eastern Granite-Rhyolite Province is about 1.4 billion years old, and the Grenville Province, about 1.1 billion years old. The Grenville Province, named from its outcrop in eastern Canada, represents the first local record of a continental collision (Hauser, 1992) along the eastern border of North America, and so it is one of the clearest, early benchmark events in local geologic history. The Grenville Province consists of metamorphic, igneous, metasedimentary, and some basaltic rocks. The Grenville event was a major one, as shown by its great lateral extent from eastern Canada into northern Mexico. Another Precambrian formation, the newly discovered Middle Run Formation, lies between these provinces and underlies our study area.

The Middle Run Formation, a thick sandstone unit, was discovered in northern Warren County in 1988 by the Ohio Division of Geological Survey while drilling a corehole through Paleozoic strata to the basement (Shrake and others, 1991). This core has greatly added to our knowledge of all the subsurface formations in our region (Fig. 17). The discovery of the Middle Run was a great surprise to the local geologic community, and has subsequently led to much study of the basement in adjacent parts of Ohio, Kentucky, and Indiana. Seismic images have played an essential role in such studies, because they permit recognition of the Middle Run Formation and other Precambrian

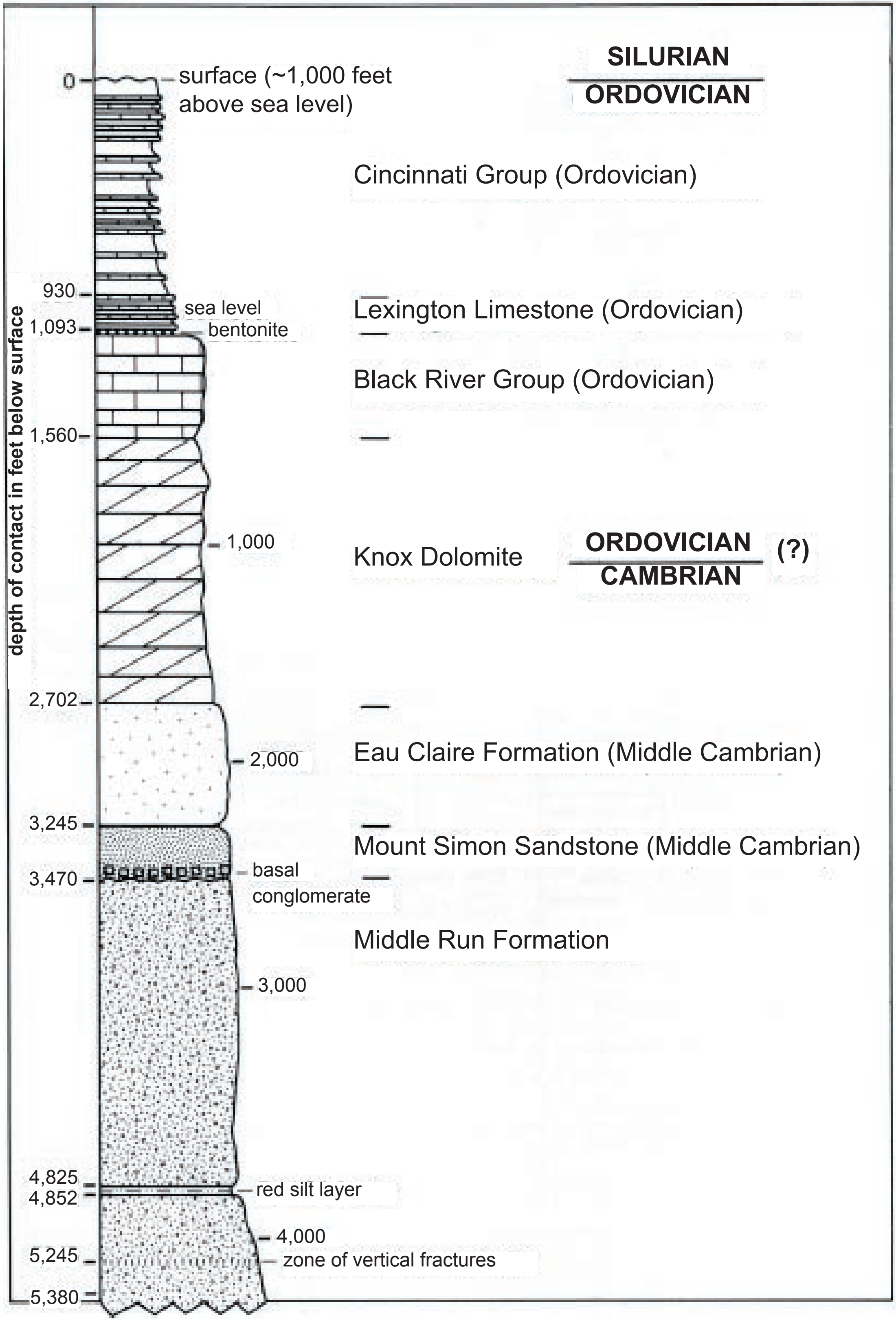


Figure 17. Geologic section encountered by the deep continuous core (DGS 2726) drilled in 1988 in northern Warren County by the Ohio Division of Geological Survey (Wolfe and others, 1989). Reprinted with the permission of the Society of Exploration Geophysicists.

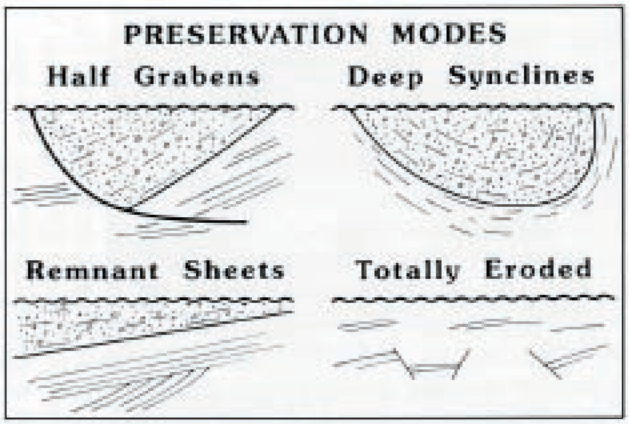


Figure 18. Probable preservation modes of the Middle Run Formation (Wolfe and others, 1993). Reprinted with the permission of the Oil and Gas Journal.

units where there are no deep wells (Fig. 6). As a result, we now know much more about the Middle Run and the other basement rocks than we did before (Shrake and others, 1990, 1991; Shrake, 1991; Drahovzal and others, 1992; Wolfe and others, 1993; Richard and others, 1997). The Middle Run Formation is known to extend from Lima, Ohio, southward to south of Louisville, Ky., although its preservation as a continuous sheet seems unlikely. These deposits occur in the East Continent Rift Basin (Drahovzal and others, 1992), which lies between the Grenville and Eastern Granite-Rhyolite Provinces. The total areal extent of the Middle Run in Ohio, Kentucky, and Indiana is not known, but it appears to range from south of Louisville to north of Lima. Judging from gravity and magnetic studies, thickness could locally exceed 10,000 feet. The Middle Run is preserved as sheets and in rifted and gently folded basins (Fig. 18).

Based mostly on the deep drill core from Warren County (OGS DH 2726) and the homogeneity of available seismic sections, the Middle Run Formation consists chiefly of fining-upward, reddish-brown, fine- to medium-grained compact sandstone with a few scattered pebbles plus some very minor reddish-brown siltstones and shales (Fig. 19). Fourteen well-defined fluvial cycles were recognized in 1,200 feet of the Middle Run in the Warren County drillhole. All this indicates a sandy, semiarid basin of deposition. Both the dominance of volcanic and metamorphic sand grains in the Middle Run (the proportions of quartz, feldspar, and rock fragments are 37:17:46) and the isotopic age of its detrital zircons (Santos and others, 2002) show that almost all of it was derived from the rocks of the Grenvillian Orogeny, whose latest major orogenesis was between 1,070 and 1,050 million years ago (Carr and others, 2000).

But much uncertainty continues about three key questions. First is the time of deposition—was the Middle Run deposited more or less concurrently or shortly after the last Grenvillian Orogeny (and thus deposited in a wide foreland basin to the west of the Grenville Mountains) or was it deposited much later, but still derived from the Grenville Mountains? One date by another isotopic method—fission track dating—indicated an age of about 700 million years (Roden-Tice and Shrake, 1998). But even at 700 million years ago, the overlying Mount Simon Sandstone was not deposited for another 160 million years. So, at present, geologic opinions are still in flux about the age of the Middle Run and its relationship to the Grenvillian rocks from which most of it was derived. The final question is even more troubling: Do the widespread reddish-brown compact fluvial sandstones of the Middle Run represent but one great pulse of sand deposition or several? Lack of fossils and isotopic dating make it almost impossible to answer this fundamental question. So, to sum up, this thick, faulted, widespread sandstone unit underlying Cambrian beds represents a major geologic event in eastern North America and is the greatest single geologic unknown of our region. A good introduction to the Precambrian is provided by Hansen (1996).

### *Paleozoic Era*

The Paleozoic Era extended from about 570 to about 225 million years ago. The rocks deposited during this interval contain a fossil record from which the evolution of life can clearly be traced. The fossil-rich Ordovician beds that crop out in the Cincinnati region represent a key step in this evolutionary process. The geologic history and evolution of life during the Paleozoic can be seen by walking and studying the 450 inscribed flagstones—each representing a million years—of the Geologic Time Line, almost a quarter of a mile long, at Sawyer Point Park.

As discussed above, a considerable period of time and erosion elapsed between the final deposition of the Middle Run Formation and the deposition of the first Paleozoic rocks in the Cincinnati region, the Mount Simon Sandstone of Middle Cambrian age (although we are not sure just how much time elapsed because of the difficulty of dating the Middle Run Formation). Thus, these two sandstones are separated by a buried landscape, or as geologists say, by a major *unconformity.* Wide spacing of wells that reach the basement makes our knowledge of this landscape very incomplete, but we can surmise that it was a treeless, low table land with long, stepped scarps (the more-resistant sandstone beds) mantled by a reddish to maroon sandy rubble. And to the east, a little beyond eastern Warren and Butler Counties, are the eroded thrust sheets of the worn-down, long-eroded Grenville Mountains that formed ridges, irregular hills, and low mountains (possibly like parts of the Piedmont of the Carolinas and Virginia?). Lichens and algae are believed to have existed on these landscapes. The encroaching sea of Cambrian time first entered shallow valleys and finally buried all this topography. See Haddock and Dott (1990) for a description and interpretation of broadly similar sedimentation of the same age along the shores of Lake Superior.

In North America, Cambrian sedimentation began mostly near the margins of the continent about 570 million years ago, but because our region is so far inboard, it occurred much later here, starting about 536 million years ago. Here, in the interior of the continent, the Cambrian is thinner than along the margins of North America.

Except for much of the Mount Simon Sandstone, the Paleozoic rocks of the Cincinnati region represent marine deposition and, in comparison to the Middle Run Formation, are incomparably better known. Almost all Paleozoic rocks have at least a few fossils, and some, such as those of Late Ordovician age, are spectacularly fossiliferous. All of these formations, especially those in the subsurface, are very far-reaching and extend well beyond the neighboring states, many as far as New York, southern Ontario, Wisconsin, and Minnesota, and one, the Knox Dolomite, extends into Texas and New Mexico, where it is known by a different name, the Ellenburger Limestone. Because these formations are so far-reaching, their names also frequently come from afar (see boxed text on p. 30 for why and how geologists give different rock units their names). The deep continuous drill core of the Ohio Geological Survey in northern Warren County (OGS DH 2726) is the principal source for much of

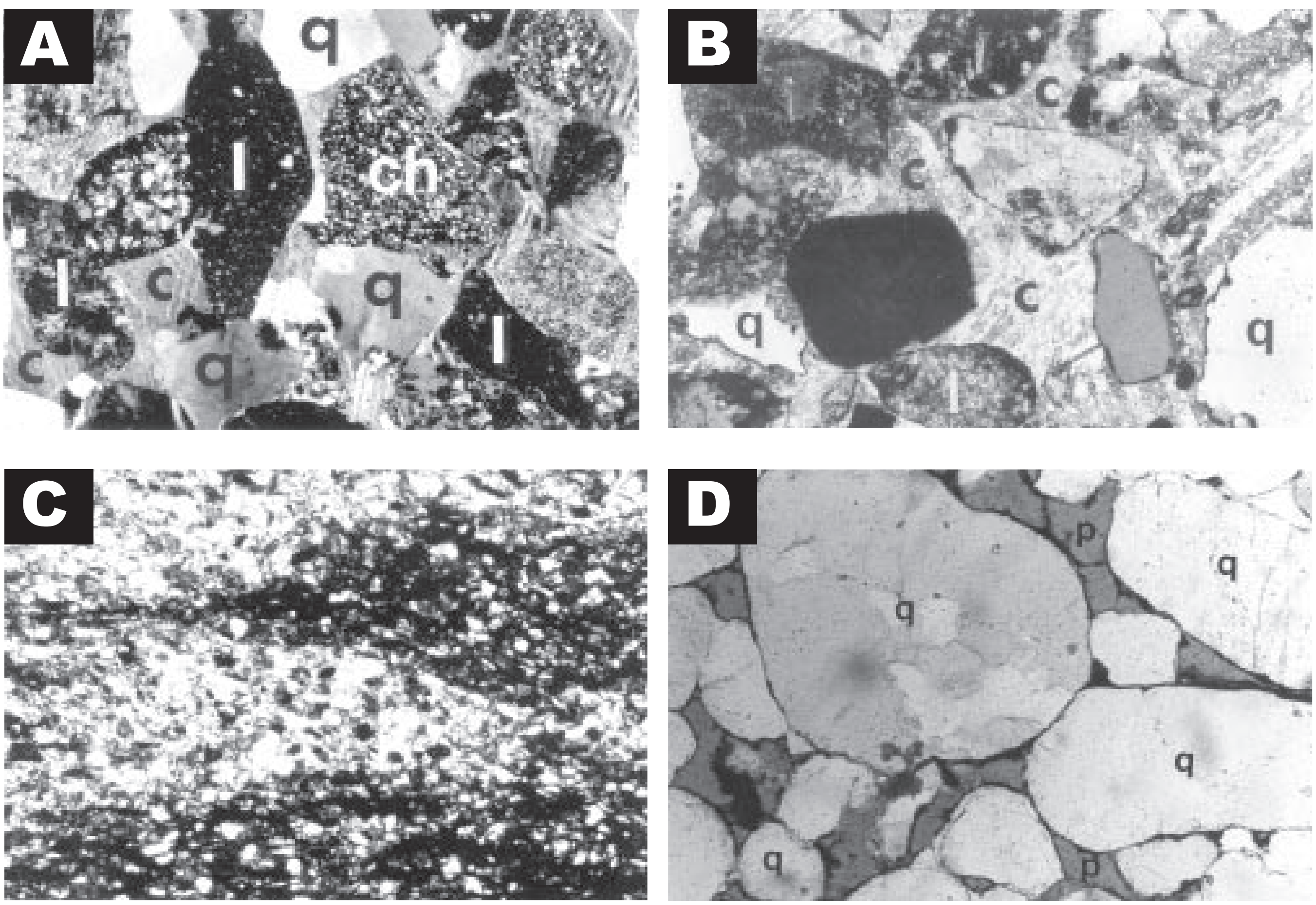


Figure 19. Photomicrographs of two major buried sandstones in the Cincinnati region. q=quartz, f=feldspar, p=pore, i=volcanic rock fragments. Top and lower left: the Middle Run Formation, X50. Note great diversity of components and carbonate cement. Lower right: Mount Simon Sandstone, X60. Note dominance of quartz and pores defined by dye in Mount Simon Sandstone. Typical quartz grain is about 150 to 250 millimeters in length. Probable preservation modes of the Middle Run Formation (Wolfe and others, 1993). Reprinted with the permission of the Oil and Gas Journal.

## Why and how geologists name rock units

Long before Columbus came to the Americas, miners, naturalists, and builders in Europe and Asia noticed that rocks varied greatly—think of granite, shale, limestone, and sandstone or of a limestone that is useful and durable in construction versus one that is not. The next step was the need to distinguish the same kind of rock in two different places. Thus place names for the same kind of rock or unit in different locations (High Bridge Group in Kentucky/Black River in Ohio) began to be used. The early settlers brought this knowledge with them, so informal names such as River Quarry Beds (today's Point Pleasant Formation and Hill Quarry Beds; Fairview and Bellevue Formations) were used to facilitate discussion, understanding, and business. Later, geologists gave more formal names, always using the geographic name of the place where the unit was well exposed and, if possible, easy to get to. This is called the *type* or *reference section.* In this way other geologists could come and see for themselves what a rock unit is really like (a variant of "a picture is worth a thousand words"). Over time, as we learn more, it is thus normal for each region to have different local names for its geologic sections. Field mapping and the study of well records and seismic sections establish lithologic equivalency, and the use of fossils and radiometric dating establish absolute ages.

The branch of geology called stratigraphy (developed in England in the mid 1700's) helps us organize these names into lithologic and time equivalents. In short, stratigraphers organize what at first sight appears to be a random, disorganized, and haphazard development of names into a coherent, meaningful, and useful equivalency. And, because lithologic equivalency and age are so important to all branches of geology, stratigraphy has been called the queen of all of its subdisciplines. This stratigraphy, based primarily on the kind of rock (lithology), is the basis for land-use planning; it contrasts with sequence stratigraphy (see boxed text on page 49), which facilitates correlation of even, thin units over wide areas.

our knowledge about the rock types underlying the Cincinnati region (Shrake and others, 1991).

Starting at the bottom of this sedimentary pile, the Mount Simon Sandstone, named from exposures in central Wisconsin, overlies an irregular (5 to 25 feet thick), ferruginous, weathered zone at its base; above this weathered zone it consists mostly of subrounded to well-rounded quartz grains plus some minor potash feldspar. The sandstone itself is incompletely cemented and thus has many open pores: what geologists call good *porosity and permeability.* The basal part was probably deposited by streams, but much of the Mount Simon is believed to represent deposition on a wide, marine, sandy shelf, probably bordered by small deltas sourced in Ontario to the north. The thickness of the Mount Simon in the Cincinnati region commonly varies from 220 to 280 feet. The water in the Mount Simon is saline and thus not suitable for drinking. Consequently, the good porosity and permeability of the Mount Simon in the eastern Midwest make it useful for the deep disposal of liquid toxic wastes; about 10 wells have been drilled into it for this purpose as of 1992 in Ohio, Kentucky, Indiana, and Illinois.

The Mount Simon is capped by another terrigenous unit, the Eau Claire Formation, consisting of thin siltstones and some minor carbonates interbedded with shale. The thickness of the Eau Claire Formation commonly varies from 570 to 620 feet in most of the Cincinnati region. The Eau Claire was deposited on a silty and muddy marine shelf with some small areas of carbonate muds offshore from the Mount Simon. Although it is far less fossil-rich than outcropping Upper Ordovician rocks, it is abundantly bioturbated, indicating that burrowing organisms were plentiful on its sea bottom. Some of these burrows were made by trilobites. These indicate a Late Cambrian age for the Eau Claire (Babcock, 1994). Thus, the underlying Mount Simon may be Middle Cambrian in age. The dominance of silt and fine sand and some mud in the Eau Claire indicates a waning supply of sand from the north. The Eau Claire Formation is notable for its abundance of glauconite, a greenish, pelletal, clay-like mineral rich in potassium that forms on the sea bottom in well-oxygenated, current- and wave-swept, shallow marine basins. Because it consists mostly of fine-grained, argillaceous siltstone interbedded with thin shales, the Eau Claire is not a source of water, and is, in fact, a good barrier to fluid flow.

Above the Eau Claire, and separated from it by a transition zone, is a thick, homogeneous dolomite, the Knox Dolomite of Ohio and Kentucky; it is called the Knox Supergroup in Indiana. The Knox also crops out in eastern Tennessee. The Knox has well-recognized subdivisions in central Kentucky and at least one in southeastern Indiana, but has been harder to subdivide in southwestern Ohio. Across the Cincinnati region it commonly varies from slightly more than 1,000 feet thick in northern Warren County to more than 1,700 feet thick in southern Boone County. The Knox characteristically consists of white to tan, fine-grained dolomite in massive to laminated beds with very minor amounts of green shale. Lithified carbonate muds, now dolomite, are also present. Masses of chert, a secondary siliceous material, are common, as are some spectacular edgewise conglomerates, which indicate wave action in very shallow water. Except for laminated stromatolitic structures, fossils and other evidence of ancient life are uncommon, although bioturbation and mottling do occur. After deposition, solution was extensive in many parts of the Knox, especially near its upper contact, so that in cores, cavities from a few millimeters to almost core width can be seen. Some of these large cavities contain flowstone or travertine, a secondary calcite deposit found in caves, and a few contain minor amounts of gypsum, an evaporite mineral. The above features, as well as fine grain size, gypsum, edgewise conglomerates, bird's-eye structures, and most important of all, the dolomite itself, all point to a shallow-water, tidal-flat depositional environment with high salinity along an arid coastline far removed from a source of sand (Fig. 20). The persistence of these features over vast areas has led to the name *the Great American Tidal Flat* for the Knox and its equivalents throughout much of North America. So widespread was this vast carbonate tidal flat that only a few scattered grains of well-rounded quartz are present in most of it throughout the Cincinnati region, although a few thin quartz sandstones occur in the Knox elsewhere. In the southern Ohio/northern Kentucky/southeastern Indiana region, the Cambrian-Ordovician boundary occurs within the Knox, but with little or no lithologic expression; to the east in central Ohio, however, thin sandstone is present at this position.

At the top of the Knox is a major, widespread unconformity that is present over much of North America and seems to have equivalents even on other continents. Here in the Cincinnati region, local relief is 30 to perhaps 90 feet on this buried surface, which also exhibits many solution features such as sinkholes. This karst topography greatly enhances the porosity of the upper part of the Knox. Thus, Knox deposition ended with the complete withdrawal of the ocean from the tidal flat, leaving a low-lying landscape with sinkholes and caves developed on an irregular, rocky, treeless surface extending for hundreds of miles in all directions. This landscape had a few isolated, sharply circumscribed hills, many 30 to 50 feet high, although outside our area some are as high as 100 feet above their surroundings. Minor amounts of pure, well-rounded quartz sand grains, concentrated from the weathering and solution of the underlying Knox, occur in scattered pockets and lows on this ancient landscape, which appears to be very similar to that of the modern Pennyrile Plateau, a famous sinkhole plain in Kentucky south of Mammoth Cave.

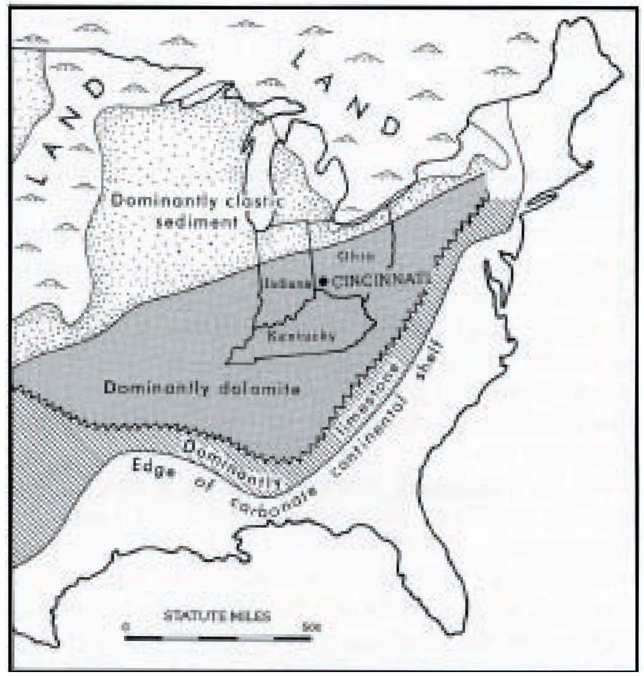


Figure 20. A vista of the vast ancient tidal flat of the carbonates of the Knox. Redrawn from Harris (1973, Fig. 1.20).

Marine invasion led to a thin, widespread deposit called the Dutchtown Formation in Indiana and the Wells Creek Formation in Ohio and Kentucky. In most of the Cincinnati region, the Dutchtown commonly varies from 30 to 60 feet thick, but where an erosional hill developed on the Knox, it was first deposited at the base of the hill and only later fully covered the hill, a process called *onlapping* by geologists. Thus, the thickness of the Wells Creek/Dutchtown depends chiefly on the space available for deposition, called *accommodation space.* Consequently, the Knox is thickest over topographic lows and thinnest over buried hills. A buried, porous Knox erosional hill or "high" surrounded and capped by low-permeability Wells Creek/Dutchtown beds forms a natural reservoir for oil or gas; it can also be used for the storage of natural gas, as happens northwest of Cincinnati in Randolph County, Ind. Natural gas and toxic liquids can be stored underground when three conditions are satisfied: the host rock has enough porosity and permeability to hold the fluid; there is an impermeable cap; and finally, a geologic trap confines lateral flow. The Wells Creek/Dutchtown consists of a greenish-gray to dark greenish-gray, finely crystalline, argillaceous dolomite with some thin clay stringers and laminae, plus abundant bioturbation and some glauconite, pyrite, and chert, as well as rare fossil debris. What emerges from these features is a picture of slow, slightly muddy, carbonate sedimentation over a vast, ancient landscape. The Wells Creek/Dutchtown is readily recognized on geophysical logs because of its clay content (good gamma-ray expression) and is thus a good marker bed in the subsurface.

Overlying the Wells Creek is the Black River Group of Ohio and Indiana and its equivalent, the High Bridge Group of Kentucky. The Black River Group takes its name from a river in upper New York state. In Kentucky, where it is named for good exposures along the Kentucky River south of Lexington, the High Bridge Group consists of the Tyrone Limestone at its top, underlain by the Oregon Formation and Camp Nelson Limestone. The Black River/High Bridge Group, about 450 to 470 feet thick in the Cincinnati region, is widely traceable and is composed chiefly of fine-grained, burrowed and mottled, light olive-gray limestones, many with lamination, mud cracks, intraformational mud-chip conglomerates, and bird's-eye structures, plus a scattering of pelecypods, ostracodes, and brachiopods. Fine-grained pelletal limestone as well as dolomite-filled burrows also can be found. In addition, some thin dolomites are present. Geophysical logs, such as the one from Campbell County (Fig. 21), reveal an amazing lateral continuity of thin units over tens of miles within the Black River/High Bridge Group. Repeated wide lateral continuity of beds in a formation implies strong cyclicity in deposition (see boxed text below). The fine grain size of these carbonate beds and the presence of lamination and bird's-eye structures all point to slow sedimentation in shallow marine waters that were better connected to the world ocean than were the tidal flats of the underlying Knox, where more saline-rich waters led to the formation of vast quantities of dolomite. See "Construction Materials" (p. 108) for the economic contribution of the Black River/High Bridge Group to the Cincinnati region.

Volcanic ash beds, called K-bentonites, occur near the top of the High Bridge/Black River Group; two of them have been traced over much of the upper Mississippi Valley and to Alabama and New York, and, even more surprisingly, their equivalents have been recognized in northern Europe (Huff and others, 1992). Two of these beds, the Mud Cave and Pencil Cave bentonites in Kentucky (and their equivalents in Ohio and Indiana, the Millbrig and Deicke bentonites), are especially easy to recognize in cores and on geophysical logs and thus are useful markers for subsurface mapping (Fig. 21). The Mud Cave and Pencil Cave bentonites can be seen in outcrops along the Kentucky River south and west of Lexington, Ky. These bentonites are a splendid example of how far-distant events, in this case a giant volcanic explosion, have influenced the geology of the Cincinnati region. The age of the upper of these two, the Millbrig, is about 453 million years (Kunk and Sutter, 2001). See McLaughlin and others (2004) for the lithology and sequence stratigraphy of these units along U.S. 127 north of Frankfort, Ky.

Two caverns for storing liquid propane, each holding 7 to 8 million gallons, have been constructed in the Black River/High Bridge Group: one at the East Works of the Cincinnati Gas and Electric Co. along Eastern Avenue in Cincinnati, and the other at Constance, Ky. There are also two limestone mines in the High Bridge Group in Kentucky, one in Gallatin County and another just south of Campbell County, plus a quarry in the Lexington Limestone in nearby Pendleton County, Ky.

### Characteristics of Cincinnatian shales

In outcrop, the most distinctive aspect of the Cincinnatian Series is its shales, starting with the Kope (nearly 85 percent shale and more than 200 feet thick), down to innumerable thin partings and laminations in limestones. Almost all of these acquire a bluish-gray color in outcrop as they weather.

These shales are very homogeneous mineralogically and texturally. Scotford (1965) found that they average 38 percent clay (particles smaller than 4 microns), 59 percent silt (4 to 62 microns), and have about 3 percent coarser than 62 microns. Dominant minerals are illite (47 percent) and quartz (24 percent), followed by carbonate (15 percent), chloritic clays (9 percent), and expandable mixed-layer clays (2 percent). Some of the illitic and chloritic clays also expand when wet. Consequently, the shales of the Kope react readily with water to become soft and deformable (Fig. 56) and are the source of most hillside colluvium. Where they occur as thin laminations and partings in a limestone in outcrop, clay laminations are removed by weathering and thus weaken and subdivide limestone beds.

Fine silts and muds were deposited both slowly during fair weather and rapidly during storms. Fines were carried in suspension by basinwide current systems away from an eastern source, and bottom sediment was resuspended periodically by storms producing dilute density currents and muddy slurries flowing along the bottom (Fig. 28). Both of these, but especially the slurries, buried alive and beautifully preserved bottom dwellers such as trilobites and crinoids. Kope shales vary from fossiliferous, with both intact to fragmental fossils, to those that are barren. See boxed text on p. 45 and 49 to see how these shales occur at different scales with different origins.

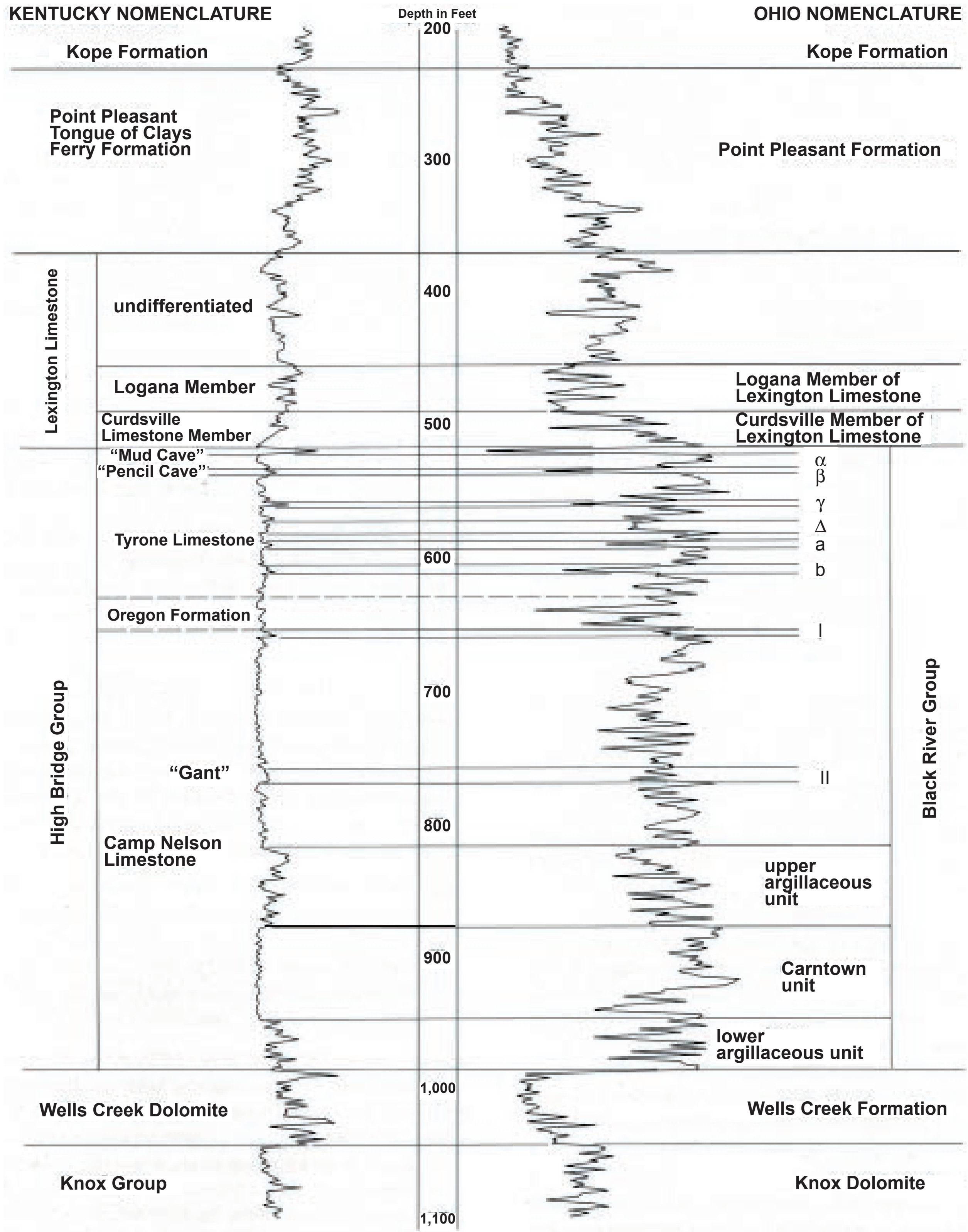


Figure 21. Geophysical log from part of the Ashland No. 1 Wilson well in Carter coordinate section 25-DD-62, Campbell County, Ky., shows the detailed stratigraphy of the Ordovician rocks from the top of the Knox to above the Trenton Limestone (Stith, 1986, Fig. 2). Compare the log patterns and their names with those shown in Figure 15. Reprinted with the permission of the Ohio Division of Geological Survey.

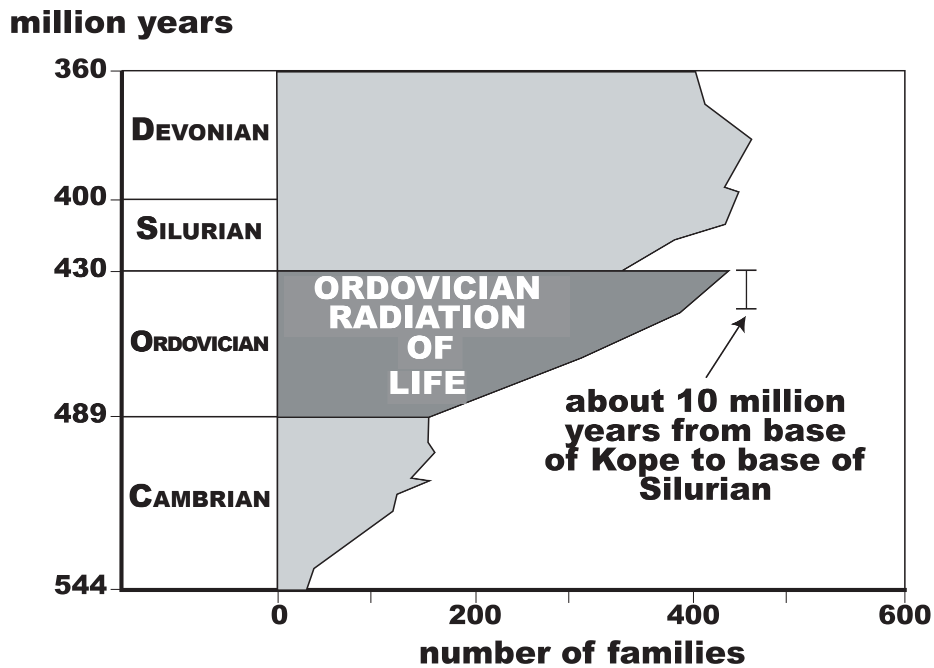


Figure 22. Worldwide increase in fossil diversity (as recorded at the family level) in the lower and middle Paleozoic and its reduction at the Ordovician-Silurian boundary (after Sepkoski, 1981, Fig. 5). This increase is called the Ordovician Radiation. Reprinted with the permission of the Paleontology Society.

A significant change in sedimentation occurred above the Black River/High Bridge Group starting with the Lexington and Trenton Limestones, a change that seems to have been virtually continent-wide, especially from the standpoint of ancient life (Fig. 22). Above this boundary was a great explosion of invertebrate life led by bryozoans, brachiopods, and echinoderms, followed by mollusks (gastropods, pelecypods, and cephalopods) plus trilobites, graptolites, and conodonts. And to all of these should be added abundant trace fossils (tracks and burrows of soft-bodied animals that crawled on or burrowed into muddy bottoms). Although many, if not almost all, of these organisms existed to some degree in the environments represented by the older rocks below, their diversity, as measured by genera, is three to four times greater in the Trenton and Lexington and overlying units than in the Black River/High Bridge Group. A well-oxygenated, low-latitude (15 to 20° south), shallow sea replaced earlier vast tidal flats and more restricted seas. In other words, an optimum environment for marine life in much of the eastern United States replaced a largely barren one. As we will see later, paleontologists have also speculated on other causes for this great multiplication of ancient invertebrate life. This increase in continental flooding even led at times to somewhat deeper water in which terrigenous muds, mostly derived from a distant rising continental border land to the east, partially inhibited carbonate deposition. Thus, for the first time since the Eau Claire Formation, shale is again a significant rock type above the Trenton and Lexington Limestones.

The Lexington Limestone of Kentucky and its Ohio and Indiana equivalent, the Trenton, range from about 140 feet thick in the northern part of the Tri-State area to almost 200 feet in the southern part. Limestones prevail and are commonly medium- to coarse-grained wackestones and packstones, most with fragmental brachiopod and bryozoan debris. Beds, commonly 20 to 30 centimeters thick, may be nodular and have some medium to dark gray shale partings and interbeds. Several thin K-bentonites are also present in the lower and upper part of the Trenton/Lexington. Some minor noncommercial gas has been found in the Trenton/Lexington in the Cincinnati region (enough so that drillers must guard against it). Several large underground liquid propane caverns are in the Trenton south of Middletown in Lemon Township.

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### *Digging Deeper*

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Cincinnati region relates to that of nearby states.

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Careful stratigraphy is supplemented by chemical analyses, polished sections, and cross sections. It is an excellent reference.

## Outcropping Formations

Bedrock is well exposed in the Cincinnati region, and collectively there must be several thousand or more outcrops in the 11-county area, thanks largely to the area's relief, drainage history, and construction. These distinctive outcropping beds extend from the Point Pleasant Formation to the base of the Silurian rocks (Fig. 15) and are called the Cincinnatian Series. In addition, the Point Pleasant Formation is well exposed, and there are two outliers of Silurian beds. Total thickness of the Cincinnatian Series is about 820 feet (Shrake, 1992, p. 5), or about 25 percent of the total thickness of the sedimentary rocks overlying the Precambrian Middle Run Formation and basement. These beds were deposited in about 9 to 11 million years, a short interval in the sweep of geologic history. During most of this time the region lay about 1,800 to 2,000 miles south of the equator (Fig. 23). The idea of a shallow sea deepening to the northwest—deposition on a ramp on the flank of the Lexington Platform—fits Cincinnatian rocks well (Fig. 24).

The great abundance and splendid preservation of its fossils, variety of bedding features (Fig. 25), the numerous superb exposures in creek beds, old quarries, and many roadcuts (Fig. 26), plus easy accessibility all combine to make the bedrock outcrops of the Tri-State a world-famous natural laboratory for amateurs and professionals alike. There is even a special park for the public to collect fossils: Trammel Fossil Park, just north of Cincinnati at Sharonville in Hamilton County. Brachiopods, bryozoans, and echinoderms dominate this fauna. Collectively, these characteristics have made the Cincinnati region the North American type section (see boxed text, p. 30) for the Upper Ordovician. In contrast to underlying Ordovician beds, shale is a conspicuous part of the Cincinnatian Series (see boxed text, p. 32). The bluish color of shales and limestones of the Cincinnatian Series as seen in outcrop gave rise to the original name for these rocks: the Blue Miami Limestone. Other names, all long abandoned, include Blue Limestone, Great Limestone Deposit, Cincinnati Group, and Cincinnati Beds Proper. Many, many papers have been published on or refer to these deposits, chiefly in regard to their paleontology and stratigraphy. Early publications include those by Locke (1838) and Orton (1873, 1878). Three later publications that integrate subsequent studies are those by Schumacher and others (1991), Holland (1993), Hansen (1997), and Davis and Cuffey (1998). In addition, the construction of the AA Highway (Ky. 9) from Alexandria to Ashland provided many new, closely spaced, deep cuts that have been studied in detail using the methodology of sequence stratigraphy. See especially the guidebooks of Algeo and Brett (2001) and McLaughlin and others (in press) for descriptions of the many new subunits of existing formations that they recognized and correlated over long distances and the summary by Holland (in press).

We will first describe the distribution and general characteristics of the Cincinnatian beds, follow with a discussion of their conditions of sedimentation and cyclic deposition, and conclude with a brief discussion of their fossils. Ten outcropping formations of the Cincinnatian and as many as 12 members are recognized in the region (Figs. 15, 27).

### *Distribution and Characteristics*

The Point Pleasant Formation, Kope Shale, and Fairview Formation form most of the many outcrops in the Kentucky and Indiana parts of the study area and in Hamilton and Clermont Counties, Ohio (deep stream dissection and only thin and isolated, pre-Illinoian glacial deposits). In most of Butler and Warren Counties, Ohio, on the other hand, Wisconsinan glaciation greatly reduced outcrops, and the younger Arnheim, Liberty, Waynesville, Whitewater, and Drakes formations are only sparingly exposed as the Cincinnati-Findlay Arch gently plunges to the northeast. Because they have so many outcrops, we will focus mostly on the Point Pleasant, Kope, and Fairview Formations.

The Point Pleasant Formation overlies the Lexington and Trenton Limestones of the subsurface and is one of the oldest outcropping units in the Cincinnati region. Its upper parts are well exposed along much of the Ohio River and tributary creeks, especially near Point Pleasant, its type section in Clermont County, and in the valley of the Licking River in southern Campbell and Kenton Counties. The Point Pleasant Formation can also be seen at low water on the Kentucky side of the Ohio River just west of Brent Spence Bridge of I-75 and I-71. There are also a few outcrops in far southwestern Boone and eastern Gallatin Counties. The Point Pleasant Formation, about 90 to 110 feet thick in Ohio, consists of variable amounts of medium- to thick-bedded, medium- to coarse-grained wackestones and packstones interbedded with medium gray shales. Bedding is notably irregular in outcrop. Ripple marks and some crossbedding are present, plus several interesting zones of widespread soft-sediment deformation. The Point Pleasant has the most limestone near its top, where it contains some of the thickest limestone beds in the Tri-State area. Because it is well exposed along the Ohio River, the Point Pleasant was convenient to quarry and ship by boat: hence, its original name, the River Quarry Beds. Even in the late 20th century, large construction projects along the river have led to new quarries in the Point Pleasant. At Lawrenceburg in Dearborn County, Ind., there was a small, shallow gas-storage field, most probably in the Point Pleasant (Dawson and Carpenter, 1963). Small pockets of natural gas are found in this formation in greater metropolitan Cincinnati. In Indiana, the Point Pleasant and underlying rocks have the name *Trenton Limestone.* This limestone produced much oil and gas across much of central Indiana over 100 years ago.

Above the Point Pleasant, and in sharp contact with it, is the Kope Formation. The base of this thick shale defines the base of the Cincinnatian Series. The Kope Formation, commonly 200 to 250 feet thick, is the thickest of all outcropping formations in the Cincinnati region and consists of 65 to 80 percent shale, dominantly medium bluish-gray with some darker gray shale at its base. Quartz silt is in all these shales, and many of its shale beds are calcareous. Shales of the Kope tend to be poorly laminated and, because they contain small amounts of expandable clay minerals, disintegrate rapidly and swell when wet. Consequently, colluvium

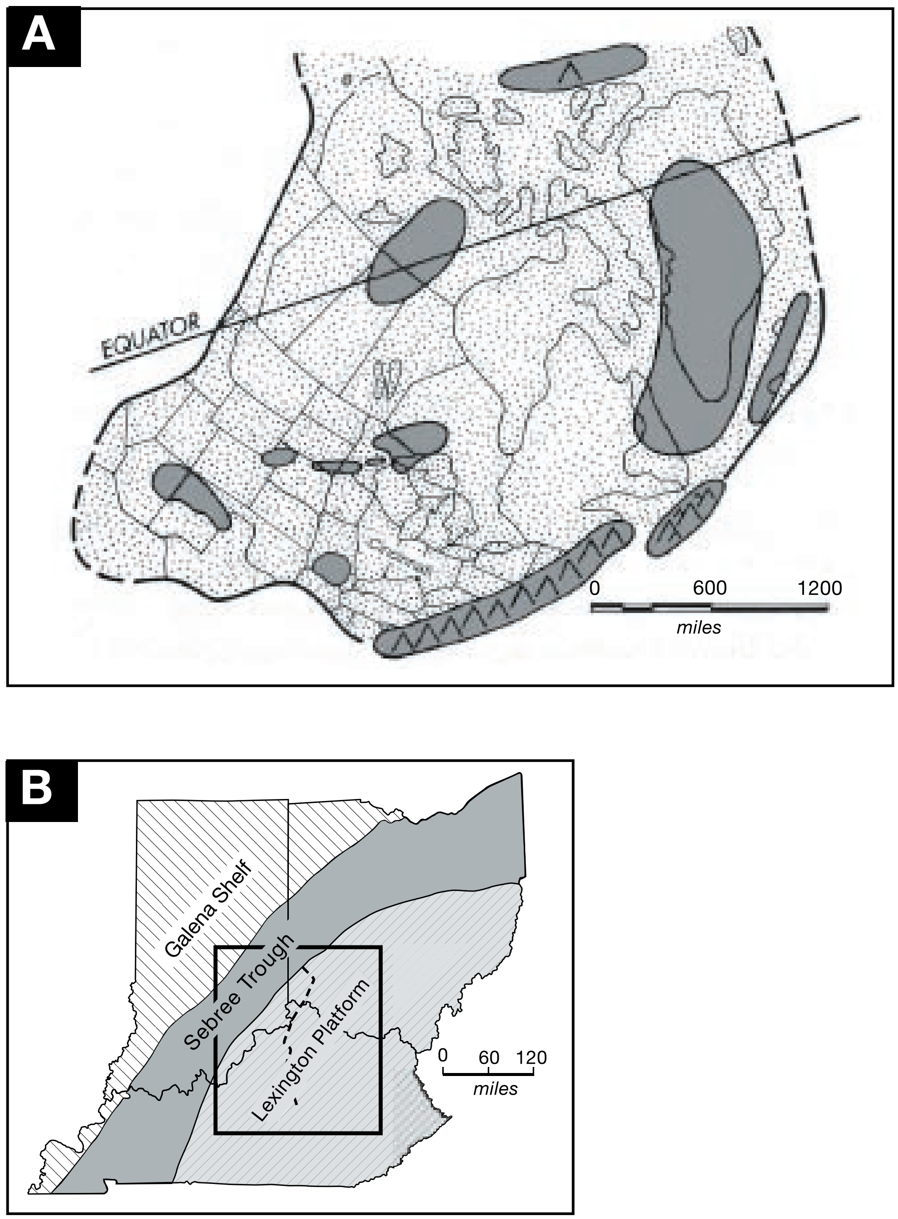



Figure 23. Paleogeography. (A) Generalized shape, position of North America in the Upper Ordovician relative to the equator, and distribution of major highlands and basins. Redrawn from Witzke (1990, Fig. 2). Reprinted with the permission of the Geological Society of London. (B) Regional features important for understanding Cincinnatian rocks (McLaughlin and others, 2004). Reprinted with the permission of Elsevier Science.

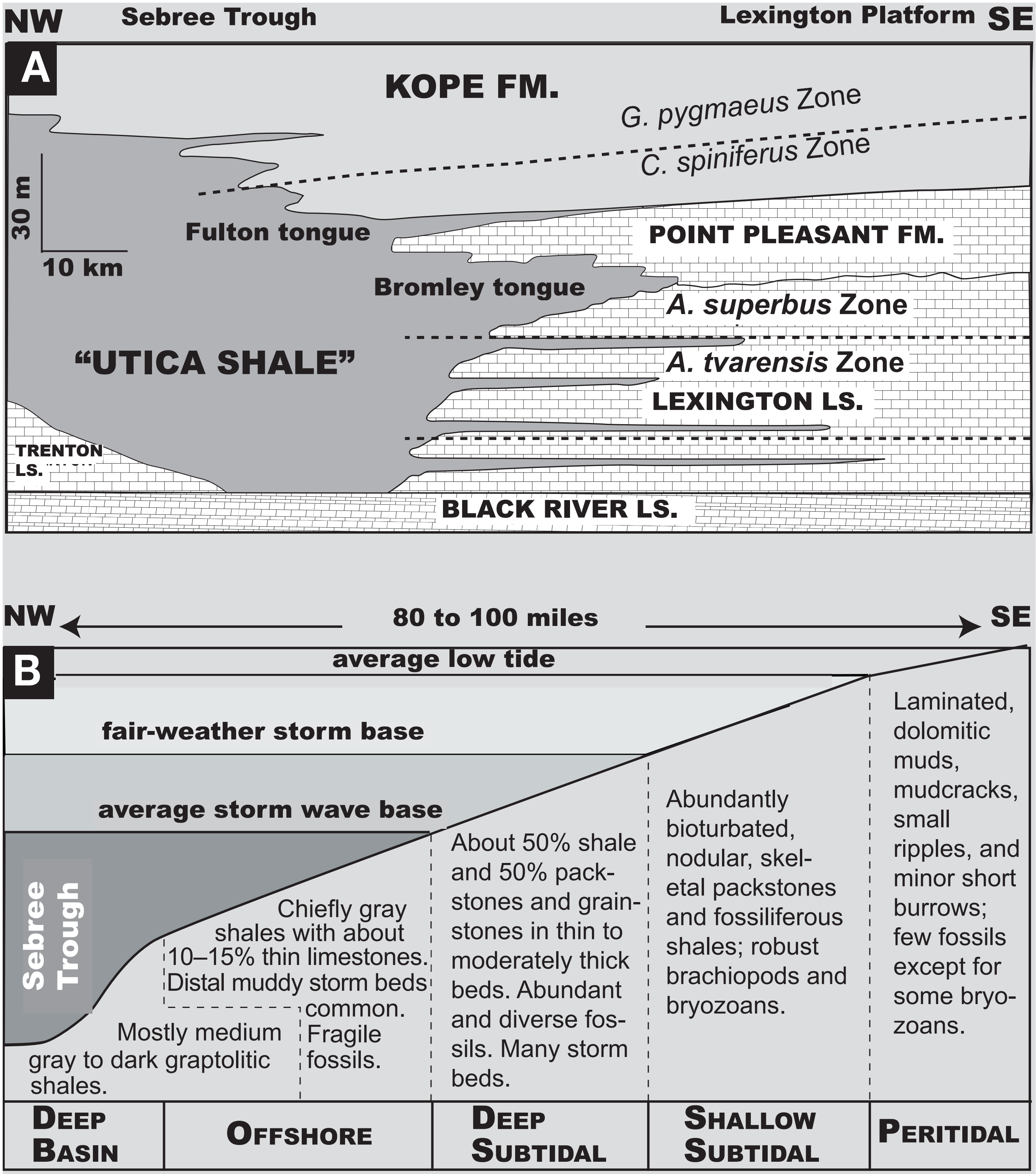



Figure 24. Regional setting. (A) Northwest–southeast cross section after Mitchell and Bergström (1991, Fig. 3) and Brett and others (in press, Fig. 1). (B) Schematic model of ramp and sedimentary environments (after Holland, in press, Fig. 2). Reprinted with the permission of the Geological Survey of Canada and the Cincinnati Museum of Natural History.

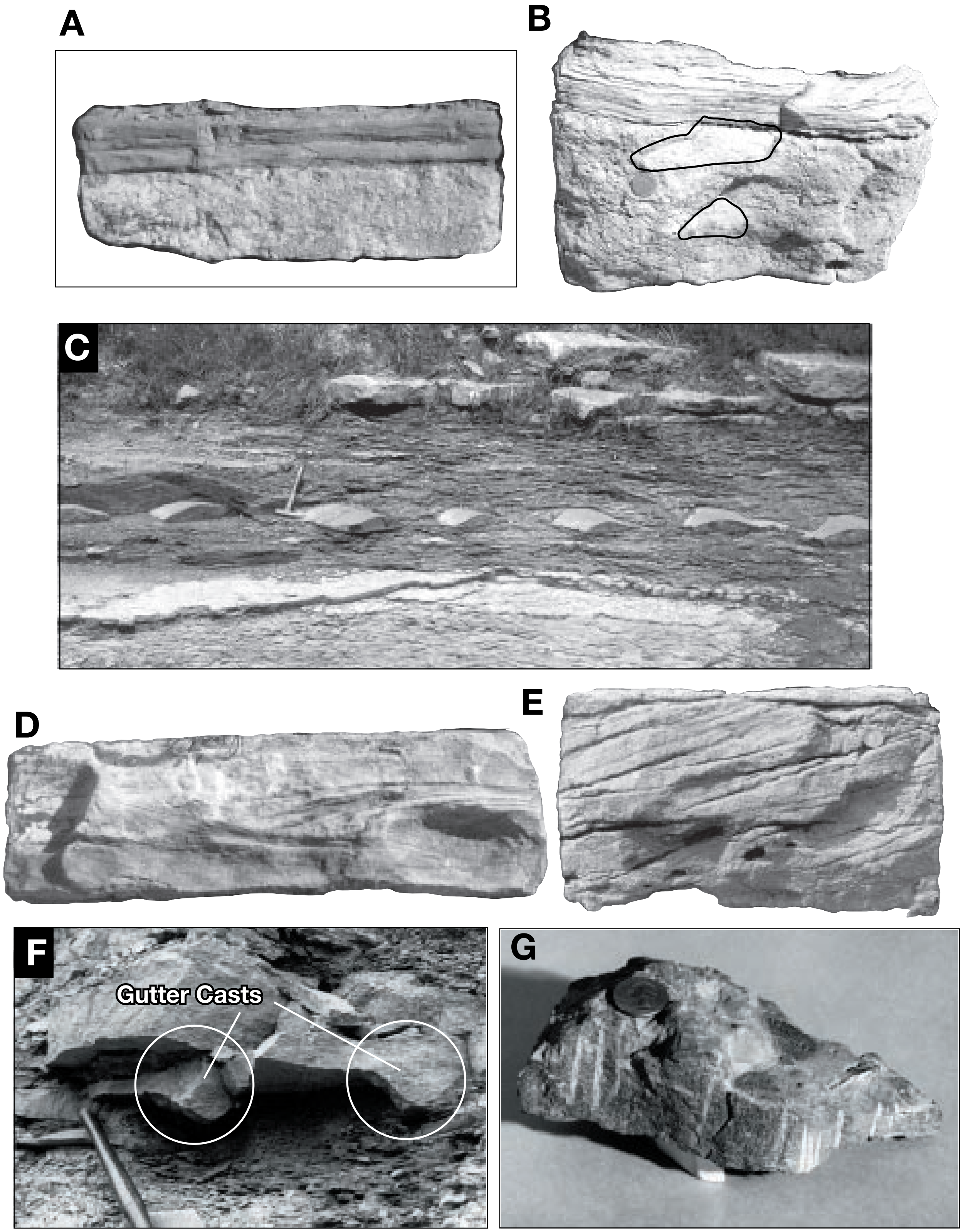



Figure 25. Sedimentary structures. (A) Classic tempestite, coarse-grained at base, capped by finer-grained laminites. (B) Thick, coarse-grained limestone with clasts at top (possible debris flow?) capped by finer-grained laminites. (C) Isolated ripples in Kope Formation. (D) Tempestite with inclined (hummocky) bedding in coarse grainstone. (E) Inclined bedding. (F) Burrowed, knobby starvation surface with minor pyrite. (G) Hardground with knobby surface, pyrite, and burrows.


Figure 26. Outcropping beds. (A) Point Pleasant Formation with Kope Formation at top in abandoned quarry at junction of Bear Creek Road and U.S. 52, southeastern Clermont County. (B) Kope Formation at base capped by Fairview Formation in west lane of I-275 due west of Ohio River, Campbell County, Ky. (C) Type section of the Fairview Formation capped by the Miamitown Shale and Bellevue Member of the Grant Lake Formation in an old, former quarry on Vine Street just below Bellevue Park. (D) Complete section of Miamitown Shale adjacent to Trammel Fossil Park off Trammel Way, Sharonville, Hamilton County, Ohio. Section is 17 feet thick. Note bounding shales. (E) Bellevue Member of the Grant Lake Formation in highwall of abandoned quarry at 420 Warner Street, Fairview, Cincinnati, Ohio. (F) Liberty Formation in spillway of Caesars Creek Reservoir in Massie Township, southwest of Waynesville, Warren County, Ohio. There are several good hardgrounds to be seen here. See Shrake (1992) for details, referenced in “Field Work in the Cincinnati Region.” Reprinted with the permission of the Ohio Division of Geological Survey.

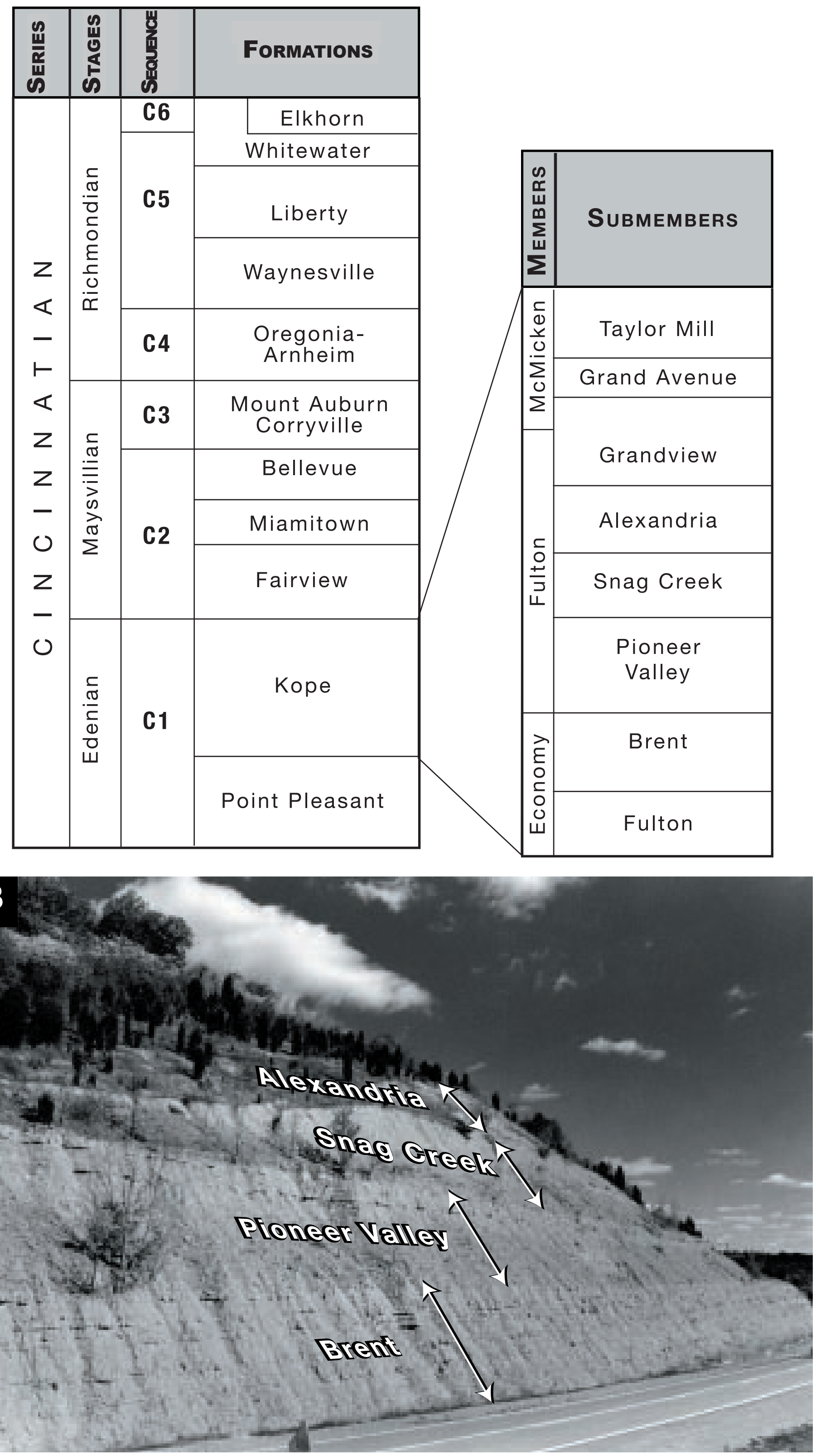



Figure 27. Stratigraphic nomenclature. (A) Sequences, series, formations, members, and submembers (after Brett and others, in press, Fig. 2; Holland, in press, Fig. 1). (B) Contacts of the submembers of the Kope Formation at its newly defined alternative section at the junction of Ky. 8 and Ky. 445 in Campbell County (Brett and others, in press, Fig. 4; Holland and others, in press). Reprinted with the permission of the Cincinnati Museum of Natural History.

is abundant on and below Kope hillsides, as are landslides. Kope shales are interbedded with a few thin-bedded, fine-grained limestones near the base of the formation, but limestones become thicker, more abundant, and more fossiliferous and coarser toward its top. Distinctive limestone beds, thickness of interbedded shales, and fossil limits have been used to divide the Kope into three members and eight submembers (Fig. 27) in both outcrop and in the subsurface (Brett and Algeo, 2001; Brett and others, 2003). These subunits range from 5 to 10 to as much as 60 feet thick and have been traced as far as Maysville. The lowermost of these, the Fulton Submember, has dark gray, graptolitic shales and is a tongue of the "Utica" fill of the Sebree Trough (Figs. 23B, 24A). See Kolata and others (2001) for a regional overview of this long narrow arm of a deeper ocean to the south. Many of the fine-grained limestones of the Kope, especially those in its middle and upper parts, are graded and are called *tempestites* or storm beds (Figs. 24, 28; see boxed text on p. 45). Because such beds are formed instantaneously (tens of minutes), tempestites belong to the larger class of *event beds.* The Kope, like the Fairview, also contains other event beds. These include beautiful large-scale ripple marks composed of well-sorted, coarse limestones (as well as some very small ripples) and some gutter casts (well-defined, linear, well-oriented grooves filled with carbonate silt at the base of a limestone bed). Also present are beds of edgewise fossils and a few beds of imbricated shells. Event beds also include thin beds with distinctive assemblages of either body or trace fossils, as well as body fossils with special preservation.

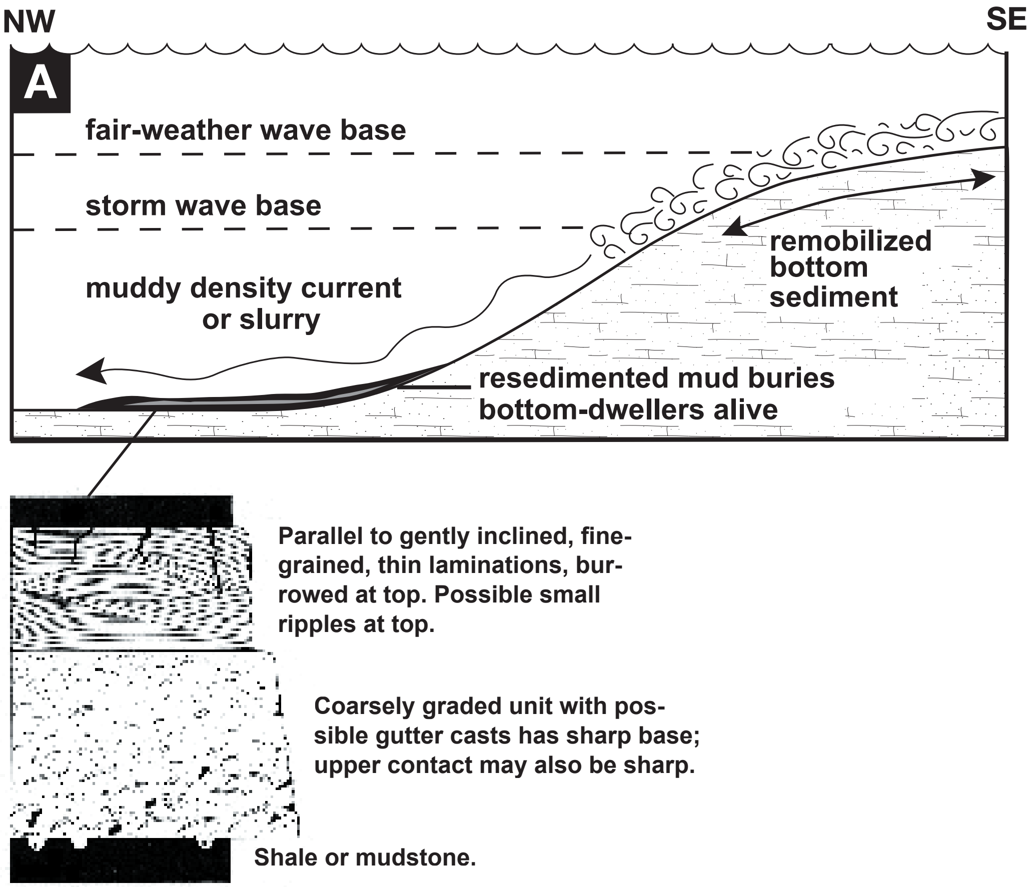
The trained eye can easily recognize a hillside underlain by the Kope by  its smooth, sweeping, concave-upward, rounded slopes, which are largely gully-free, probably because of a thick mantle of permeable colluvium. And, where capped by the limestone-rich Fairview Formation, a sharp break in slope is readily apparent to mark the top of the Kope. When disturbed by humans or undercut by a stream, however, Kope hillsides, with their thick mantle of colluvium, are landslide-prone and may have small gullies.

In comparison to both the over- and underlying limestone-rich units, the fauna of the Kope is smaller and more delicate. The brachiopods and branching bryozoans in the Kope have thinner, more delicate shell structure than elsewhere in the Cincinnatian Series, largely because currents were weak. Three other distinctive paleontological aspects of the Kope are oriented packets of delicate crinoid stems, graptolites that tend to be well oriented, and rare beds of totally fragmented, well-sorted, small crinoid stems. The trace fossil *Chondrites* is rather common, as are both *Diplocraterion* and delicate impressions of grazing trails. Creek beds or new roadcuts generally provide the best opportunity to collect fossils from the Kope, which can be seen in all the counties of the Tri-State area except most of Warren and Butler Counties. A new alternative type section has been established (Holland and others, 2006) at the intersection of Ky. 8 and Ky. 445 in Campbell County (Fig. 27B).

The Fairview Formation has an abrupt, well-defined contact with the underlying Kope Formation (Fig. 29), is about 100 feet thick, consists of approximately 50 percent bluish-gray shale interbedded with shelly limestones in well-defined beds, and forms the hilltops bordering the Ohio River from as far away as Maysville, Ky., to Vevay, Ind. Many of its beds are tempestites (see boxed text on p. 45) with distinct graded bedding and good lateral continuity and were used for construction for many years: thus their original name, the Hill Quarry Beds. The sedimentary structures of the Fairview are broadly the same as those of the Kope Formation, although tempestites are more common in its more abundant limestones (more storms impinging the bottom). The fossils of the Fairview are robust, abundant, and diverse—bryozoans, crinoids, and brachiopods dominate, but there are many others—so collecting is easy. The many limestones of the Fairview make it good for hillside foundations and also inhibit development of colluvium. The type section for the Fairview Formation is an abandoned highwall face below Bellevue Park overlooking Vine Street south of the University of Cincinnati.

The next overlying formation is the Miamitown Shale, named after exposures near Miamitown in western Hamilton County. It is a thin, shale-rich formation that thickens northwestward as it intertongues with the Fairview. Exposures are not abundant south of the Ohio River. The Miamitown, with its notable gastropod fauna, has a maximum thickness of about 50 feet in northwestern Butler County. Trammel Park in Sharonville, where it is 17 feet thick, is the best place to see it. More coreholes through the Miamitown would help us understand this thin, but interesting, unit.

Above the Miamitown is the Grant Lake Formation, which contains three members in the Cincinnati region: the Bellevue, Corryville, and Mount Auburn. These members were first recognized on hillsides in neighborhoods near the University of Cincinnati. These beds are called the Dillsboro Formation in Indiana, and are equivalent to part of the Bull Fork Formation in northern Kentucky and the Grant Lake Limestone in Ohio. The Bellevue and Corryville range in thickness from about 20 to 60 feet, and the Mount Auburn ranges from about 18 to 24 feet. Notable features of the Bellevue include irregular pinch and swell, wavy bedding, a prolific fauna, and



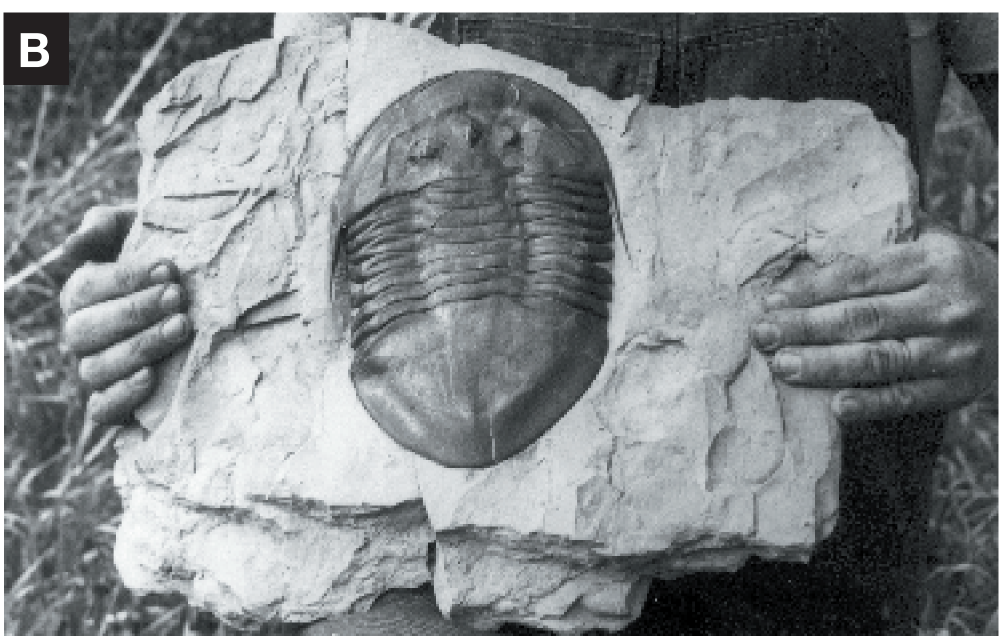




Figure 28. Consequences of a storm impinging a muddy, fossil-rich sea bottom. Contact of Kope and Fairview Formations. (A) The graded and hummocky stratification in a limestone bed forms in shallow water and the "stirred-up" mud is deposited downdip in less turbulent water by either a dilute density current or a muddy slurry (Miller and others, 1988, Fig. 5). Reprinted with the permission of the Society for Sedimentary Geology. (B) Giant *Isotelus* Ordovician trilobite smothered and buried alive by a mudflow. Photograph courtesy of Dan Cooper.

## Storms and limestone-shale interbeds

The explanation for coarse shelly limestones (turbulent water) interbedded with shale (quiet water) long troubled local geologists, but a solution was proposed in Europe in the early 1960's and is summed up in a single word: *tempestite.* Think as follows. Storm waves erode and resuspend muddy, shelly, unconsolidated bottom sediment, injecting it into bottom water as a cloud of skeletal debris, living bottom-dwellers, sand- and silt-size particles of carbonate, and silty, clay-rich mud. Such a mixture settles out by size—the larger particles almost at once and nearby, and the smallest much later as the finer debris is carried away. This differential settling effectively separates skeletal debris from mud and also grades the skeletal debris from coarse to fine as it settles out to form a limestone bed. During this process of settling, wave motion produces the wavy or hummocky stratification seen within the bed (Fig. 28). And what of the mud? Some of the suspended mud travels downslope along the bottom as a dilute density current, some as a dense slurry (mud flow) to form widespread mud blankets, and some is broadly dispersed as a dilute, turbid cloud. Modern muddy slurries move rapidly along the bottom (even on gentle slopes) and thus explain beautifully preserved trilobites and delicate crinoids being buried alive, as found in some Cincinnatian shales (Velbel, 1985; Schumacher and Shrake, 1996). Thus, these "slurry shales" with their transported, intact trilobites and buried-alive fauna are also event beds. The concept of tempestites goes far to explain much of the small-scale limestone-shale interbedding of the Cincinnatian Series and the beautiful sedimentary structures of these rocks.

On a larger scale, the seven far-ranging, 20- to more than 40-foot-thick "Big Shales" recognized in the Kope (Brett and Algeo, 2001) have a very different origin. Their great extent and thickness suggest a basinwide change in water depth. Separating the different kinds of shales in the Kope deserves much more attention.

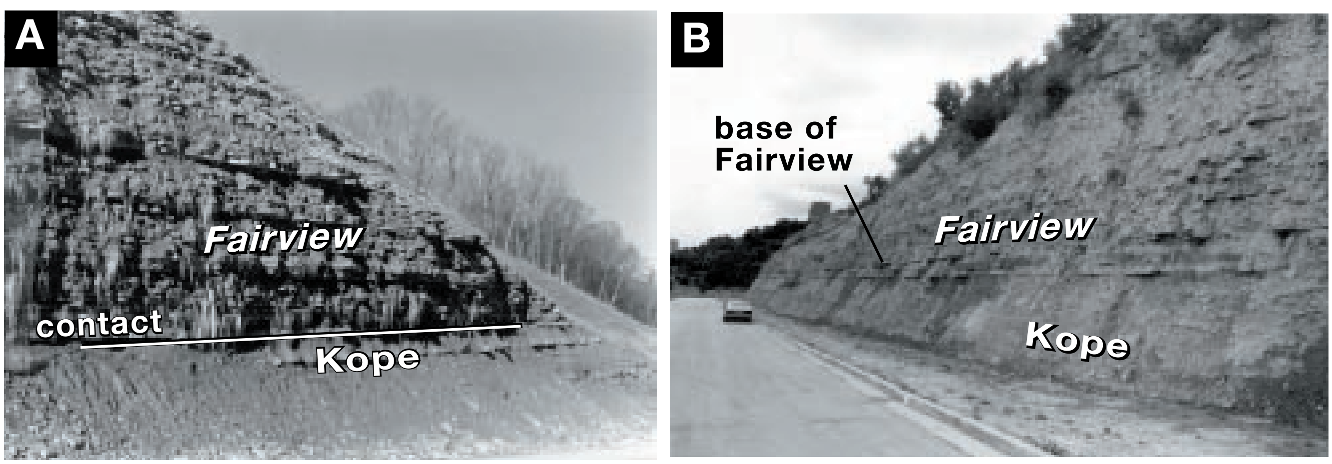




Figure 29. The Fairview-Kope contact is one of the most important for engineering geology in the metropolitan area (easy, secure siting in limestones versus trouble-prone siting in Kope shale). (A) Northwest corner of large cut on Ky. 17 about 2 miles north of Independence, Kenton County. (B) Exposure below Bald Knob on Radcliff Drive, South Fairmont neighborhood, Cincinnati. (C) New (2007) roadcut shows all of the Fairview and some units above and below it on Ind. 48 in Lawrenceburg, Dearborn County.

20 to 50 percent fossiliferous shale. The Corryville has about 35 to 70 percent shale interbedded with dominantly planar to lenticular limestones beds. The Mount Auburn has the most shale, about 50 to 80 percent, and contains wavy- to nodular-bedded limestones. Considering all the beds from the base of the Kope through the Bellevue, the Bellevue is the culmination of progressively shoaling waters.

The Arnheim, Waynesville, Liberty, Whitewater, and Drakes Formations are all recognized in Warren and Butler Counties. Because of both Wisconsinan glaciation and lesser relief, exposures of these formations are far less plentiful then those of the Kope, Fairview, and Grant Lake, however. The Arnheim is limestone-rich, whereas the Waynesville is shale-rich and is, in many ways, similar to the Kope. Both the Whitewater and Drakes Formations represent progressive shallowing of the sea bottom, and the Drakes is a good example of a carbonate tidal flat. The uppermost beds of the Drakes contain a few maroon shales in northeastern and northern Warren County. These red muds probably were derived from far to the east. Like the Bellevue, the Drakes represents the culmination of another shallowing cycle.

Just above these maroon shales are very different rocks: the Brassfield Formation, the lowermost easily recognized formation of the Silurian System. The Brassfield is only present as small outliers in parts of northern and eastern Warren County and at one outcrop in Milford Township in Butler County. Here it forms several low hills that rise 40 to 70 feet above underlying Ordovician rocks. The Brassfield consists chiefly of pink to medium brownish crinoidal and calcareous packstones with a few greenish-gray shale partings. It has well-developed fractures, which commonly feed springs at its base, above the more impermeable Drakes Formation. The environments of deposition of the Brassfield include several very thin, shallow-water marine cycles followed by tidal flats.

### *Sedimentation, Cycles, and Sequences*

Interbeds of shales and limestones are, second to its fossils, the most characteristic feature of the outcrops of the Cincinnatian Series and are best explained as the result of storms remobilizing shell-rich muddy bottoms (see boxed text on p. 45). This idea is attractive because deposits on modern marine stormy shelves have sedimentary structures similar to those of many of the limestones of the Cincinnatian Series. Other storm structures include crossbedding, gutter casts, some shallow channels, and possibly some of the large megaripples. During fair weather between storms, some mud also accumulated in lows on the ramp as a gentle "rain" or "snow." The deepest part of the ramp, on the other hand, borders the Sebree Trough, and in the trough dark gray, graptolitic shales predominate, the result of deposition from weak distal density currents. Some tidal currents may have also been present. Evidence for these currents is provided by back-and-forth prod casts (made by fossil debris) on some siltstones and ripples with variable orientation (nodular, bioturbated bedding has also been cited).

Deformed beds formed on the sea bottom and are present in the Point Pleasant and Fairview Formations and the Kope Formation in Clermont and Campbell Counties (Fig. 30). These range up to 6 feet or more in thickness, occur at selected horizons, and most are widely traceable, some as far as Maysville, Ky. (Brett and Algeo, 2001, p. 72–73; Schumacher, 2001). All formed by liquefaction in calcareous silts (calcisiltites) and fine calcareous sands on the sea bottom. Both seismic shocks and storms may have caused these beds.

The orientation of ripple marks and crossbedding, gutter casts, and fossils (graptolites in shales and mostly crinoidal debris in limestones) has been used to infer paleocurrent patterns in Cincinnatian rocks, but with diverse results (Hofmann, 1966; Potter and Pettijohn, 1977, Figs. 4-15–4-16; Jennette and Pryor, 1993). Armed with the recently recognized widespread lateral extent of many thin units, an effort to sort out these results should be rewarding.

The changing proportions of shale in the Ordovician outcrops of the Greater Cincinnati region (think Kope, Miamitown, and Waynesville versus Point Pleasant, Fairview, and Bellevue) suggest a formational cycle of about 300 feet and smaller subcycles of 15 to 60 feet (the submembers of the Kope, for example) and the smallest of, say, 3 feet (Fig. 31A). Cycles are an old topic in geology, one with many different views (see boxed text on p. 49). Such cycles have been recognized at all scales—thin to thick, short to long in time—but all are nothing more than recurring patterns of deposition. See Hay and others (1981), Tobin (1986), Jennette and Pryor (1993), Dattilo (1996), Holland and others (1997, 2000), Algeo and Brett (2001), Webber (2002), and McLaughlin and others (in press) for the evolution of ideas about cycles in the local rocks and Holland (in press) for an excellent summary on which much of this section is based.

The 3-foot cycles are typically best seen in the deep tidal and offshore beds such as those of the Kope, Miamitown, and Waynesville, where shale is abundant. Of the several cycles that have been proposed, the cycle by Dattilo (1996) is easy to visualize and accommodates variable thicknesses of both shale and limestone (Fig. 31A). Updip cycles have more limestone, whereas downdip cycles have more shale—think of the Sebree Trough filled with dark, graptolitic

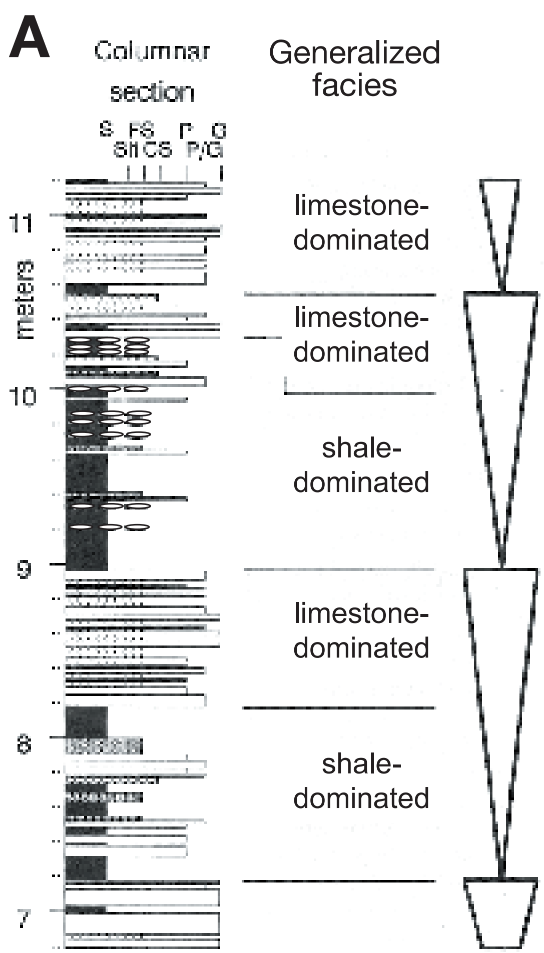
Figure 30. Thick, spectacular deformed bed near base of Fairview Formation on Cloverlick Creek near its mouth at Harshaw Lake in Williamsburg Township, Clermont County. Deformed bed is 4 to 5 feet thick.

shales (Mitchell and Bergström, 1991; Kolata and others, 2001). Flattened carbonate concretions (Fig. 31B), some longer than a foot and others only inches long, may be present in these cycles and mark a slowing of sedimentation (starvation surface). Storm beds predominate in the limestones of the upper part of the cycles where hardgrounds also may occur. Although not every limestone-shale sequence easily fits this pattern, the flexibility seen in Figure 31 makes it useful. As many as 41 of these cycles have been recognized in the Kope Formation (Holland and others, 1997, 2000, Fig. 1). There is as yet no consensus as to the origin of these cycles, but their traceability over distances as far as 50 miles points to a basinwide cause. Most likely this is either a sea-level or climate change (more rainfall in the source region supplying more mud to the basin or perhaps more storms).

Two thicker cycles have also been recognized: a group of cycles of about 15 to 60 feet and the other approximately on the scale of formations. Sequence stratigraphy is the key to understanding both of these larger cycles (see boxed text on p. 49).

Eight 15- to 60-foot-thick submember cycles are best seen in the Kope. Here, their basal parts are more shale-rich (seven widespread "Big Shales" are recognized in the Kope), whereas their upper parts have more limestone and a shallower-water, more robust fauna—clearly pointing to an upward shoaling that terminates with abrupt flooding by the shales of the next cycle. Brett and Algeo (2001, p. 65–92) recognized eight such cycles in the Kope, leading to eight named submembers. Basinwide changes of water depths that initiated abrupt flooding seem to explain these cycles.

The longest cycles are called *depositional sequences* and numbered C1 to C6. All six begin with initial flooding or deepening (as seen by both lithology and fossils), followed by a thicker interval of shallowing. In sequence-stratigraphic terms, the deepening beds above a disconformable contact (hardground, omission, or scour surface) mark a sequence boundary followed by a maximum flooding surface, and finally, the high-



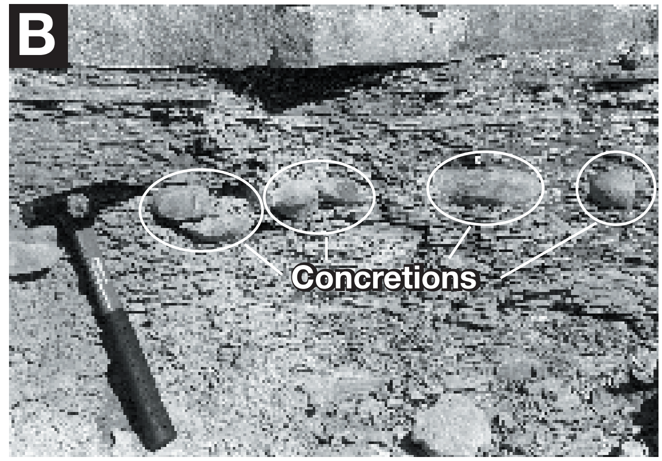




Figure 31. The 3- to 10-foot cycle of the Kope shale. (A) Cycles proposed by Dattilo (1996, Fig. 5), which include concretions. Reprinted with the permission of the International Paleontological Association. (B) Flattened, carbonate concretions seen at the junction of Ky. 8 and Ky. 445 in Campbell County, Ky.

stand beds of shallowing water. Sequences C1 through C6 have been widely identified across much of the United States (Holland, in press) and point to worldwide changes in sea level as their origin. McLaughlin and others (2004) showed how sequence stratigraphy was applied regionally to the Upper Ordovician outcrop. A future task is readily identifying sequences C1 through C6 in the subsurface.

### Fossils

Mention the words “Cincinnati Arch” to students of sedimentary rocks and fossils and most will instantly think of spectacular fossil-collecting plus many opportunities for paleontological study. And how right they are—all because of a happy coincidence of both abundant outcrops and invertebrate fossils. Fossils include bryozoans, brachiopods, mollusks (gastropods and cephalopods), echinoderms (crinoids, blastoids, and edrioasteroids), as well as corals, sponges, graptolites, and many varieties of trace fossils or ichnofossils (Fig. 32). A well-known and talented amateur group, the Dry Dredgers (drydredgers.org), has some 250 members and thrives on these local fossils. In addition, there are a thousand or more references to the paleontology and geology of the Cincinnatian Series (Davis and Cuffey, 1998). See also the comprehensive Web site, The Stratigraphy and Fossils of the Upper Ordovician Near Cincinnati, Ohio (www.uga.edu/strata/cincy/), for a growing list of these fossils. And both the city of Cincinnati and the state of Ohio have adopted Ordovician fossils as official fossils: the edrioasteroid *Isorophus cincinnatiensis* by the city (Stores, 2002) and the trilobite *Isotelus maximus* by the state (Hansen, 1985; House Bill 145).

Careful observation of the morphology (types), abundance, preservation (in-place or transported and abraded?), and placement of fossils in locally recognized cycles leads to sounder insights about paleowater depths and important details of deposition. For example, either storms or possible seismic shocks caused liquefaction of bottom sediment and far-traveled, water-bottom mud slurries that flowed downdip and buried intact trilobites (Fig. 28) and crinoids alive, as documented by Velbel (1985) and Hughes and Cooper

## Cycles and first steps in sequence stratigraphy

Repetition of beds and sedimentary cycles helps us organize, correlate, and understand the vertical sedimentary succession at individual outcrops and also helps correlate across wide areas—even entire sedimentary basins. These cyclic repetitions of sedimentary rocks have long been recognized from the scale of laminations (varves) to single beds (think of tempestites in single limestone beds) to cycles that range from a few to hundreds of feet in thickness (in the Kope and Fairview Formations, three cycles are recognized—about 3 to 10, 30, and 300 feet thick).

There is a vast literature about cycles. Four key questions help us clarify many of the issues that arise in discussion about cycles: (1) What are the recurring rocks or units of the cycle, the players? (2) Where does the cycle start and stop (this is the main reason five different cycles have been proposed for the 3- to 10-foot cycles of the Cincinnatian)? (3) What does the cycle represent (how did it form)? (4) And once recognized, what are they good for?

Cycles are of interest to geologists because they help us understand how a sedimentary basin was filled, and in so doing, help us physically correlate its rock units. It is here that sequence stratigraphy, developed in the 1980's, made a significant contribution.

Sequence stratigraphy is based on variations in relative sea level inferred from changes in deposition as water depths varied with time in and across a basin of deposition. Three factors are involved in relative sea level: (1) the subsidence rate of the basin, (2) its sediment supply (either carbonate mud and skeletal material produced within the basin or mud and sand brought into the basin), and (3) changes in world sea level. It is the interaction of all three that determines accommodation, the space available for deposition (water depth). There are many possibilities here. For example, think of a hardground as a starvation surface (ample space for deposition, but no supply, so bottom dwellers constantly rework the bottom sediment) or the contrasting limestone/shale ratio between the Kope and Fairview (there is ample accommodation for mud in the Kope, but less for the Fairview, with resultant winnowing of mud). Another possibility is a lowering of sea level sufficient to produce subaerial exposure (zero accommodation). Thus, as accommodation shifts across a basin from highstand of relative sea level (shoreline far inshore) to lowstand (shoreline far basinward), sedimentary environments shift to produce the changes we see laterally and vertically in outcrops and wells. Minor but traceable erosion surfaces bound such shifts and define the sequences we call C1 through C6. Because we live on a wide craton, changes in water depths extend over wide areas, and thus even thin cycles are likely to be traceable for many miles (Holland and others, 2006). A well-illustrated book on sequence stratigraphy is Coe (2002).

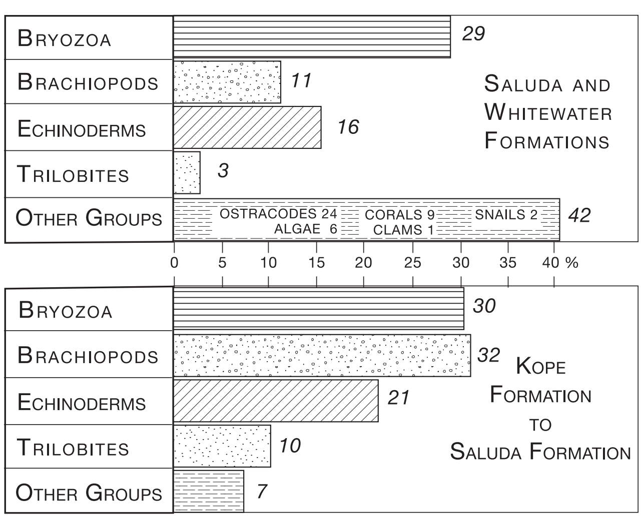



Figure 32. Fossil abundances of the Cincinnatian Series determined by thin-section study. After Martin (1975, Fig. 6). Reprinted with the permission of the Society for Sedimentary Geology.

(1999), whereas slower, normal, fair-weather sedimentation provided ample time for scavengers and currents to leave few bottom dwellers intact after death. Three excellent sources for local stratigraphic and sedimentologic literature are Davis and Cuffey (1998), Algeo and Brett (2001), and McLaughlin and others (in press).

Locally, a broad, shallow, gently northwest-sloping ramp flooded by warm, well-oxygenated water rich in nutrients—some nutrients derived from eroding mountains to the east and some from deep ocean water entering from the Sebree Trough—was an ideal setting for bottom life. Occasional storms deposited tempestites and slurry deposits, and longer term, accommodation oscillated between mud-rich Kope, Miamitown, and Waynesville and lime-rich Fairview, Bellevue, and Whitewater. But always, local invertebrate life flourished until the very end of the Ordovician, when the sea over the Cincinnati Arch suddenly shallowed, as shown by a touch of reddish unfossiliferous shales and fossil-barren, in-shore tidal deposits just below

Silurian beds at the very top of the Cincinnatian along the eastern side of the arch (Drakes Formation).

The great local abundance and diversity of Upper Ordovician fossils at the family and generic levels parallels changing abundances observed worldwide (Fig. 22). This great Ordovician Radiation was one of the most extensive radiations in geologic history (Miller, 1997; Sepkoski, 1997). It was interrupted abruptly, however, by a major extinction at the Ordovician-Silurian boundary (Fig. 33), and fossil diversity decreased by as much as one-third to one-fourth. One possible cause of this abrupt worldwide decrease in local fossil abundance may have been Late Ordovician glaciation (Fig. 22) that "locked up" seawater in widespread ice sheets that extended across several Southern Hemisphere continents (Brenchly, 2004). This would have caused world sea levels to fall and inland seas either to withdraw from continental interiors or become shallower. Thus, reduced fossil abundances and diversity in beds near the top of the Ordovician in the Greater Cincinnati area may well be linked to a worldwide cooling in Late Ordovician time (see "Geologic History and Influence of Far-Distant Events," p. 67, for more).

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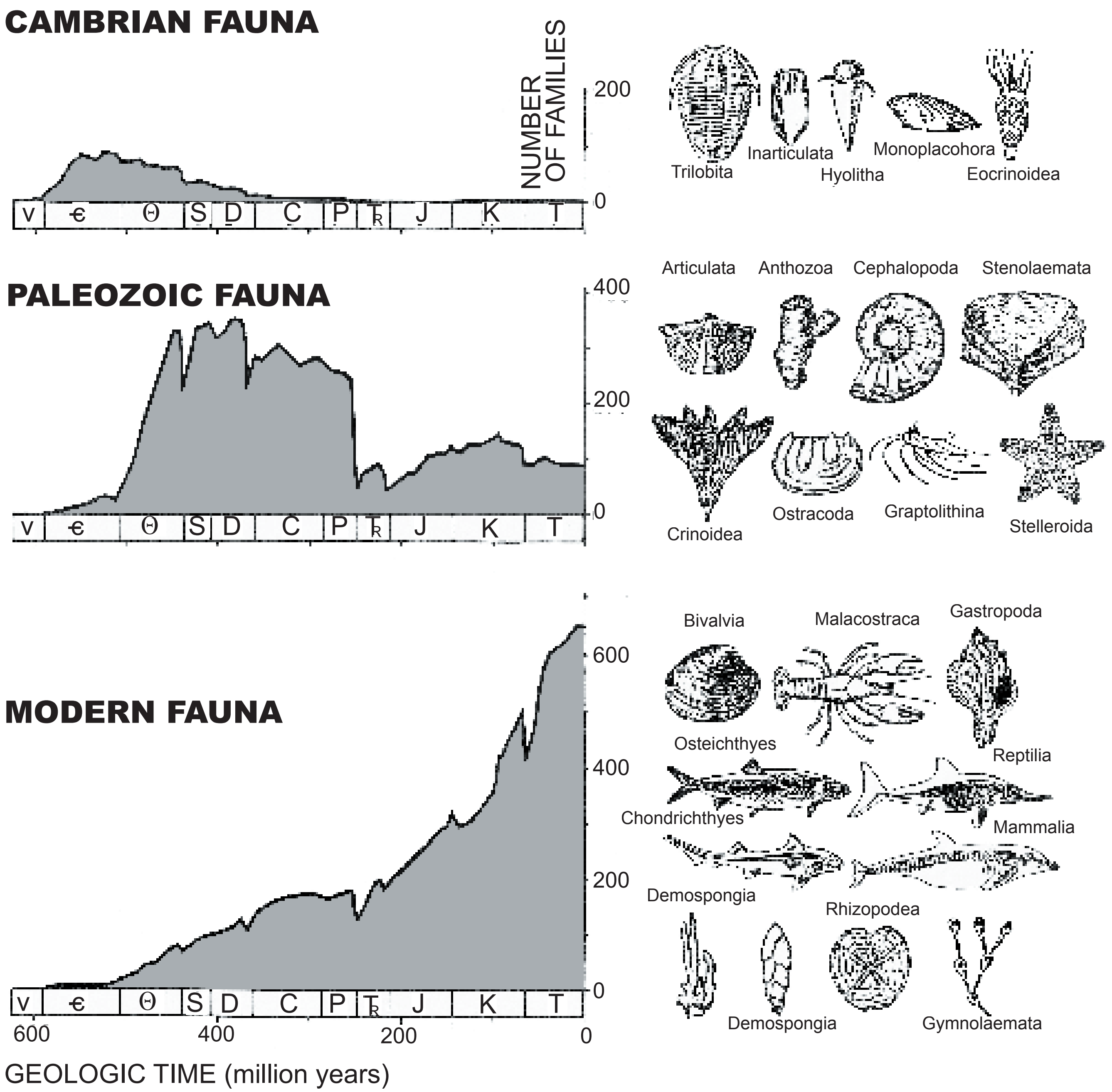


Figure 33. Long-term changes in the Paleozoic, Mesozoic, and modern faunas at the family level and some of their typical fossils. After Sepkoski (1984, Fig. 1). Reprinted with the permission of the Paleontology Society.

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## Geologic Structure and the Cincinnati Arch

To the casual eye, virtually all the outcropping beds of the Cincinnati region seem horizontal, and indeed their inclination is very low, nearly everywhere less than a degree. But careful mapping using either outcrop or subsurface well data reveals a consistent regional pattern of geologic structure: the Cincinnati Arch (Fig. 34). Why are such maps useful for a metropolitan area? First, such a map is a guide to the structure (the depth of buried geologic formations) with either economic or engineering significance that underlie the Cincinnati region. Second, the dip or structural attitude of the bedrock can often exercise control on (and thus help explain) the origin of both surficial deposits and landscape. The first structure map of southwestern Ohio was made from well data gathered for an early study of groundwater by Fuller and Clapp (1912). Later, Hofmann (1966) and Ford (1967), both using outcrop data, made structure maps for parts of Hamilton County. Subsequently, all the 1:24,000-scale geologic quadrangle maps for Kentucky, as well as all the open-file 1:24,000-scale maps for Ohio, showed structure, although not on a common horizon.

The highest and best-defined subsurface feature across the Cincinnati region is the top of the Black River/High Bridge Group with its associated bentonites, the Mud Cave (Millbrig) and the Pencil Cave (Deicke). Both bentonites are easy to identity on gamma-ray logs and in cores (Fig. 21). Both are only about 350 feet below the surface of downtown Cincinnati. The steepest structural dip on this buried surface is about 25 feet per mile in Carroll, Henry, Trimble, and Mason Counties, Ky., but more typical are dips from 7 to 10 feet per mile across much of Campbell, Kenton, and Boone Counties, Ky. In most of Hamilton, Butler, Warren, and Clermont Counties, Ohio, dips are less, normally between 4 and 7 feet per mile, chiefly to the north-northeast. It is this low dip—almost flat to the eye—that makes our skyline so level.

Two structural axes, both gentle and wide and yet clearly defined, dominate the Greater Cincinnati region. One, called the Cincinnati Arch, extends across the Tri-State from Harrison County, Ky., north to Hamilton County, Ohio, where it turns northeastward starting in Warren County, Ohio, and becomes the Findlay Arch. The other prominent arch extends from Hamilton County northwestward into Henry County, Ind., and beyond and is called the Kankakee Arch. A smaller, but very distinct structure, the Cairntown-Moscow Anticline, branches northwestward from the Cincinnati Arch in Pendleton County, Ky., and crosses the Ohio River between Point Pleasant in Clermont County, Ohio, and Foster in Bracken County, Ky. Roadcuts along Ky. 9 (the AA Highway) in Pendleton and Bracken Counties show some of the strongest dips of the Tri-State and are related to this structural axis, which brings the Point Pleasant Formation to the surface at its type section. A smaller and shorter structural axis, also diverging from the Cincinnati Arch, the Carrollton Nose, extends across Owen County, Ky., northwestward into Carroll County. This picture of gentle, patterned deformation at the top of the Black River/High Bridge Group adds more detail to the picture of deeper basement structure shown in Figure 6. The richly fossiliferous Upper Ordovician rocks of the Tri-State area are exposed only because of the broad uplift of the Cincinnati Arch, which had its beginnings in latest Ordovician/Early Silurian time (Fig. 34).

Superimposed on the features displayed in Figure 34, and mappable in areas of good outcrops, are much smaller, gentle folds, rarely more than 1 to 2 miles wide, that seem to occur all across the Cincinnati region. These folds are seen on the scale of a 1:24,000-scale map and can be significant in the design of a deep highway cut: When beds dip toward a rock cut, water will flow along bedding planes into the cut and en-

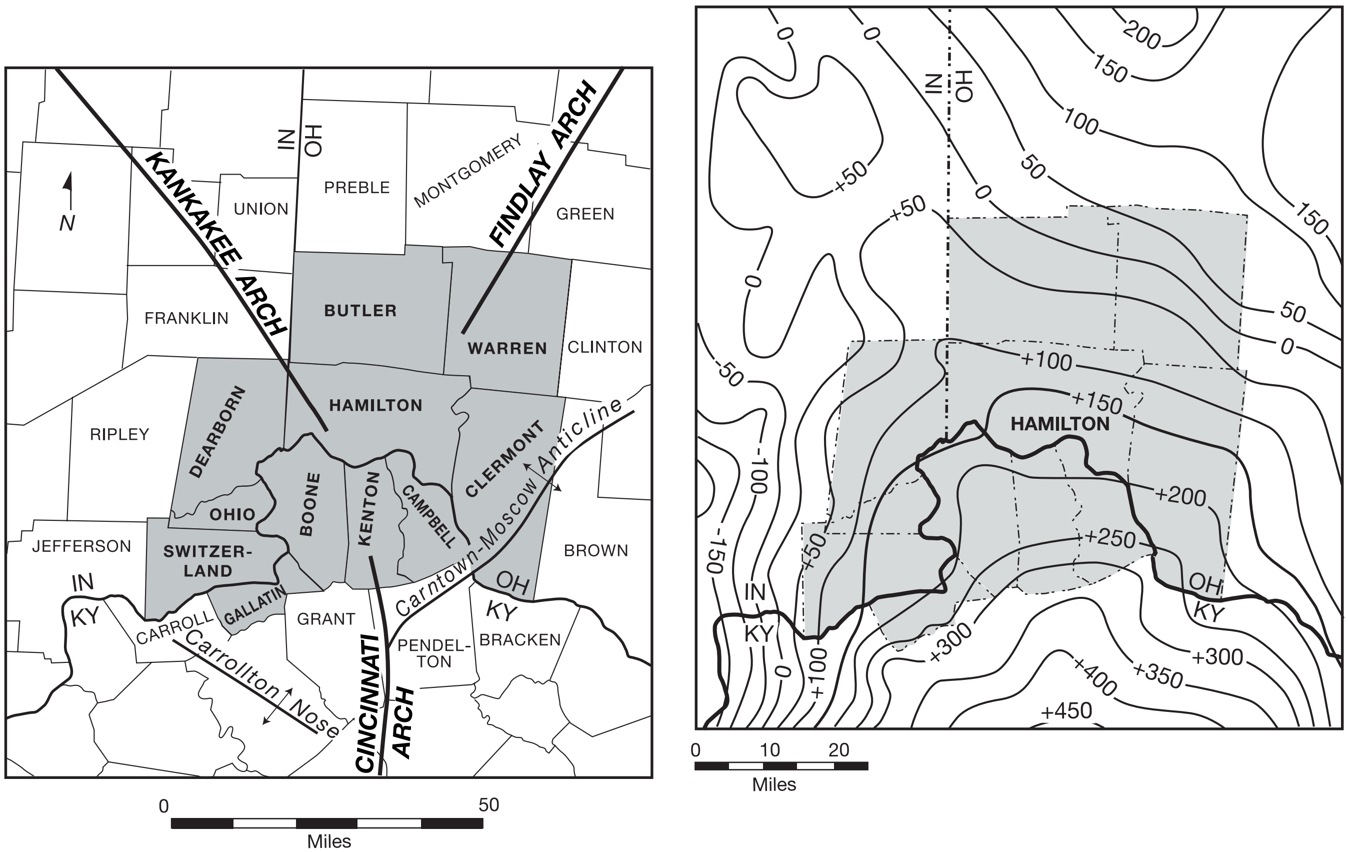


Figure 34. Structural setting. (A) Crests of arches in study area. (B) Structure of the top of the Black River. From Potter (1993, Figs. 1, 3).

hance the possibility of failure (see "Mass Wasting" in "Surface Processes," p. 75).

Fractures or joints are also present in all the well-bedded limestones, both in outcrop and at depth. Although there are little or no published data on the orientation of such fractures in the Cincinnati region itself, there is probably a regional joint pattern in the Cincinnati area similar to the one mapped across Indiana (Alt, 1989). Where glacial drift or residual soil is thin, solution may enlarge a joint, especially in the Fairview and other limestone-rich formations, and cause a fracture to have a linear surface expression.

Superimposed on regional patterns of joints are local joint sets related to valley topography, and small-scale structures also can be seen in some creek beds. These structures are mostly gentle upward folds called stream anticlines; some rare small-scale thrusts also occur. These thrusts are in deeply incised valleys, especially those that cut into the Kope, and are caused by lateral pressure from the valley sides (Ferguson, 1967; Matheson and Thompson, 1973). See Hofmann (1966) for a complete discussion of these interesting structures in Hamilton County, Ohio.

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## Glacial Deposits

The unconsolidated deposits of the Cincinnati region, also called soil or overburden (Fig. 35), vary from a few feet thick on uplands to 200 feet thick or more in valleys. Although such thicknesses are insignificant in comparison to the 3,500 feet of Paleozoic bedrock underlying the Cincinnati region, because we live on top of them, they have great significance for us. These deposits are of four major types: (1) glacial, (2) alluvial deposits (floodplains and terraces), (3) soils (plus colluvium), and (4) some very thin, wind-deposited loess. Because this unconsolidated material was the last deposited, it and the present landscape are intimately related (Fig. 36). Certainly it is fair to say that repeated continental glaciations during the Pleistocene Epoch have had a greater impact on the inhabitants of the Cincinnati region than any other event. Think of initial settlement on a glacial terrace safely above flooding by the Ohio River, subsequent industrial expansion northward in Mill Creek Valley, and how foundation design varies with different geologic materials (geotechnical engineering); contrast the calcareous porous soils developed on Wisconsinan deposits with those developed on leached, older, tight Illinoian soils, and the local political and cultural differences induced by the hilly topography bordering the Ohio River. It is worth remembering that the first geologic observations in 1796 by Volney (1803) noted terraces composed of material from the northeast and that soon afterward Drake (1815) and Lyell (1845) commented on local glacial deposits. Frank Leverett was, however, the first to map them systematically in 1902. Thus, since the very first geological observations in our region, the importance of glacial deposits has been recognized.

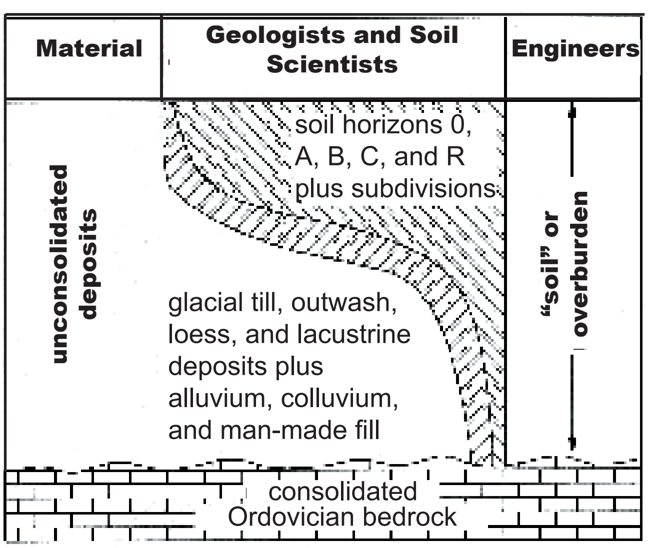


Figure 35. Diverse terminology used by soil scientists, engineers, and geologists to describe weathering and rock alteration at the earth's surface.

### *Types and Distribution*

The Greater Cincinnati region has two distinct and easily recognized deposits made by ice sheets and one or two less obvious ones (Fig. 1, Table 4). The well-defined deposits are called Wisconsinan and Illinoian and the older ones are simply called pre-Illinoian. These are older and less well-preserved glacial deposits, hard to separate one from another, and are found mostly in southeastern Indiana and south of the Ohio River.

Glaciers came to the Greater Cincinnati region late in geologic history—only in the last million years or so—and did not extend much farther south than the Ohio River, because as we saw earlier, much of the present Ohio River is an ice-margin stream. As ice sheets advanced south from Canada, they eroded bedrock and redeposited it in at least four different major ways: (1) as several types of tills in close contact with ice, (2) as outwash sand and gravel in valleys flooded by meltwater from the ice sheet, (3) as laminated clays deposited in temporary glacial lakes, and (4) as wind-blown silt called *loess* derived from braided valleys flooded with outwash. Collectively, all these deposits have been called *drift*, an Old English term that is still useful to be aware of, because it implies something out of place and foreign to the underlying bedrock, exactly what glacial deposits are.

All the unconsolidated deposits, glacial or not, are closely related to landscape and topography. This has given rise to the concept of a *geological land system*—the distinct elements that make up a landscape. A landscape system helps us make order out of complexity and it facilitates deductions about what underlies the surface. Our region has two very different land systems (Fig. 36).

Glacial tills are of four types (Fig. 37), and range widely in texture, depending on the type of depositional process and the kind of bedrock over which the glacier advanced. The term *till* is used only when we are sure of a glacial origin; if we are not sure, the broader term *diamicton* is preferred.

Typical lodgment tills in the Cincinnati region (Figs. 38–39) contain a wide range of clasts in an unstratified matrix of silty, gritty, compact clay and have a bluish-gray color when fresh. Some far-traveled igneous rocks are present (Fig. 40), including some large glacial erratics—an exceptional glacial erratic derived from local Silurian bedrock in Warren County was es-

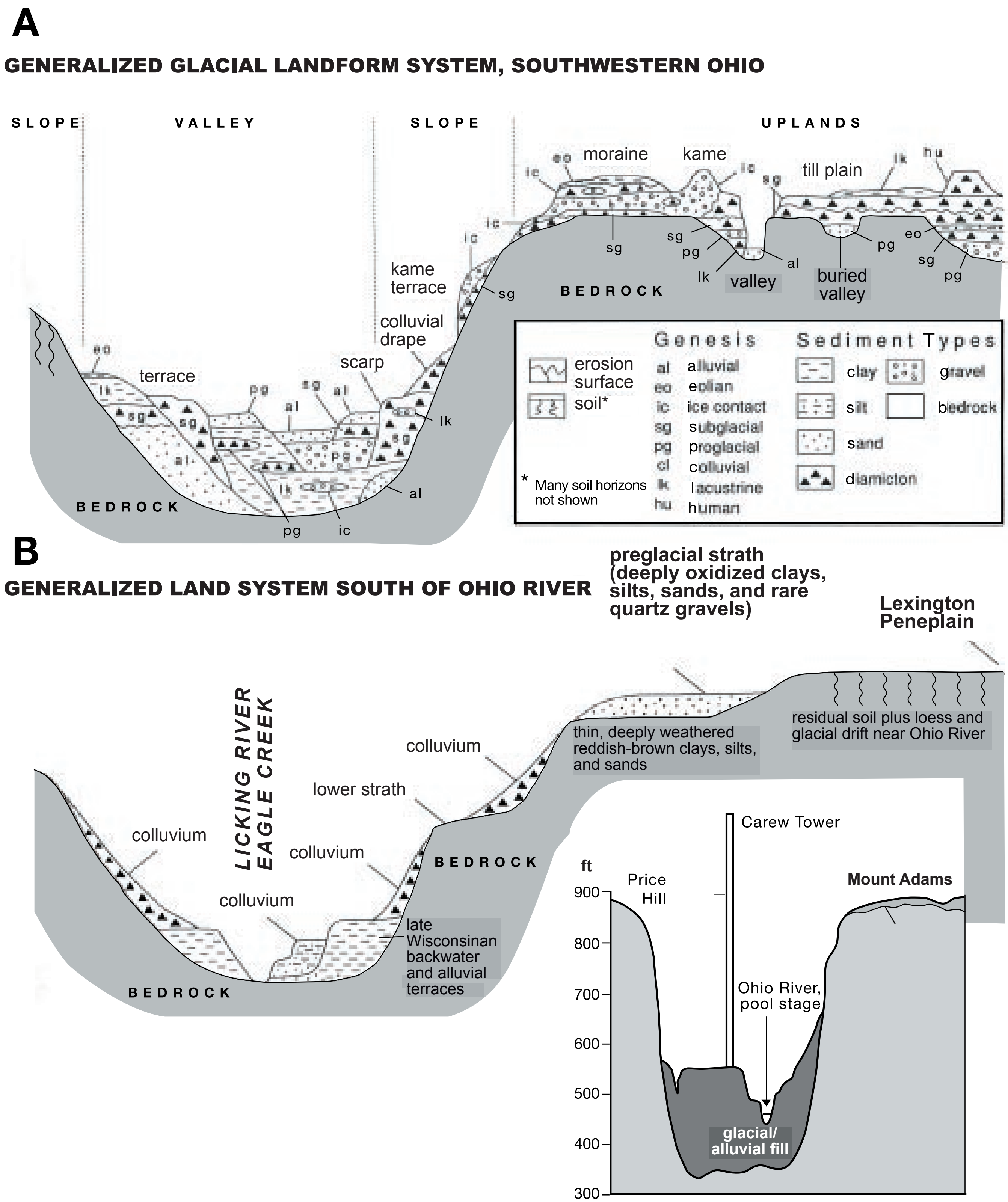


Figure 36. Generalized land systems. (A) Glacial landform system; applies to most of the study area north of the Ohio River. (B) Nonglacial land system; applies to most of the region south of the Ohio River, although some old, thin, limited glacial deposits are present in southeastern Indiana and parts of Kenton, Boone, and Gallatin Counties, Ky. Land systems diagram courtesy of Thomas Lowell.

**Table 4.** Distribution and kinds of Holocene, Pleistocene, and Tertiary deposits in 11-county study area.

<table>
<tr><th></th><th>Southwestern Ohio</th><th>Southeastern Indiana</th><th>Northern Kentucky</th></tr>
<tr><td>Holocene</td><td>Floodplains bordered by low terraces. Some small alluvial fans and several abandoned channels in lower parts of Little and Great Miami Rivers (the Oxbow).</td><td>Wide, majestic floodplain and very low terraces along Ohio River, but elsewhere floodplains are restricted and narrow.</td><td>Restricted floodplains except in Boone County along the Ohio River.</td></tr>
<tr><td>Wisconsinan</td><td>Well-defined terminal moraine, but thin, stony, calcareous tills on uplands, but much thicker deposits in both small and large valleys. Great Miami and Little Miami Rivers were principal meltwater sluiceways (thick outwash). Glacial landforms well preserved. Thin upland loess cap.</td><td>Glacial fill occurs only north of the Whitewater River where it is thin to moderately thick. Glacial landforms well preserved. Thick outwash and spectacular outwash terraces in Whitewater valley. Thin upland loess cap.</td><td>Only Wisconsinan outwash terraces in Boone and Gallatin Counties along Ohio River, but backwater fill and terraces along the Licking River and Eagle and Gunpowder Creeks. Thin loess cap.</td></tr>
<tr><td colspan="4">Sangamonian<br>Few, if any, deposits recognized, so interval preserved mostly in soil profiles south of limit of Wisconsinan ice.</td></tr>
<tr><td>Illinoian</td><td>Till, with some gravel and sand interbeds, covers most of the upland of Clermont and parts of Hamilton Counties, and like Wisconsinan deposits, is thickest in former Teays valleys. High terraces near Coney Island probably Illinoian (till in adjacent tributary creeks flowing into the Ohio River). North-flowing valleys and those joining major sluiceways likely to have lacustrine clays. Mass wasting has destroyed almost all glacial relief. Well-developed fragipan soils.</td><td>Till not identified in outcrop, but some buried outwash along sides of Ohio River Valley in Ohio and Switzerland Counties is possible.</td><td>Till not recognized except for a possible small area in northern Campbell County, but some highly weathered gravel terraces in Boone County may be Illinoian.</td></tr>
<tr><td colspan="4">Pre-Illinoian<br>Scattered deposits of this long interval occur on uplands in a narrow band south of the Ohio River in Kenton, Boone, and Gallatin Counties and on uplands in Dearborn, Ohio, and Switzerland Counties, and in southwestern Hamilton County. All have deep weathering profiles capped by Wisconsinan loess and all are best preserved in small upland valleys. At least two tills are present. Ages are uncertain, but it is likely they predate Deep Stage entrenchment.</td></tr>
<tr><td colspan="4">Tertiary<br>Only deposits may be those of the shallow pre–Deep Stage valley of the Licking River.</td></tr>
</table>

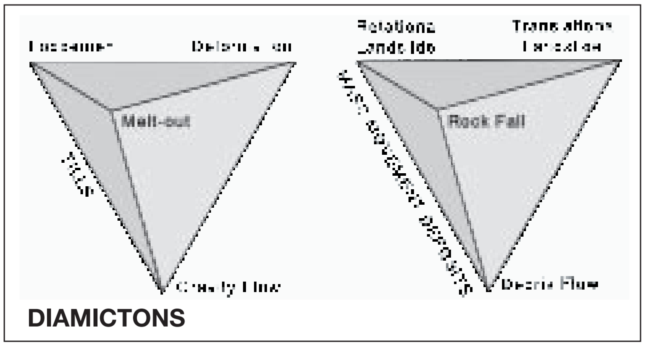


Figure 37. Diamictons include four types of glacial till: lodgment (massive and deposited directly from and under the ice), deformation (contorted by ice movements), melt-out (somewhat sandy and partially stratified), and gravity-flow (a mass-movement debris on the surface or in front of the ice). Modified in part from Dremanis (1988, Fig. 1).

timated by Wolford (1942) to weigh about 13,000 tons. Characteristically, however, dominant clasts by far are limestones derived from the local Cincinnatian bedrock. Glacial striations and facets are common on many of the clasts embedded in these tills. The landform expression of till includes ground and terminal moraines, both of which are easy to recognize in Wisconsinan landscapes of the Tri-State, but are less obvious in the landscapes of the earlier ice sheets that occur in most of Clermont County, Indiana's three southeasternmost counties, and Kentucky, where erosion has greatly modified the original glacial landscape. Dense, overcompacted clay- and sand-rich tills prevail in most of the Cincinnati region and are excellent for foundations of all types and, because they transmit fluids poorly, are good sites for landfills where they are thick and the site is properly prepared (conversely, they are very poor for home septic tanks).

Stratified glacial materials include all those deposited by meltwater from ice. Well-stratified and well-washed sand and gravel called *outwash* (Figs. 41–44) occur along the glacial sluiceways of the Tri-State area; much less commonly they occur in sand and gravel as scattered, low hills composed of sand and gravel called *kames,* the best examples being along Ohio 741 just north of Mason in Warren County (Fig. 45). See Webb (1970) for careful documentation of outwash in southeastern Indiana along the Ohio River, and see Cobb and Fraser (1981) for the general pattern of downstream variation of size and sorting in glacial outwash. Illinoian and older outwash deposits can be partially or almost totally cemented, as, for example, at the bluffs of Boone Cliffs in western Boone County, Ky. (Fig. 43). Lacustrine deposits (Fig. 46) are another type of glacial stratified material: clays, silts, and fine sands that were deposited in a temporary lake when an ice mass or its aggrading outwash dammed either a major preglacial valley or a smaller side tributary of such a sluiceway. Also it is good to remember that even the smallest glacial, north-draining valley probably has some lacustrine clays. The best ex-

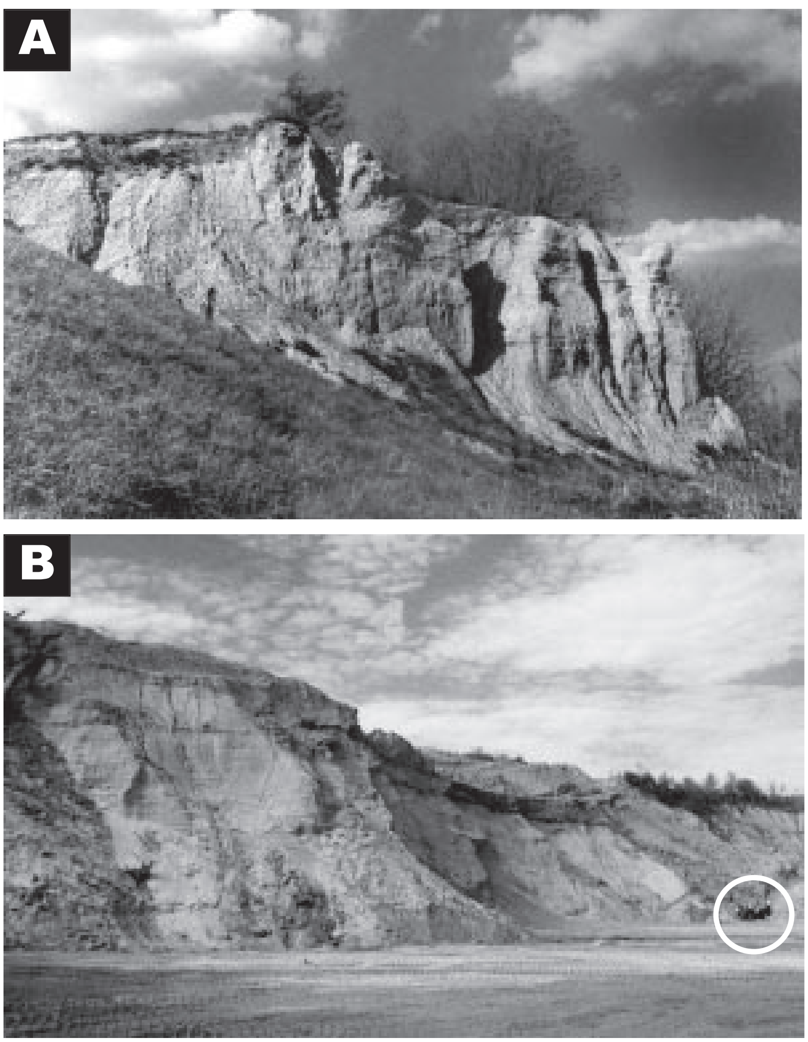


Figure 38. Pre-Wisconsinan deposits in middle Mill Creek Valley. (A) Illinoian till, slightly stratified at former Elda landfill. (B) Underlying, pre-Illinoian unnamed quartz-rich sand in nearby former Rack Brothers pit. The quartzose character of sand in the pit shows that it was deposited by the preglacial Licking River flowing to the north. Circle indicates visiting geologists.

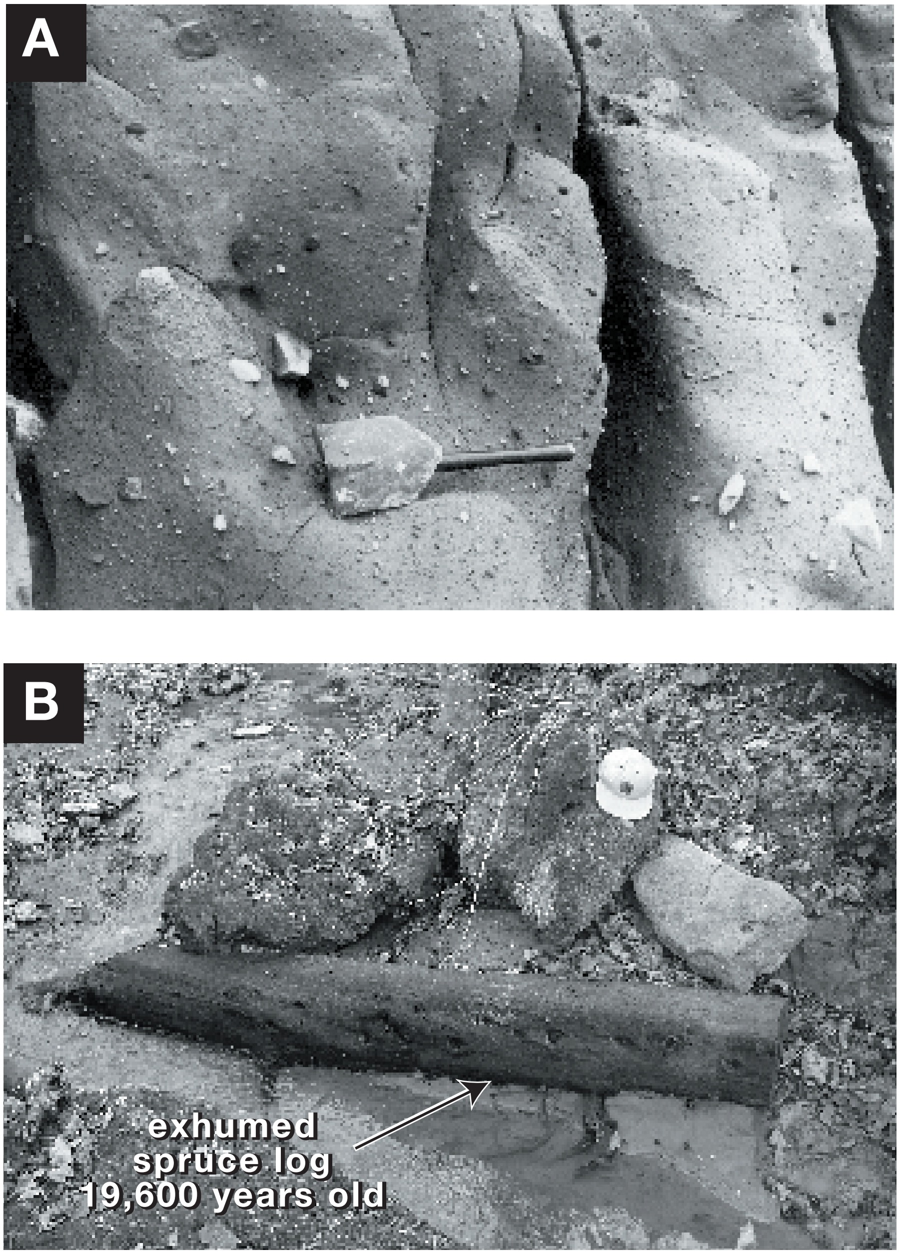


Figure 39. Wisconsinan deposits. (A) Typical unstratified clay-rich till with randomly scattered clasts. (B) A 19,600-year-old spruce tree overrun by ice and buried in till at side by Mill Creek Valley in Sharonville, Hamilton County. Photos courtesy of Thomas Lowell.

amples of lacustrine deposits in the Cincinnati region are in the valley of the Licking River, where they are 70 to 90 or more feet thick and form conspicuous terraces called *slackwater terraces.* Other deposits occur along almost all the smaller tributaries of the Ohio River and along the sides and tributaries of Mill Creek. Preglacial valleys draining northward commonly have lacustrine clays, because they were blocked by advancing ice. Lacustrine clays are very fine grained and subject to landslides, even on low slopes. Hence, identifying their occurrence is vital.

Windblown loess, mostly fine silt with some clay and minor very fine sand, is also present as a thin cover in all 11 counties (Ruhe, 1983). Although never conspicuous, it was given much attention by Fenneman (1916). Loess forms an integral uppermost part of most soils in the Cincinnati region. Thicknesses of 1 to 3 feet are present along glacial outwash streams. This thin

Figure 40. Large glacial boulder at Rock House County Park (near Ohio 123 and Interstate 71) in Warren County. The boulder was carried from Canada by Wisconsinan ice.

cover is most apparent on Illinoian or older landscapes, where it overlies a buried or residual soil. Weathering after deposition commonly has enhanced the clay content of this loess, which after years of leaching is nearly always noncalcareous.

The thickness of unconsolidated deposits is mapped using data from water wells and other sources to produce either a drift-thickness (Powers and Swinford, 2004) or bedrock-topography map; the latter outlines the relief of the buried bedrock surface. Both maps are among the most valuable that the geologist can make, and answer these questions: How far to solid rock? How thick are possible aquifers? Where are potential sources of sand and gravel? In the Cincinnati region there is a distinct correlation between drift thickness and topography: upland areas have the thinnest drift, whereas valleys have the thickest. Excluding rare and isolated kames, drift on uplands tends to be thin—large areas have less than 20 feet and some only a few feet—whereas drift in both large and small valleys is thick, for several reasons. First of all, remember that ice, water, and debris always move toward a topographic low. Thus, major sluiceways such as the Great and Little Miami River Valleys have thick outwash, lacustrine, and till deposits, some 120 feet or more. The thickest drift in the Cincinnati region appears to be in the Great Miami Valley, near Franklin in Warren and Butler Counties, where over 250 feet is reported. Smaller valleys tended to be filled with a thin basal lodgment till, followed by flow tills and other gravity deposits—water and debris always flow toward a topographic low—plus possible lake clays, and later with tills and outwash. In sum, glacial sedimentation is best preserved in preglacial valleys, both large and small. The sand and gravel deposits of these glacial valley fills are the best source of groundwater in the Cincinnati region. In the old glacial deposits of northern Kentucky, the best outcrops occur in small preglacial valleys on the uplands (where drift was initially thickest and best protected from long erosion).

Each glaciation blocked or diverted preexisting drainage and produced a wide variety of diversions, well summarized by Durrell (1961, 1977). These diversions included abandonment of major valleys, as well as the formation of short, steep-sided narrows. Examples of major abandoned valleys include the drift-filled valley of the Norwood Trough, all of Mill Creek Valley, and the wide valley between Fernald and Harrison in Hamilton County (Fig. 9C). Examples of narrows include the Little Miami River from south of Waynesville to near Morrow in Warren County and from South Lebanon to Loveland in Clermont County; the valley of the Great Miami River from south of Fernald to Cleves; the drainage divide at Anderson Ferry (Fig. 13); the Dry Fork of the Whitewater River north of New Haven in northwestern Hamilton County (Fig. 9C); and the narrows of Caesars Creek below Caesars Creek Reservoir in Warren County. Another abandoned valley extends from Kings Mills to Middletown, where it contains more that 200 feet of glacial fill, the upper part of the fill capped by substantial lacustrine deposits. Each of the larger abandoned valleys is a major aquifer.

### *Dating Local Ice Sheets*

Establishing the ages of Wisconsinan and Illinoian ice sheets of the Greater Cincinnati region is fairly straightforward, using wood for radiocarbon dating for Wisconsinan deposits (Lowell and others, 1990) and evidence from ice volumes from a famous ice core drilled in the Antarctic ice cap (Alley, 2000). But the age of the earlier ice sheets of northern Kentucky and southeastern Indiana, plus the dating of the Deep Stage entrenchment of preglacial drainage, remain elusive. There are two reasons for this—one instrumental and the other geological. The instrumental reason is simple: at present we have no single instrumental method (or combination of methods) for easily dating Pleistocene events extending back 1.8 million years. Second, outcrops of the pre-Illinoian deposits are few, scattered and mostly separated from Illinoian and Wisconsinan deposits by the deep entrenchment of the Ohio River and its tributaries. Thus, their pre-Illinoian ages remain speculative, although earlier workers were bolder and assigned them to the Kansan and Nebraskan ice advances (Ray, 1966). Figure 47 provides one interpretation of the ages of all the glacial deposits in the study area, but be aware that there may be other interpretations for the pre-Illinoian deposits.

Many radiocarbon dates establish the last Wisconsinan ice advance at Sharonville, which buried a spruce forest along the sides of Mill Creek Valley,

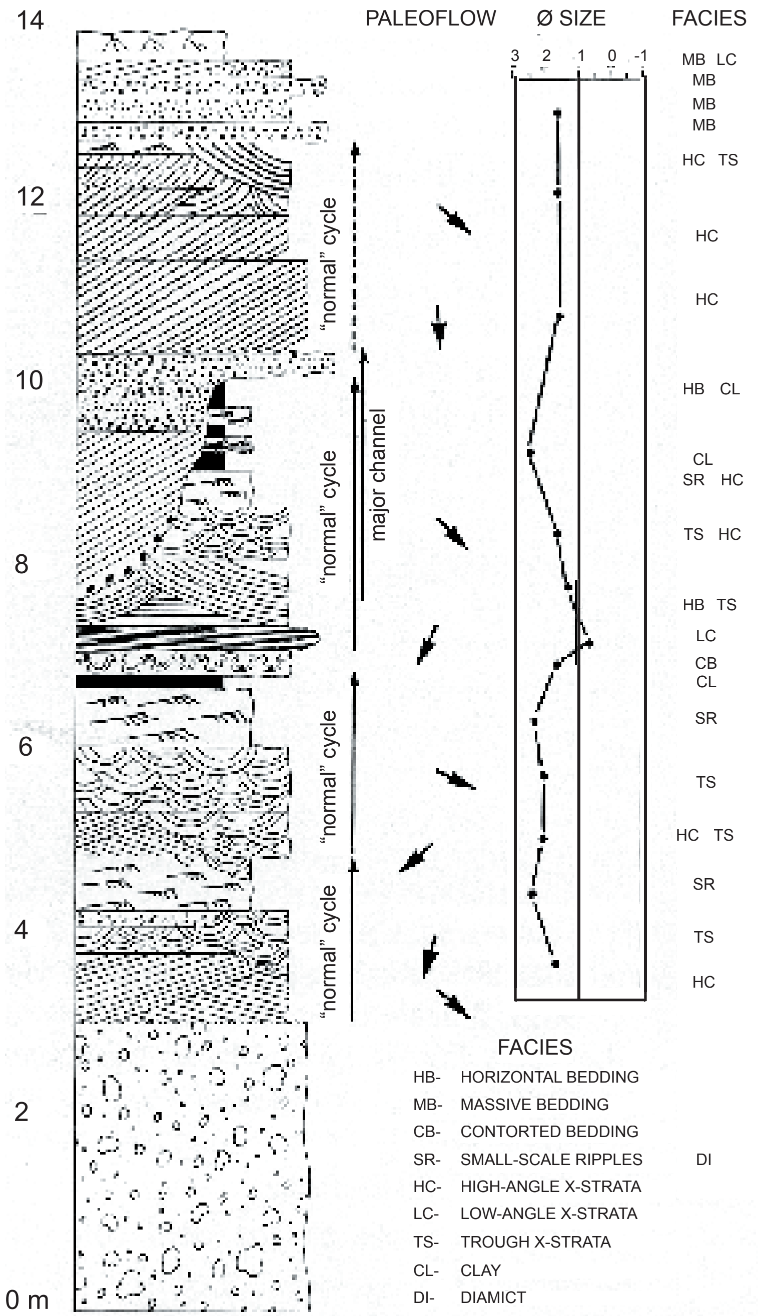


Figure 41. Detailed diagram of glacial outwash overlying a diamicton in the cutbank of Dry Fork of the Whitewater River, Miami-Whitewater County Park, western Hamilton County. Courtesy of Mark Barnhart. Section is about 300 feet southwest of the intersection of West and Timberlake Roads. Arrows show paleocurrent directions of the now-vanished streams that deposited these sands and gravels (only Dry Run remains).

at 19,600 years before the present (Lowell and others, 1990). This was followed by deposits of thin loess derived from Wisconsinan outwash (Ruhe, 1983). Judging by the Vostok core in Antarctica (Alley, 2000), the Illinoian ice sheet was present in our area some 150,000 years ago when it blocked the northern loop of the ancestral Ohio River at Hamilton, filled the Norwood Trough with drift, and caused the diversion of the Ohio River at Anderson Ferry.

Qualitative evidence also supports the date of about 150,000 years for the Illinoian ice sheet. This evidence is provided by comparison of the comparative morphology and soil development of Wisconsinan and Illinoian ice sheets. Wisconsinan landscapes have calcareous soils with good tilth and freshly minted glacial landscapes plus clearly expressed terminal and ground moraines, whereas older, Illinoian landscapes have leached, tight soils with well-developed fragipans and few landforms of glacial origin. Thus, *qualitatively* we have good consistency between absolute age estimates and relative geologic preservation.

But farther back in time beyond the Illinoian ice sheet, we can only speculate about the ages of the drift sheets in Kentucky and southeastern Indiana. Judging by their limited preservation and geomorphic expression, they were deposited before the initial entrenchment of the Licking River, before the Deep Stage. Three cosmogenic dates point to an early glaciation in the eastern Midwest at about 1.13 million years ago (Granger and Smith, 1998). Thus, these pre-Illinoian ice sheets could be at least middle or early Pleistocene in age. Determining the age of the Deep Stage entrenchment, the age of the Claryville Clay in Campbell County (Teller and Last, 1981), and the age of the pre-Illinoian ice sheets is a major goal of local Quaternary geology.

Figure 37 also demonstrates how important it is to be aware of the short time that ice sheets in the Cincinnati area were present in comparison to the long intervals of their absence (Alley, 2000, Figs. 11.1–11.2). Judging by ice volumes, the cycle is as follows: short-lived ice sheets in the study area → rapid warming (our era) → long interval of gradual cooling → short-lived ice sheet. Between ice sheets there is leveling of topography by erosion and accelerated soil development, whereas beyond each ice sheet soil development continued, producing leached, tight soils, some of which (Avonburg and Clermont Series) are present today (unless buried and preserved as unmodified paleosoils by later ice sheets).

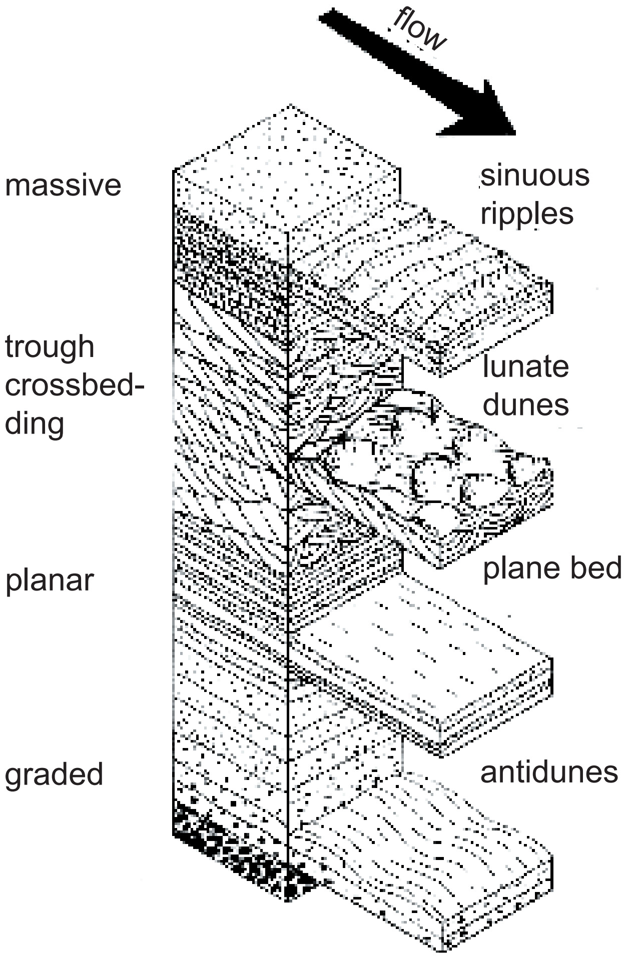


Figure 42. Typical sedimentary structures and their vertical sequence in fluvial deposits. Modified from Shelby (1985, Fig. 9.11). Reprinted with the permission of Oxford University Press.

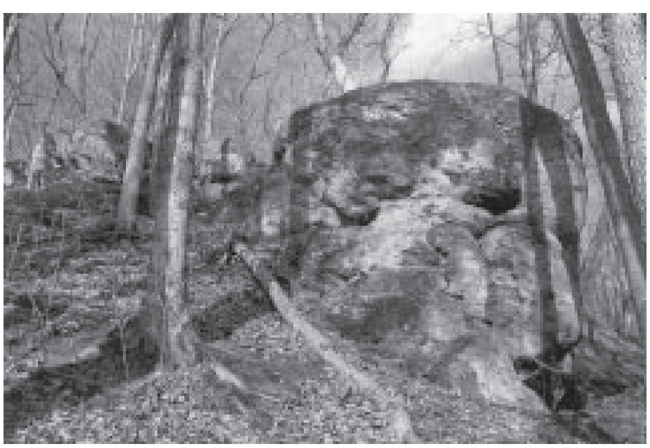

Figure 43. Bluffs of cemented pre-Illinoian outwash gravel at Boone Cliffs Nature Preserve, far western Boone County. The position of these gravels on high uplands is a good indication of their antiquity.

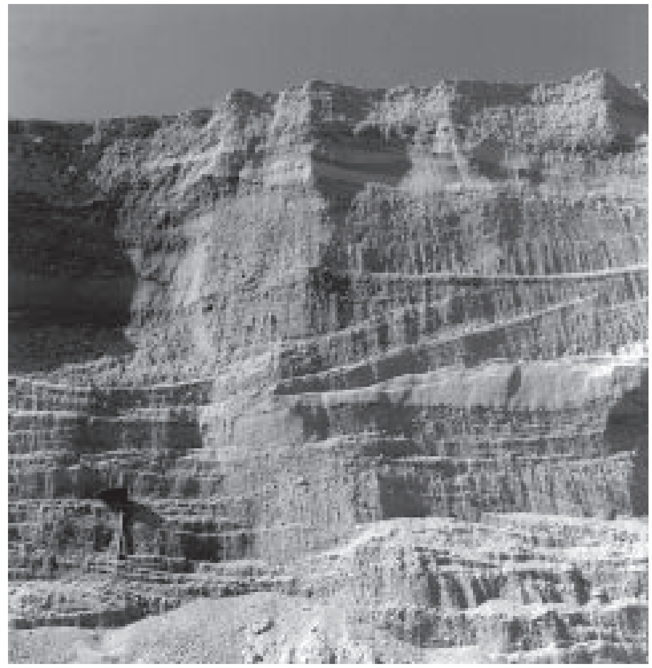

Figure 44. Well-washed and stratified outwash sand and gravel near Harrison, Hamilton County. These deposits furnish relatively inexpensive sand and gravel to the northern Kentucky/Cincinnati region. Compare with Figures 46 and 47.

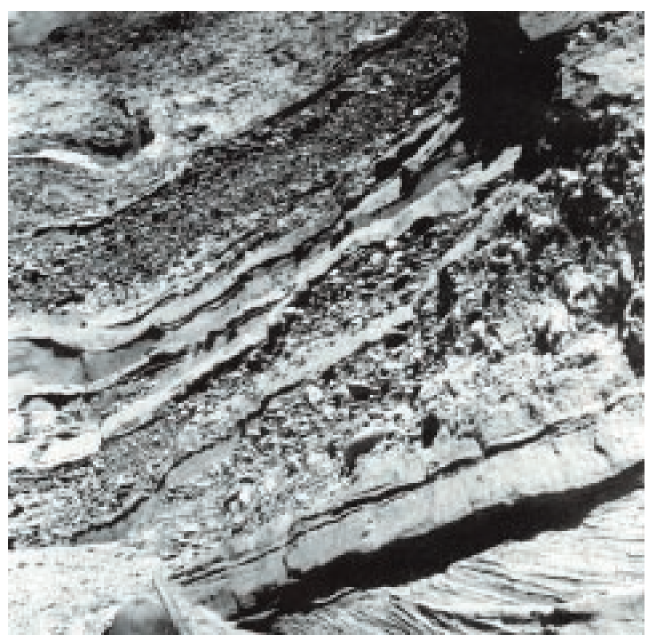

Figure 45. Contrasting types of stratification in a kame may include steeply dipping beds. Unsteady flow in this ice-margin setting near Mason, Butler County, Ohio, produced this stratification.

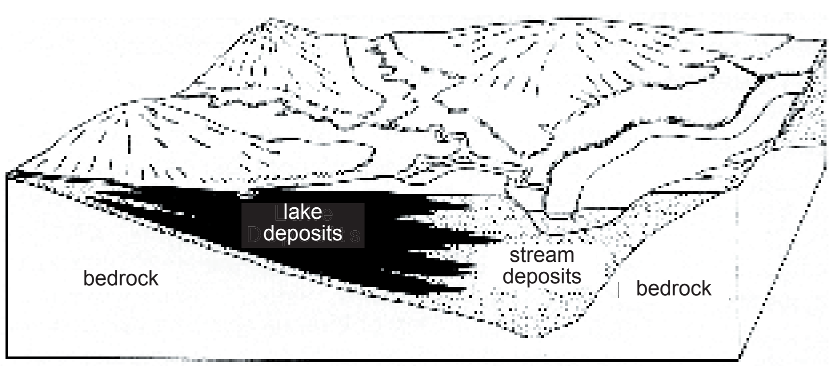


Figure 46. Relation of lacustrine backwater deposits to a glacial sluiceway (Gray, 1971, Fig. 1). As a main valley aggrades with outwash, its tributaries are dammed and flooded and trap fine sands, silts, and clays in temporary lakes. Such clays can fail on very low slopes; thus, recognizing them is of great importance to engineers, builders, and homeowners. (Hint: lacustrine clays are common in north-trending valleys overrun by advancing ice.) Such clays are also a poor source of groundwater because they are of low permeability. Reprinted with the permission of the Indiana Geological Survey.

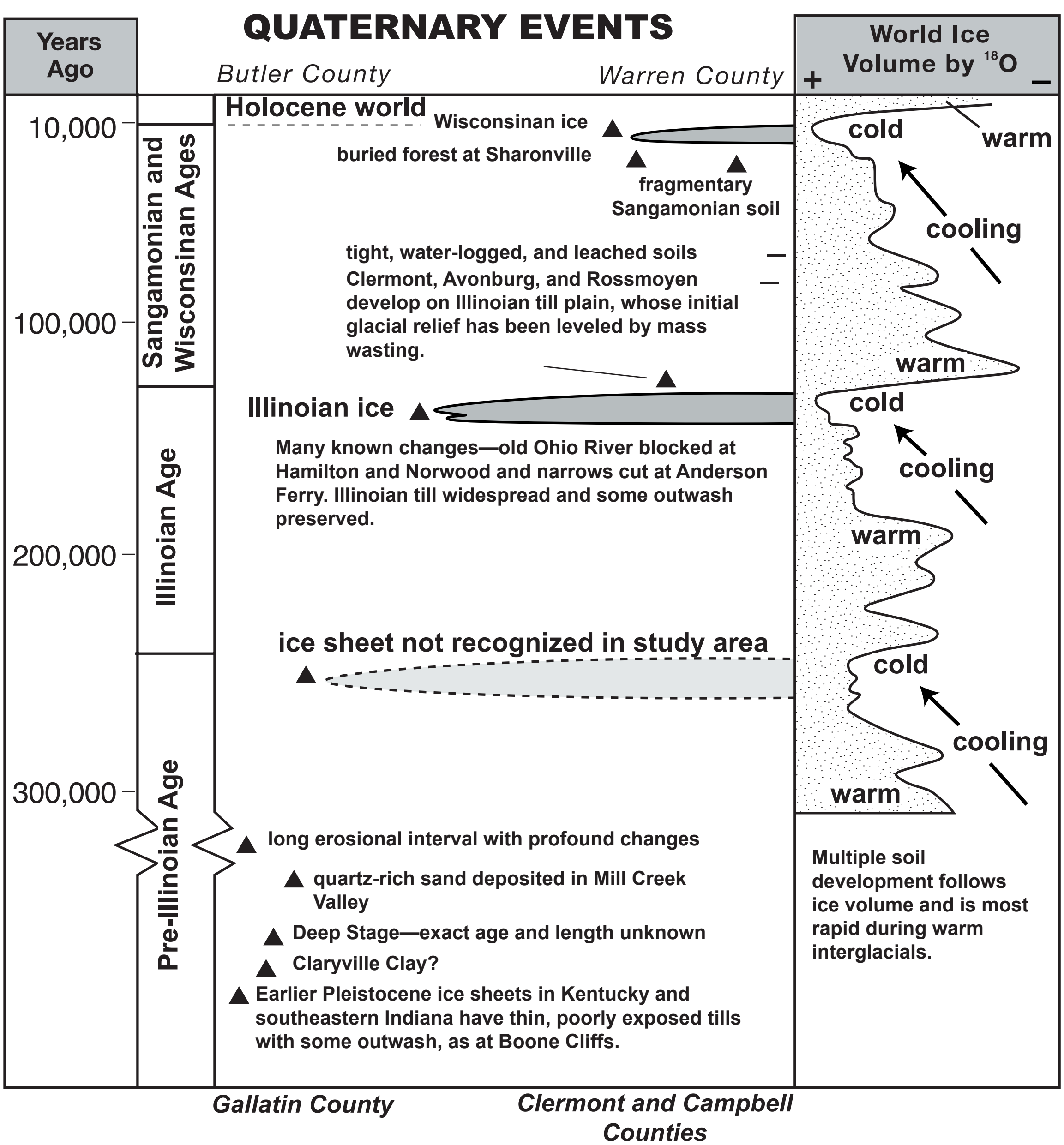


Figure 47. Interpretation of ages of ice sheets and selected glacial deposits in the 11-county study area. Inspired by Thomas Lowell.

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Wolford, J.J., 1942, A record size glacial erratic: American Journal of Science, ser. 5, v. 24, p. 362–367.


### Digging Deeper

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Subtitled "Ice Cores, Abrupt Climate Change and the Future," this readable book provides a good introduction to the Vostok ice cores taken by the Russians in a remote part of Antarctica. See especially Figures 11.1 and 11.2. It is worth your time to look at this book and related sources.

Amaral, E.J., 1994, Sand and gravel resources along the Ohio River in Boone, Gallatin, and Carroll Counties, Kentucky: Kentucky Geological Survey, ser. 11, Report of Investigations 8, 59 p.

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its clear presentation of the stratigraphy of these deposits and for its regional overview of Pleistocene history. It is an excellent source of data on an increasingly valuable resource for the northern Kentucky/Cincinnati/southeastern Indiana region. It contains two extended appendices and over 50 references.

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This detailed delineation of the unconsolidated deposits of Indiana is rich in details, recognizing many subdivisions.

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This detailed article by soil scientists and a glacial geologist describes an important glacial outcrop.

Pavey, R.R., Goldthwait, R.P., Brockman, C.S., Hull, D.N., Swinford, E.M., and Van Horn, R.G., 1999, Quaternary geology of Ohio: Ohio Division of Geological Survey Map 2, scale 1:500,000.

This latest map of Ohio's unconsolidated deposits recognizes six major units, some with as many as eight subdivisions.

Powers, D.M., and Swinford, E.M., 2004, Shaded drift thickness map of Ohio: Ohio Geological Survey Map SG-3, scale 1:500,000.

This attractive, detailed, color map of drift thickness (bedrock elevations subtracted from surface elevations) has a short text and four small supplementary color figures.

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This is a good, short introduction to these interesting early deposits, including the glacial gravels at Boone Cliffs in western Boone County.

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Brief text accompanies a remarkable colored regional thickness map extending from west of St. Louis into eastern Ohio. See also Soller (1998b).

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This easy-to-read paper provides a compact history of the study of glacial deposits in much of the Midwest, and specifically mentions early workers in Cincinnati and Ohio.

## Geologic History and Influence of Far-Distant Events

Thus far we have largely focused on the rocks and deposits in and near the Cincinnati region. Now let us turn our attention to a very different topic: relationships between local geologic features and features of a subcontinental, continental, intercontinental, or perhaps even a global scale. In other words, let us relate local geology to big-picture geology (such as possible distant continental collisions) or to even larger and truly global events (such as changes in world sea level or global cooling). In short, let us not hesitate to look far afield in our search for explanations of local geology.

At least 10 major events stand out in the geologic history of the Greater Cincinnati region (Fig. 48). The earliest and least understood is the deep seismic layering that has been widely identified in the eastern Midwest. Two younger Precambrian events are those that formed the overlying Eastern Granite-Rhyolite and Grenville Provinces, which are about 1.3 to 1.5 and 0.9 to 1.1 billion years old, respectively. Between these two provinces, and possibly above and younger than both, are the thick, reddish sandstones of the Middle Run Formation. A major unconformity at the base of the Paleozoic overlies all three formations. The first Paleozoic marine sea flooded this ancient landscape and culminated in the Great American Tidal Flat. This vast tidal flat was followed by another major unconformity, more carbonates (some including widespread bentonites), the great abundance of invertebrate life in the Upper Ordovician, the formation of the Cincinnati Arch, the Teays drainage system, and most recently, Pleistocene glaciation, which largely created our present landscape (Table 5).

### *Precambrian*

The deep, widespread, layered material that underlies much of the Eastern Granite-Rhyolite Province is believed to be of Proterozoic age and seems to represent one or more great sedimentary basins, whose existence was never suspected until first noted by oil companies in the 1980's and by a consortium of universities called COCORP (Hansen, 1987, 1989). This deep layering extends at least 8 to 10 miles below the surface, and little else is currently seen below it on seismic records. Because it has never been drilled, we know very little about it.

Overlying the deep-layered sequence are the rocks of the Eastern Granite-Rhyolite Province, formed about 1.3 to 1.5 billion years ago. These rocks can be seen at the surface in the St. Francis Mountains, where they are the core of the Ozarks in Missouri. East of this province is the Grenville Province. The Middle Run Formation occurs in a north–south band roughly along and subparallel to the common boundary of these two provinces.

The sandstones of the Middle Run Formation were mostly derived from the erosion of Grenvillian mountains, as shown by sand-size grains of metamorphic rocks, granites, and basalts. Dating of single crystals of zircon washed into Middle Run basins indicates an age of about 1.048 billion years for the latest of the four Grenvillian orogenies (Orestes and others, 2002). What is not clear, however, is the exact age of the Middle Run—was it deposited earlier, was it contem-

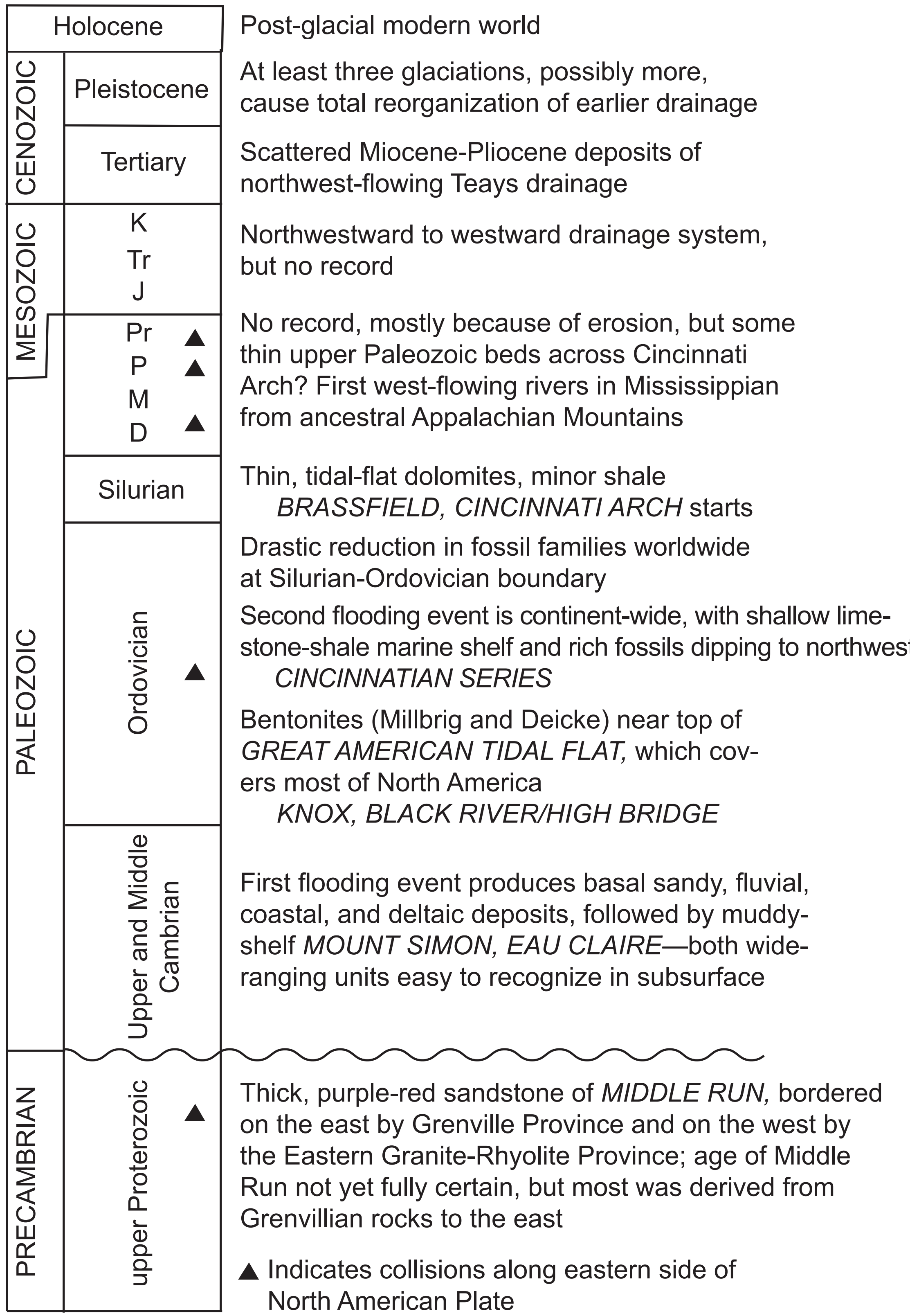


Figure 48. Major events in the geologic evolution of the Greater Cincinnati metropolitan area.

**Table 5.** Essential geologic history of the Cincinnati region.

| | |
|---|---|
| PLEISTOCENE | At least three glaciations, possibly more, greatly altered earlier landscape and caused total reorganization of its drainage. |
| TERTIARY | Scattered Miocene-Pliocene sands and clay derived from tropical and subtropical regolith deposited by northwest-trending streams. |
| CRETACEOUS TO DEVONIAN | No record, mostly because of erosion, but some thin Devonian, Mississippian, or Pennsylvanian beds on and across the Cincinnati Arch are possible. |
| SILURIAN | Tidal-flat dolomites and some shales. Initial development of Cincinnati Arch. *Brassfield.* |
| ORDOVICIAN | Second and largest flooding event was continent-wide, and produced a shallow marine shelf with rich fauna; the shelf shallows into a tidal flat and minor red beds to the east. *Cincinnatian Series.* |
| CAMBRIAN TO ORDOVICIAN | Great American Tidal Flat, as above. *Knox.* |
| MIDDLE CAMBRIAN | First flooding event produced basal, fluvial, coastal, and deltaic sands, followed by a muddy shelf. *Mount Simon, Eau Claire.* |
| PRECAMBRIAN (UPPER PROTEROZOIC) | Thick, purple-reddish sandstone of *Middle Run Formation* (part of Midcontinent Rift System) is bordered on the east by the Grenville Province and on the west by the Eastern Granite-Rhyolite Province. |

poraneous with the latest Grenville orogeny, or was it deposited much later? See Dean and Baranoski (2002a, b) and Richard and others (1997) for some of the contrasting views about the Middle Run. Only more seismic lines and cores with new dating techniques will resolve these uncertainties. We can be sure, however, that the thick, widespread, reddish-brown sandstone deposits of the Middle Run represent a major event in eastern North America.

The deposition of the Middle Run was followed by an interval of erosion that extended well into Cambrian time, so there is a great break in the geologic record between the base of the Mount Simon Formation, the lowermost Cambrian unit of the Paleozoic in the eastern Midwest, and underlying Precambrian rocks. Because the age of the Middle Run has yet to be accurately determined, this time gap could range from as little as 30 to 40 million years to as much as 400 million years.

The widely spaced deep wells that pass through the Mount Simon and penetrate the underlying Precambrian are too few to provide a full picture of this buried landscape, but a plausible sketch of it is possible, based on landscape evolution and coastal processes as seen today, combined with geologic imagination—always a vital part of geologic analysis. This ancient landscape lacked trees and plants, though it may have been partially covered with lichens and algae. Low, irregular hills prevailed over much of it, some 100 or more feet above sandy streams. The hills and their intervening slopes were covered with a thin, rubbly, reddish, sandy, weathered zone. The stream pattern was southerly, ranging from southeast to southwest.

### Paleozoic Era

As the advancing Middle Cambrian sea neared the Cincinnati region (Babcock, 1994), streams aggraded their valleys until gradually everything was covered with water except for a few of the highest hills, which may have formed low, cliffed islands and headlands bordered by sandy beaches. Finally, all the landscape was covered and transgressed by a shallow, widespread, sandy sea that advanced from the south or southeast. This first Phanerozoic sea, which spread far across much of the North American craton, is a major landmark in the geologic history of the Cincinnati region. The overlying Eau Claire Formation, mostly siltstone but with some minor shale and carbonate, was deposited in a more open marine sea. Although not rich in fossils, the Eau Claire has very abundant bioturbation, indicating that organisms, including some trilobites, thrived on its sea bottom (Babcock, 1994).

The vast carbonate tidal flat of the Knox followed, and covered so much of North America that it is informally called the Great American Tidal Flat. Its deposition was terminated by the continent-wide erosion that appears to be related to continental collisions along the eastern border of the continent. A worldwide drop in sea level also played a part in ending deposition of the Great American Tidal Flat. The surface that formed has a relief of tens of feet, largely related to irregular sinkholes and solution features similar to those that abound near Mammoth Cave in Kentucky. This surface was also treeless and thinly and irregularly veneered with rocky carbonate debris. Thus, two major unconformities in the buried geologic record underlie the Cincinnati region, the second recording but a small fraction of the time represented by the break at the base of the Mount Simon.

In the upper part of the Black River/High Bridge Group are thin beds of volcanic ash. One of the thickest, the Mud Cave or Millbrig, is the most widespread and even has an equivalent in the greater Baltic region (Huff and others, 1992). The vast area covered by this bentonite (Fig. 49), plus its estimated volume of about 175 cubic miles, suggests that it was produced by one of the greatest volcanic eruptions of all Phanerozoic time. This event occurred some 453 million years ago, southeast of the Cincinnati region, somewhere in the Iapetus Ocean, which once separated North America from ancestral Europe and Africa. The intercontinental correlation of this bentonite by a team of Midwestern researchers using a combination of stratigraphic, paleontologic, and chemical techniques surely demonstrates the exciting geology contained in the buried rocks of the Cincinnati region and how some of its deposits are a response to very far-distant, catastrophic events. As we learn more about the buried rocks under the Cincinnati region, many more surprises can be expected.

In our area, a significant paleontological change also occurs at the level of the bentonites. The carbonate rocks overlying these bentonites are much more fossiliferous than those below them. Several factors seem to be involved in this change. First, the shallow-water, restricted tidal flats of the Knox and Black River/High Bridge Group below the bentonites, largely unfavorable to life, gave way to the open-marine, coarse-grained, abundantly fossiliferous carbonates with interbedded shales above the bentonites. Such a marked change from a largely unfavorable to a favorable habitat for bottom dwellers supports greater abundance and diversity. But a significant change in kind of organisms was also under way at this time: An earlier fauna dominated by trilobites was being replaced by brachiopods, followed by corals, echinoderms, and bryozoans. This change has been documented all across North America and seems to have occurred at much the same time throughout the entire world, starting in the Late Cambrian and accelerating into the Middle and Late Ordovician. The spectacularly fossiliferous Upper Ordovician Cincinnatian Series records the replacement of the typical Cambrian trilobite fauna by the brachiopods, bryozoans, corals, and echinoderms so characteristic of most of the Paleozoic (Sepkoski and Miller, 1985). The outcrops in the Cincinnati region give us a unique opportunity to study the early expression of this great change.

The shallowing of the sea at the end of the Ordovician is seen throughout most of North America and occurred also in the British Isles, North Africa, and the Amazon Basin of Brazil. This shallowing or drawing down of the world ocean was caused by a Late Ordovician glaciation in Africa (Fig. 50) and Saudi Arabia that temporarily transferred part of the volume of the world ocean to a continental ice sheet (Beuf and others, 1971; Vaslet, 1989). The careful correlation of events across the world has great value for the explanation of local features and demonstrates that global geology is interconnected.

### *Origin of the Cincinnati Arch*

The age and origin of the Cincinnati Arch has been a major topic among geologists of the region for over a century. Three key questions are: When did the arch first form? What was its subsequent history of activity? And what explanations can be offered for it?

As with the underlying Grenville Province and Middle Run Formation, geologic events along the eastern side of North America provide the best explanation of both the origin of the Cincinnati Arch and changes in the amount of shale seen in outcrops of the Cincinnatian Series (Fig. 51). Collisions between the eastern side of the North American Plate and the ancestral plates of Europe, North Africa, and South America formed marginal mountains that depressed the crust immediately in front of it to form a long, narrow trough (foreland basin) beyond which local forebulges such as the Cincinnati Arch and Nashville Dome developed (Quinlin and Beaumont, 1984). Once formed, such a bulge may slowly migrate, but more likely will stay in place and have both active and passive intervals related to marginal, episodic plate collisions. See Tankard (1986) and Ettensohn (1992) for a full explanation of all the fascinating details of how these distant events affected our region. The first of these collisions began in Middle Ordovician time—the Taconic Orogeny—and the last occurred in the Late Pennsylvanian and Permian to form the Allegheny Mountains. When two plates actively collided, marginal mountains were high and shed much sand, silt, and clay inboard into the nearby foreland basin where most was trapped and deposited, although some was transported westward into the shallow seas that covered the North American craton. Today, we locally recognize these muds as the

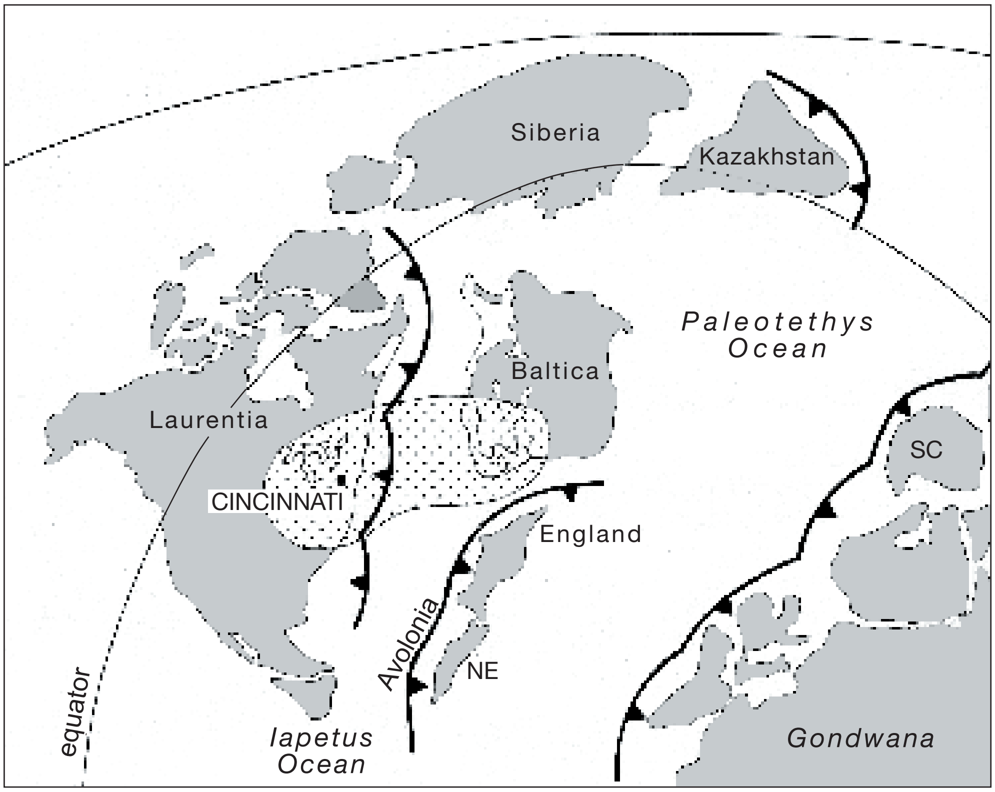


Figure 49. Wide distribution of the Millbrig bentonite at the top of the Black River/High Bridge Group. Redrawn from Huff and others (1992, Fig. 1). This ash bed, only about 150 feet below the surface of downtown Cincinnati and Covington, is believed to be one of the most widespread in the geologic record. Reprinted with the permission of the Geological Society of America.

Bromley and Kope shales, the shales of the Waynesville Formation, plus all the numerous thin shale interbeds seen in Cincinnatian outcrops. The widespread unconformity at the top of the Knox, with its many sinkholes (certain evidence of subaerial exposure), marks the first response of our area to the Taconic Orogeny, and the development of the Cincinnati Arch toward the end of the Ordovician marks the orogeny's termination. The shallower deposits of the Saluda, Whitewater, and Drakes Formations—plus the thin overlying Silurian dolomites north of Warren and Butler Counties—all point to the existence of the arch in latest Ordovician and Early Silurian time.

In latest Ordovician time, another distant event affected our area: the development of an ice sheet in the southern polar regions, whose deposits are widespread in northern Africa and Arabia (Brenchley, 2004). This ice sheet lowered world sea level and also cooled the world ocean. Falling sea levels plus the broad swell of the Cincinnati Arch produced the unconformity between Ordovician and Silurian rocks—the Cherokee Unconformity. In addition, falling sea levels and cooler oceans worldwide drastically modified the living conditions of countless bottom dwellers adapted to shallow, warm, well-oxygenated bottoms. The result was a major worldwide extinction at the end of Ordovician time.

### *The Big Gap: Silurian to Late Tertiary Time*

Why—with the exception of several Silurian outliers in Warren County—are there no other sedimentary rock and sediments until the high-level Claryville Clay deposits of late Tertiary age in Campbell County in our area? Probably younger Silurian, Devonian, and even some Mississippian,

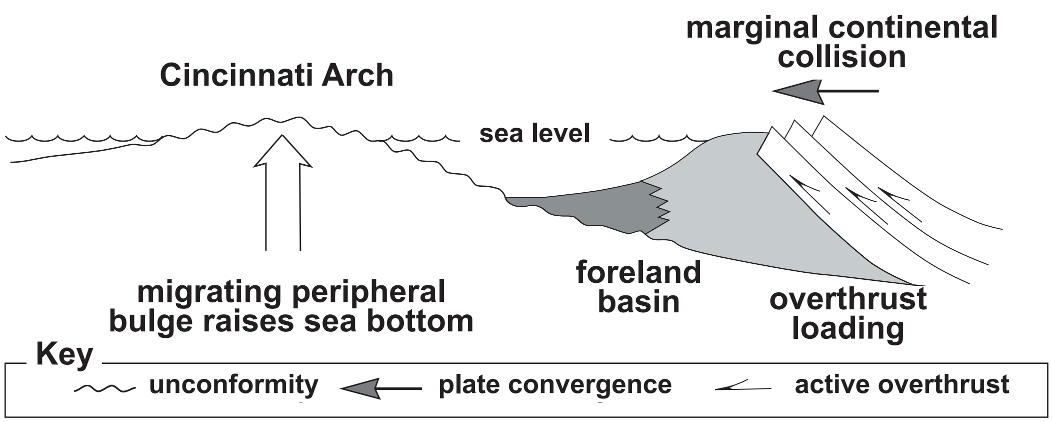


Figure 50. Schematic cross section of the origin of the Cincinnati Arch (interior forebulge) in response to plate collision and thrusting along the eastern margin of the North American craton. The many shales of the Cincinnatian Series are a westward expression of the shale-rich foreland basin to the east. After Ettensohn (1991, Fig. 2) and Quinlin and Beaumont (1984, Fig. 18). Reprinted with the permission of the Geological Survey of Canada.

Pennsylvanian, and Permian rocks were deposited across the arch, but after the final Permian uplift of the Appalachians some 260 million years ago, all of the eastern and central Midwest was eroded by westward drainage, mostly toward the ancestral Mississippi River and nearby Canada (Judson, 1975). Fortunately, late Tertiary remnants of this drainage are preserved as the paleovalleys and deposits of the ancient Teays System (see "Landscape," p. 10).

Estimating the thickness of former cover over the arch is most uncertain; however, an estimated 1,000 feet of eroded rock in eastern Kentucky (Goodmann, 1992) suggests that the missing overburden across the Cincinnati Arch may have been as little as only several hundred feet.

Figure 51. Striated surface of Late Ordovician glaciation as seen in the Sahara Desert in Tassilli, southern Algeria. Glacial till overlies this surface.

### *Pleistocene Glaciations*

Interesting and important as the earlier events may be, they hardly match those of the Pleistocene, with its multiple glaciations and drainage diversions. Because these glacial events happened just yesterday, so to speak, they have had the most impact on the Cincinnati region. The fundamental question about these glaciations is: What caused them? Although this is much discussed, one thing is certain: The cause or causes of Pleistocene glaciations acted on a global scale.

With everyday discussion of global warming, geologists, oceanographers, marine geologists, and many others have given much attention to this question. Underlying these efforts is the hope that if we can better understand past climatic changes, we can better predict future ones.

Hypotheses include changing positions of the continents and oceans, the accelerated elevation of the continents (global mountain building) in the last 15 million years, the closing of several key gateways between oceans such as the Isthmus of Panama and those of the eastern Mediterranean, changes in oceanic currents, variations in solar energy, and long-term change in atmospheric carbon dioxide levels. Although none of these by themselves is universally agreed upon, the idea that the uplift of high mountains in the Americas and across Eurasia caused a fall in world temperatures to set the stage for ice sheets shows both the interrelations that need to be unraveled and the global scope of the problem. Another factor is the rhythmic variations in the shape and size of the earth's orbit that operate at cycles of 20,000, 40,000, and 100,000 years. These cycles change the amount of energy from the sun intercepted by the earth, and were first suggested by Milankovitch in the early 1900's as a cause of periodic Pleistocene glaciations. See Ruddiman (2001) for advanced insights into global climate change.

Summing up, the geologic history of the Tri-State region reaches over a billion years back in time, includes two major intervals of ancient mountain-building, long periods of erosion (with some buried landscapes that look like parts of arid Utah), and many invasions and retreats of ancient seas. Real as these are, it is the Pleistocene glaciations and their climatic changes plus Deep Stage entrenchment that have had the greatest impact on the inhabitants of the Tri-State.

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### *Digging Deeper*

Dawson, A.G., 1992, Ice age earth: New York, Rutledge (Chapman and Hall), 293 p.

> This thoughtful, broad overview simplifies and connects the many diverse disciplines needed to unravel and better understand the climatic changes of the late Quaternary. The interval between the last interglacial period some 130,000 years ago and the last of the great ice sheets, about 7,000 years ago, is covered. Moderately advanced reading is made easier by good writing style.

Miller, A.J., and Mao, S., 1995, Association of orogenic activity with the Ordovician radiation of marine life: Geology, v. 23, p. 305–308.

> The authors speculate that the radiation of Ordovician marine life and great increase in biodiversity was one of the most remarkable in all earth history, and coincided with active mountain building.

Ruddiman, W.F., 2001, Earth's climate change: Past and future: New York, W.H. Freeman, 465 p.

> Nineteen chapters divided into five parts plus many color, schematic figures and a glossary make this an important reference for global climate change. Background is required.

# Living and Working with Our Inheritance

The idea of working with nature might be best expressed as "Don't build through it—build with it." And the more urbanized the area and the denser its population, the more applicable the rule and the greater the role for geology. Where to build a landfill? How many hillsides should be developed and how? Ban deep toxic waste wells forever or design them properly to provide a cleaner, safer surface environment and facilitate industrial growth and local jobs? How to minimize the costs of annual cleanup of ditches filled by the mass wasting of the Kope Formation? Where to locate and how to design a septic tank? Which soils need special protection from erosion during construction? Should all parking lots be neatly paved and impermeable or only be surfaced with gravel to recharge the aquifer and reduce surface run-off? Urban mining: good or bad? Construction materials in 2050: nearby sand and gravel; far-transported, expensive crushed limestone; or a convenient, nearby underground source in the Black River Group? Taken together, all of the above questions fall broadly under the heading of land-use planning, which includes both consideration of unconsolidated deposits and bedrock, plus surface ecology. Clearly, the geology of the Cincinnati region has a thousand uses that span much of a small universe. There are many important connections—some direct and straightforward and others more subtle—between the geology of the Cincinnati region and its plants, animals, and humans.

## Surface Processes

Soils, mass movements, floodplains, and urban sedimentation form the heart of surface processes, and all four directly affect human activities and vice versa. Vegetative cover and slope also need mention here. Erosion is rapid on an unconsolidated, unvegetated slope, but minimal on low, vegetated slopes. Thus, as a first approximation, think of slope and vegetative cover as background controls on the *intensity* of soil development, mass movements, and the amount of sediment brought to streams. Another important intensity factor in all of the above is *water:* how much and how distributed throughout the year? And, of course, an unconsolidated deposit in our area erodes more readily than Ordovician limestone. Let's start first with the soils developed on glacial deposits.

### *Soils*

Soils are best thought of as three-dimensional unconsolidated deposits at the earth's surface that support plants. We study soils of the Greater Cincinnati region because they are its greatest natural resource, easily surpassing in value all of its other combined natural resources. As we will see below, the great variety of soils in the study area results from a long geologic evolution rich in different events.

Soils, like rock units, are named for places where they are well expressed, but are called *series* rather than formations. Hence, we have names such as Pate, Cynthiana, Clermont, Miamian, and Eden for some of the major soil series in our area. Topography (slope), parent material, and time (how long the surface has been exposed to weathering) are key factors controlling these different soil types. We have a wide range of names in our 11-county area for two reasons (Fig. 52). First, our landscape varies greatly in age from less than 19,600 years where glaciated by Wisconsinan ice to more than 300,000 years in northern Kentucky and southeastern Indiana. Second, the entrenchment of the Ohio River greatly modified upland soils, forming steep, rocky, colluvial soils on hillsides plus the young and very different floodplain and terrace soils of the bottoms of the Ohio River. Each soil series is subdivided by slope and texture (percentages of clay, silt, sand, large clasts of limestone, etc.) into eight or more subtypes. Slope is the key variable because it controls surface erodibility (thus texture) and the uses of a soil (Fig. 53). Detailed soil maps are available for all 11 counties, and all have complete tables for the suitability of each soil series for a wide range of uses from farming to construction to suitability for septic tanks to landslides and green space. Thus, county soil reports and their maps are essential for best management practices and development of our Greater Cincinnati region.

These useful soil reports are available from the Natural Resources Conservation Service (formerly the Soil Conservation Service) for each of the 11 counties of the study area (Garner and others, 1973; Weisenberger and others, 1973; Lerch and others, 1975, 1980, 1982; Weisenberger and Richardson, 1976; Nickell and others, 1981; Nickell and Stephenson, 1987).

Now let us look into how soils are divided into horizons, which are three in number (Fig. 54). At the surface is the A horizon, which is commonly the thinnest, has good permeability and tilth, and is dominated by organic matter. Underneath it is the B horizon, which is hard, blocky and difficult for both roots and water to penetrate. The term *fragipan* is used for a dense, tight B horizon. Horizons A and B together are called the *solum,* a useful term, because A and B together are the horizons most closely linked to plant, animal, and human use. The C horizon consists of oxidized and

## Role of geographic information systems for better living and working with our inheritance

Geographic information systems are computer programs and data that allow us to view maps with other geographic features and thus explore relationships among their many combinations. This is accomplished by digitizing map coordinates for every feature using a topographic, geologic, soil, or other base map. Many layers of digitized information can be added from existing sources; for example, property boundaries could be obtained from the county property valuation office (see **GIS Resources,** below) or pictures of geologic features can be linked. Once all the necessary data have been added to the system, GIS software can show—both graphically and quantitatively—the relationships among the different variables. It is the near-instant graphic display supported by quantitative data of the GIS that makes it so powerful for the urban planner, transportation engineer, conservationist, or even individual homeowners who wish to know more about their backyard.

Consider these examples. Impermeable glacial till greater than 5 feet thick is needed for the floor of a new landfill site. Where are such areas above which are municipal land holdings, all greater than 30 acres? Or think of identifying geologic and soil units prone to landslides, and comparing them to steep hillside slopes—a key consideration for construction of highways or planning a new development. Whatever the relationship, once a geographic information system is in place, new layers can be easily added to the database to answer a variety of societal questions. Because geographic information systems integrate and display information of all kinds from many different disciplines, their use is essential for helping us live and work better with our geologic inheritance.

**Some GIS Resources in the Tri-State Region:**
Ohio Geological Survey, www.dnr.state.oh.us/geosurvey/ogcim/petrol/petdig.htm
Ohio property GIS links, www.gispilot.com/States/Ohio.html
Butler County (Ohio) GIS, maps.butlercountyohio.org/index.cfm?tab=data
Warren County (Ohio) GIS, www.co.warren.oh.us/warrengis/
Kentucky Geological Survey, www.uky.edu/KGS/gis/
Kentucky Division of GIS, gis.ky.gov/index.htm
Boone County (Ky.) GIS, www.boonecountygis.com/
Northern Kentucky Area Planning Commission, www.nkapc.org/
Indiana Geological Survey, 129.79.145.7/arcims/statewide_mxd/download.html
Natural Resources Conservation System Soils, www.ky.nrcs.usda.gov/technical/GIS/
Geospatial One Stop, www.geodata.gov

possibly leached parent material that clearly, however, shows its affinities to parent material. Older soils have thicker, well-developed B horizons, because with time, more and more fine clays infiltrate from the A horizon into the B horizon. It is these older, thicker fragipans of the Avonburg, Rossmoyne, and Clermont Series soils that reduce the effectiveness of home septic systems. The other extremes are young alluvial soils on floodplains and lower terraces—the Huntington Series, for example—which lack fragipans.

There is one last concept we need to be aware of—the idea of a *polygenetic soil profile.* Think of a foot or two of loess deposited on top of a waterlogged, tight soil with a thick fragipan. Such an event seals the old A horizon from weathering so that we now have a buried paleosol—and we start with a new A at the surface and also begin a new, thin B below it. We now have a polygenetic soil formed at two different times. With sufficient time, however, distinction between the new and the old B horizons becomes increasingly difficult as unweathered loess is leached and transformed slowly into a B horizon. Hence, some of the thick fragipans along watershed divides of the Outer Bluegrass and Dearborn Upland regions represent not only very long periods but also different Pleistocene climatic events.

### *Mass Wasting*

The term *mass wasting* (also *mass movement)* refers to the downslope movement, either rapid or imperceptible, of a mass of consolidated or unconsolidated material. This type of transport contrasts totally with the particle-by-particle transport of sand, silt, and mud in a stream. Mass movements are a universal and natural part of normal geologic erosion, and occur wherever gravity and water act together on slopes. Thus, there were mass movements in the Greater Cincinnati region long, long before humans arrived. With the exception of rare rockfalls in abandoned quarries, vir-

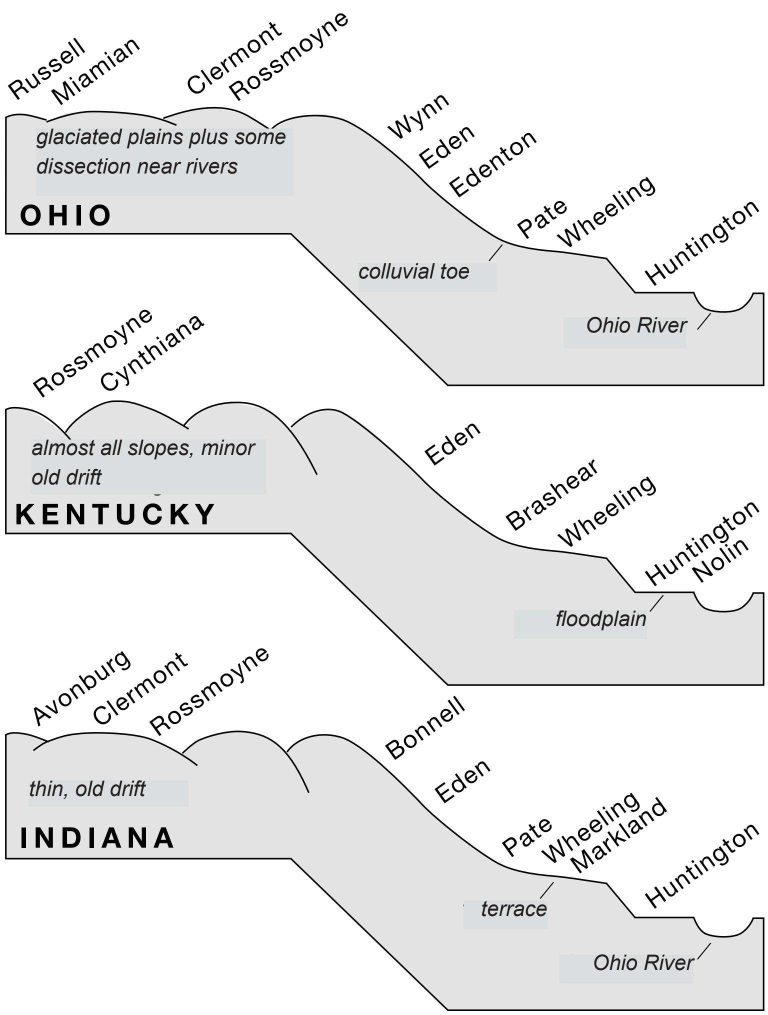


Figure 52. Schematic diagram of nomenclature of principal soil series in Ohio, Indiana, and Kentucky in study area. Note that the deep entrenchment and terraces along the Ohio River provide the most important control, followed by glaciation.

tually all the mass movements of our region occur in colluvium, alluvium, or glacial materials rather than Ordovician bedrock. Water is the dominant driving force, because it adds extra weight to the unconsolidated mass and at the same time reduces the shear strength of the unconsolidated material. All mass movements occur on slopes—or adjacent to steep cuts or stream banks—and the types of mass movements vary with slope angle, amount of water, and nature and thickness of the geologic materials (Fig. 55). All the shales of the Cincinnatian Series are very reactive to water—they disintegrate (slake) quickly (Fig. 56) and thus, as they weather in outcrop, generously yield colluvium. Because the Kope has the most shale, it generates more and thicker colluvium than any other outcropping unit and therefore its outcrop belt, especially those parts with slopes steeper than 20 percent (11.3°), is landslide-prone (Hough and Fleming, 1974). Colluvium thickens, as a rule, downslope (Fig. 57). Much of the following is summarized from Fleming (1975), Fleming and others (1981), and Fleming and Johnson (1994), the latter reference providing many technical details and specific examples. See also Pohana and Jamison (1993).

Different processes operate on different parts of a hillside (Fig. 58). In the Tri-State area the common types of mass movements are creep and translational and rotational landslides, virtually all of which occur in unconsolidated overburden rather than bedrock.

Creep is the slow, imperceptible downhill movement of unconsolidated material; it can crack and tilt walls; tilt fences, trees, and utility poles; and break underground pipelines (Fig. 59). Creep may occur alone or may be active in a rotational landslide between major pulses of activity.

In a translational landslide, a relatively thin sheet of colluvium separates from the underlying bedrock and slides catastrophically downslope, more or less as a coherent sheet, until it abruptly stops and becomes a crumpled, disorganized pile of debris and trees (Figs. 60–61). Such failures are common on the steeper slopes of the Kope Formation, especially in the spring when both the colluvium and the weathered, more permeable bedrock below it are fully saturated with water. Parts of the Fairview Formation may share a translational landslide with the Kope. Translational landslides typically occur where colluvium is less than 6 feet thick.

Rotational landslides occur in the thicker colluvium derived from the Kope, in alluvium, and in some glacial deposits, chiefly lacustrine clays and silts formed as north-flowing Teays drainage was blocked at different times by south-moving ice sheets. Rotational landslides have a predictable surface expression associated with a mostly hidden fault plane with characteristic geometry. The crown or head area has tension cracks or small scarps; the nose or toe has transverse, moraine-like ridges; a rarely exposed glide plane (fault with slickensides) connects the head to the toe, commonly in the weathered, permeable bedrock just below the colluvium or lake beds. Small initial tension cracks in the crown become large scarps as material moves downslope and small bulges in the toe become large ones. Movement is likely to be slow, perhaps inches to several feet a year, and is most likely in the spring. Living tree roots go far to stabilize even steep colluvial slopes (Riestenberg and Sovonick-

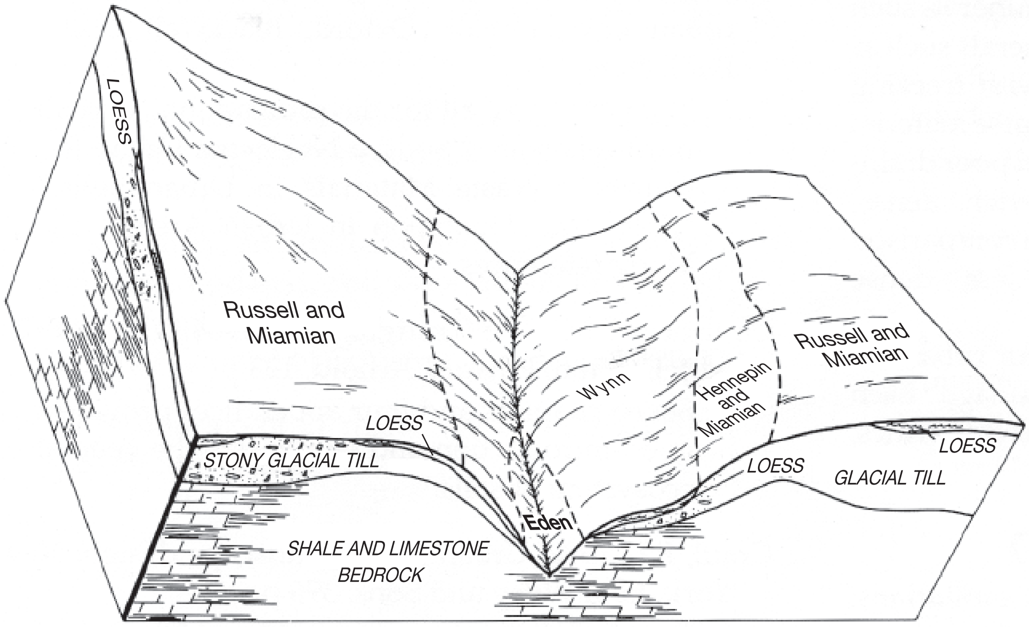


Figure 53. Variation of soil terminology with slope in northern glaciated part of study area (Lerch and others, 1980, Fig. 1).

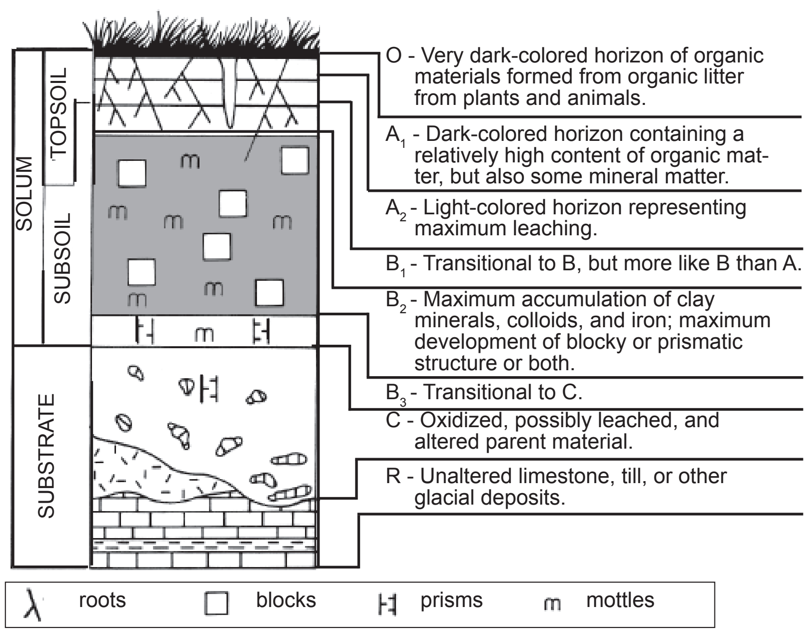


Figure 54. Soil terminology and horizons. Adapted from Aller (1982, Fig. 1). Reprinted with the permission of the Ohio Department of Health.

Dunford, 1983). Hence, cutting trees blocking a hillside view is a mistake. Overloading lake clays next to a stream bank is another, but less common, type of failure. Here, the lake clays are squeezed toward the stream, causing creep and subsidence as the clays are removed. Deformed clays along the side of the stream are an indication of this type of failure.

Every landslide can occur in any of three stages: incipient, active, or relic. Also, either by overloading or undercutting, relic landslides can be reactivated. Evidence for an old landslide includes trees with

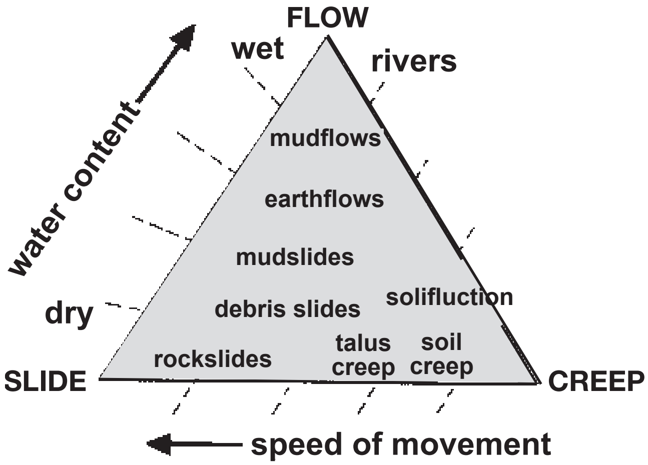


Figure 55. Mass-wasting triangle for controlling factors and nomenclature of mass movements (after Nuhfer and others, 1993). Reprinted with the permission of the American Institute of Professional Geologists.

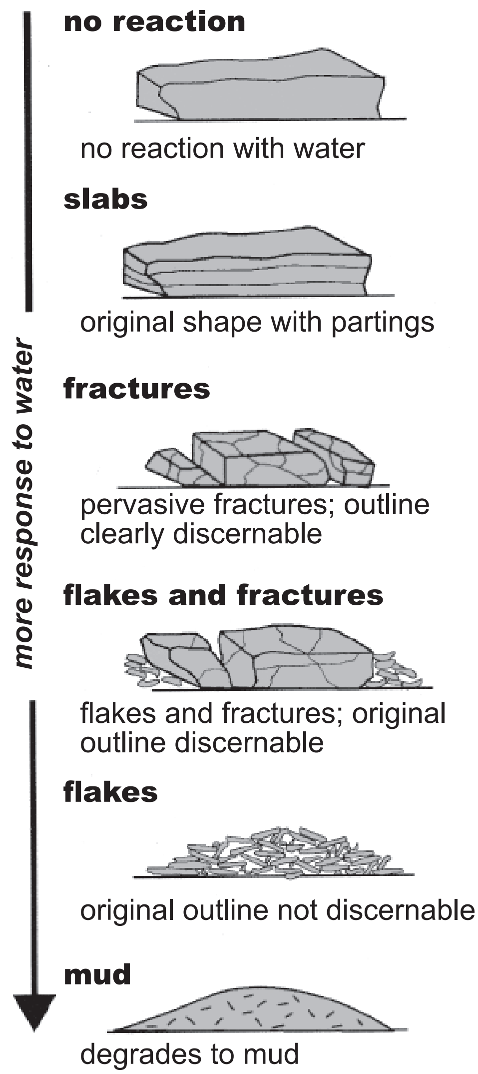


Figure 56. How water reacts with shales—calcareous or siliceous shale shows little or no reaction (top) whereas the other extreme is total reduction to mud (bottom). Place pieces of shale in water and see for yourself. After Santi (1998, Fig. 1). Reprinted with the permission of the Association of Engineering Geologists.

curved trunks, tilted trees, and undulating, hummocky ground, as well as cracked and leaning walls. To track a landslide and its repair on a major highway is a sobering experience. See "Geologic Hazards" (p. 96) to learn how to recognize landslides in our region and best cope with them.

Can landslides be related to time of year, vegetation, and slope orientation? The answer is a strong yes. A study in Hamilton County (Merritt, 1975) concentrated on a critical slope of 15 percent (8.5°) and considered vegetation and soil type. Where colluvium is thin on such slopes, translational landslides prevail, whereas where colluvium is thicker, say 10 or more feet, rotational slides are more likely. Rotational slides also occur in Illinoian lacustrine deposits, and to some degree, in Illinoian tills. Many of the lake deposits partially fill tributaries of major Deep Stage drainages, especially in old valleys with north-flowing streams, and are likely to be capped by till. Thus, the distribution of lake deposits is far less regular than that of the Kope and thus harder to predict. Slope failures do occur in till, but are commonly of small magnitude.

### *Swelling Soil, Fill, Shale*

We learned in the previous section that the mixture of water, shale, and colluvium on a slope favors mass movements. In addition, wet soil and fill—even on level ground—may be prone to swelling, causing the cracking and breaking of walls and floors (mixed-layer clay minerals absorb water and expand, leading to an increase in volume). County soil reports provide a guide to soils that are prone to heaving and swelling. Another possibility is the cracking and heaving of a concrete floor poured over a damp or wet shale. Alternatively, expandable materials, when dried, crack. Thus, a clay liner for a pond, if allowed to dry, will crack and lose most of its seal efficiency.

### *Floodplains*

Low, relatively level areas bordering a river or stream that flood almost every year or only occasionally, say once every 50 to 100 years, are called floodplains (Fig. 62). In the Cincinnati region, these low areas are called *bottoms,* short for bottomlands. The earliest settlement of the Columbia River was made in 1788 near the mouth of the Little Miami River on a low bottom, and was promptly flooded and abandoned. The flood-

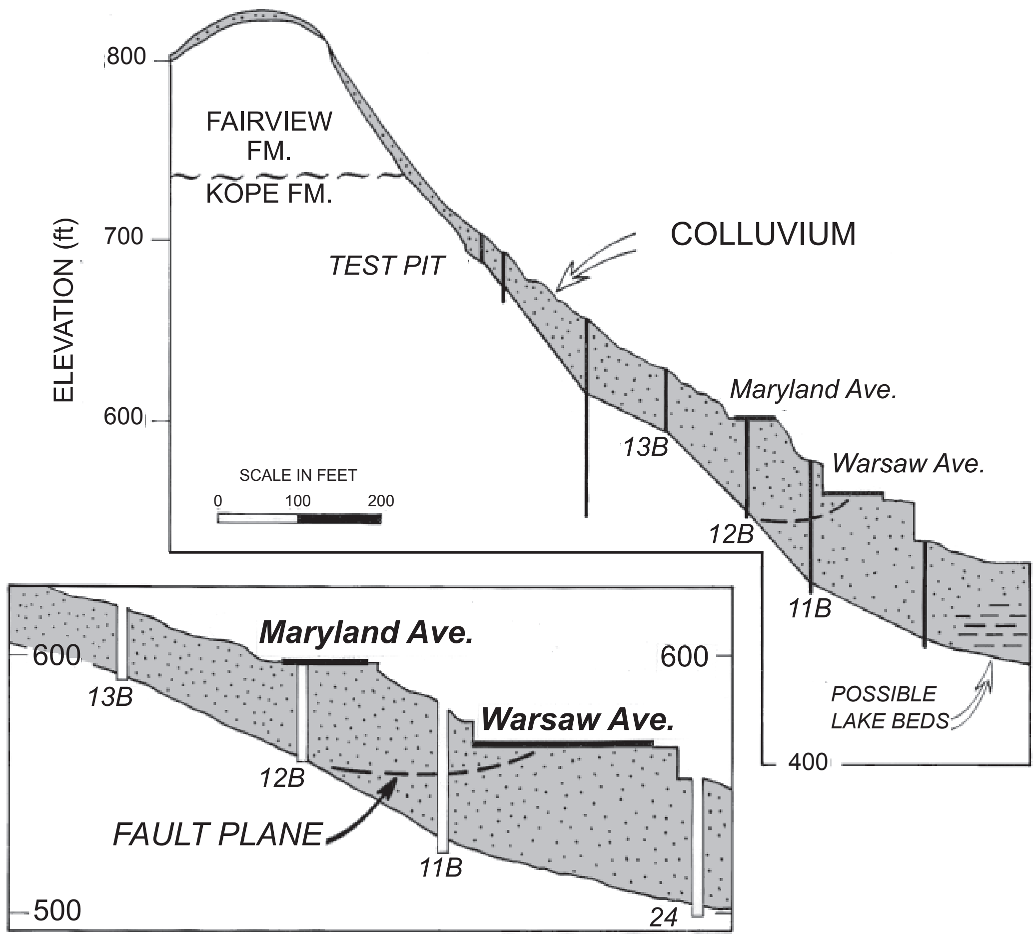


Figure 57. Colluvium thickens downslope, where it may interfinger with alluvial or lake deposits at the base of the slope.

plains of the Cincinnati region are bounded either by steep bedrock hills or, more commonly, by the low scarps of terraces; most are of late Wisconsinan age, although a few, such as in far western Boone County and near Coney Island, are of Illinoian age.

Floodprone areas form a complex pattern in the Cincinnati region (Figs. 62–63). The origin of this pattern is directly related to both present drainage and local glacial history. Though these areas form only a small percentage of the Tri-State area, they contain a disproportionate amount of its industry and population. This is because floodplains, terraces, people, and cities everywhere form a natural association—Floodplains have plentiful water, easy transportation either by water or on the floodplain itself, and provide level areas for urban development; in addition, they have rich, easily tillable land for profitable agriculture. To these factors one more should be added: floodplains are commonly good sources of both groundwater and sand and gravel. Early inhabitants of the Cincinnati region settled on floodplains more than 10,000 years ago for many of the above reasons. With this information in hand, it is easy to answer the question, Could the metropolitan area of the Tri-State have developed as it has if the Ohio River and its tributaries lacked floodplains and terraces and instead were bounded by steep valleys as at Anderson Ferry?

The origin of the floodplains of the Cincinnati region is best understood in terms of the history of late Wisconsinan glaciation. As the Wisconsinan ice began to melt and withdraw from the basins of the Great and Little Miami and Whitewater Rivers about 19,000 years ago, these valleys were filled with outwash sand and gravel, which formed a long valley train along the Ohio River, resulting in a braided stream extending as far downstream as Louisville. Only toward the end of this braided interval did our rivers begin to develop meanders. This mainstream alluviation produced many small slackwater deposits in the temporary lakes or tributaries of the Ohio, and also was responsible for the thin but widespread loess cap of the Cincinnati region. This loess cap formed when the Ohio River, the two Miami Rivers, and the Whitewater River were braided streams, especially during periods of low flow when

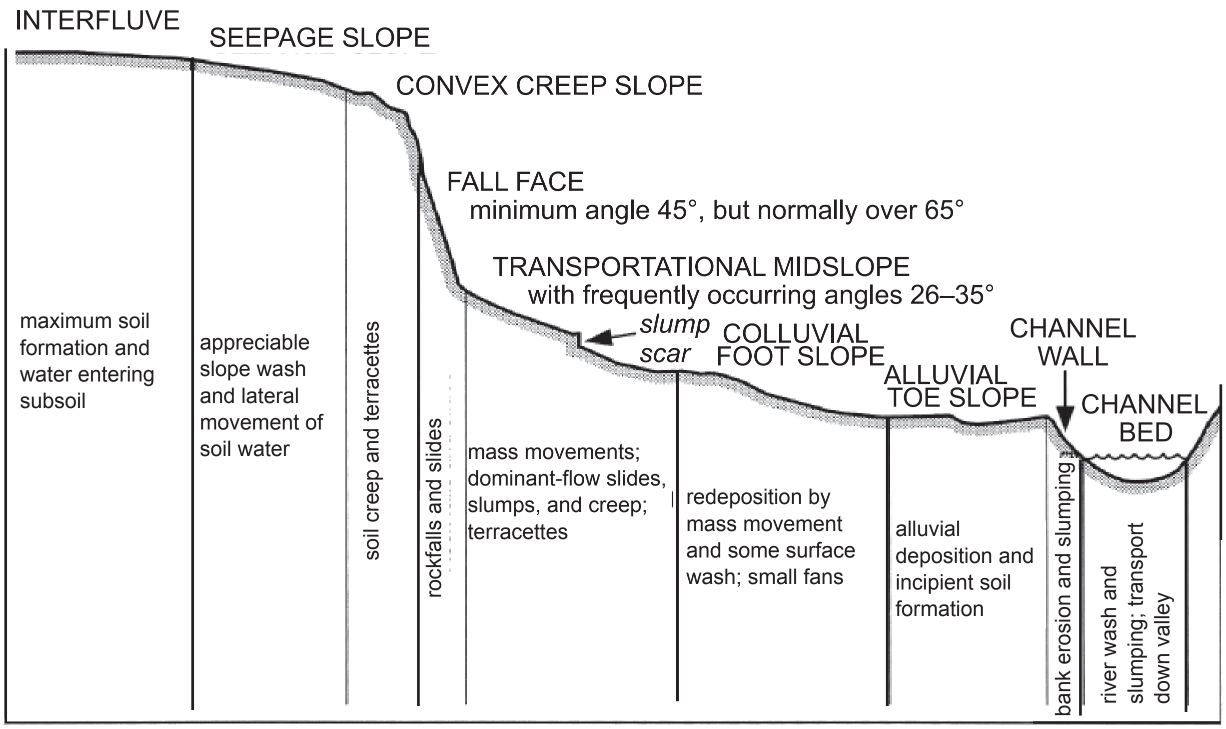


Figure 58. Definition diagram for hillside processes. Redrawn from Dalrymple and others (1968, Fig. 1). Reprinted with the permission of Gebrüder Borntraeger Verlagsbuchhandlung.

the wind blew dust across the stream surfaces onto the uplands. We are not sure of the length of this loess interval, but it may have been 2,000 to 5,000 years. This interval was followed by downcutting, perhaps caused by a warmer, drier climate and different vegetation. Judging from the evidence at Louisville, about 10,000 years ago the flow in the Ohio River and the morphology of its floodplains were not too different than they are today.

A floodplain forms by lateral accretion as a river migrates slowly from one side of its valley to the other (Fig. 64). This produces an orderly, predictable growth of the floodplain, which is underlain by channel deposits of sand and gravel (riverwash) capped by overbank silts and clays deposited from suspension *(overbank deposits).* In detail, a typical vertical sequence is coarse gravel plus perhaps a few logs at its base, followed by finer gravel, gravel and sand, sand, silt, and overbank silts and clays deposited from suspension on the floodplain. Such a sequence may be truncated by erosion or by glacial till so that the deposits underlying a floodplain may represent a complex sequence of interrupted successive fills rather than simply one pulse. Gravel is transported by rolling and sliding along the bottom as bedload, whereas sand is transported both along the bottom and also by suspension during faster flow. These channel deposits form point bars (Fig. 65) on the sharp bends of a river and longitudinal or side bars on straighter river segments. Wiethe (1970) described the systematic variation of grain size in such bars. Near the mouth of the Great Miami River, there is an oxbow lake, formed from an abandoned meander loop. Natural levees—low linear ridges adjacent to the channel—are formed during floods. During floods, finer sands and coarse silt are deposited near the channel as levee deposits, whereas the finer silt and mud are deposited from suspension beyond the levee in the quiet water in a temporary lake to form a sheet, called the *clay cap* (Fig. 66). Virtually all the morphologic

Figure 59. Creep tilts a shallow wall on lower Straight Street in Cincinnati.

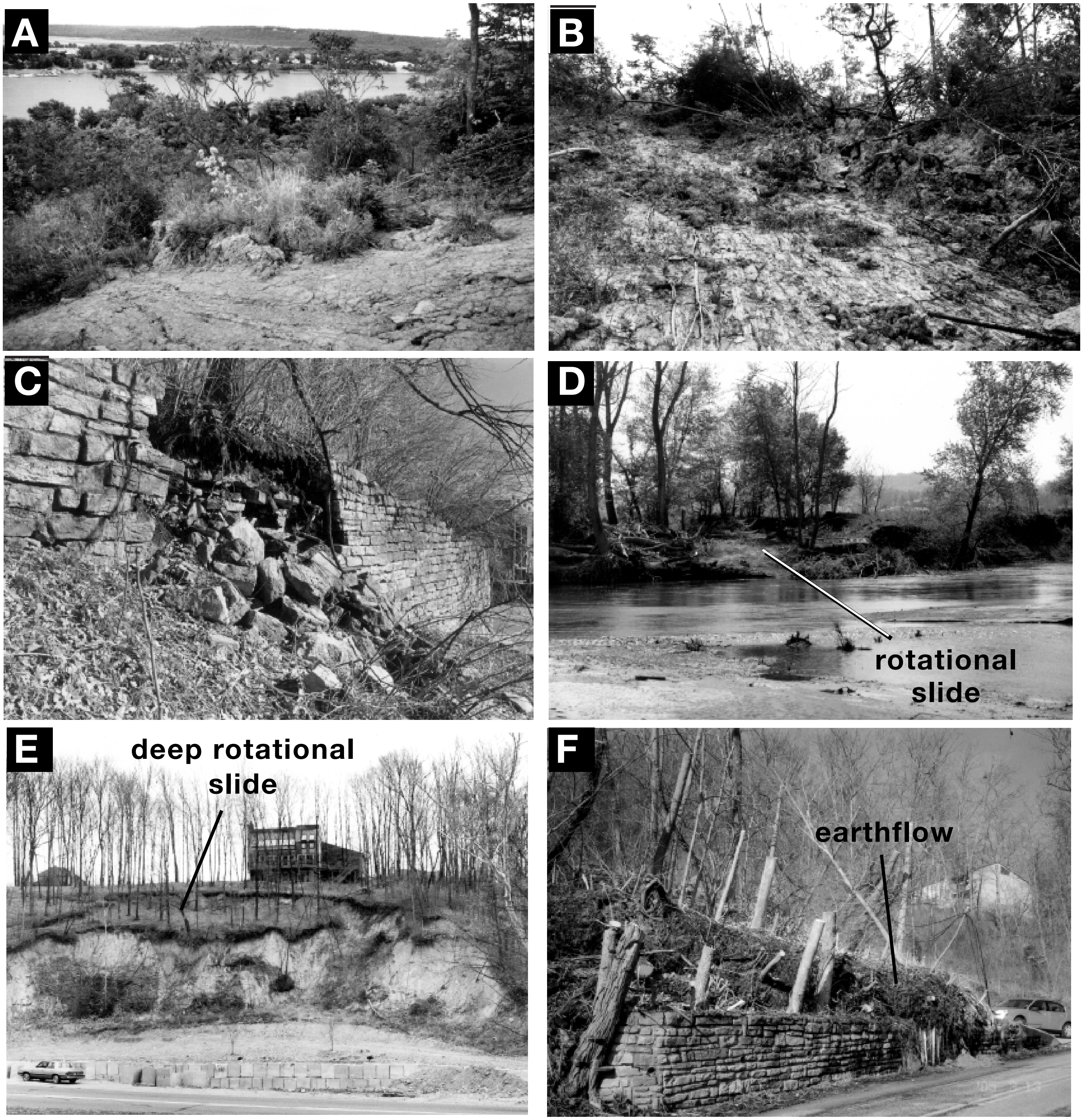


Figure 60. Diverse landslides in the Cincinnati area. (A) Rotational landslide at oversteepened hillside, Walnut Hills, Cincinnati. (B) Rockfall in abandoned quarry along Highland Avenue, Mount Auburn, Cincinnati, and spectacular translational landslide in thin colluvium developed on Kope Formation near Ky. 8, southeast of Dayton, Campbell County, Ky. (note striations on slide plane and disorganized transported debris). (C) Wet-spring collapse of old rock wall in small park on Liberty Street in Cincinnati. (D) Large rotational slide at cutbank of Whitewater River just north of U.S. 50 west of Cleaves, far western Hamilton County, Ohio (see also Figure 65A). (E) Unusally large and deep rotational slide on Clough Pike, eastern Hamilton County, Ohio. (F) Landslide overtops stone wall on Montage Avenue, Covington, Kenton County, Ky. (F) Earthflow on Montagne Avenue breaks and overrides stone wall in Covington, Kenton County, Ky.

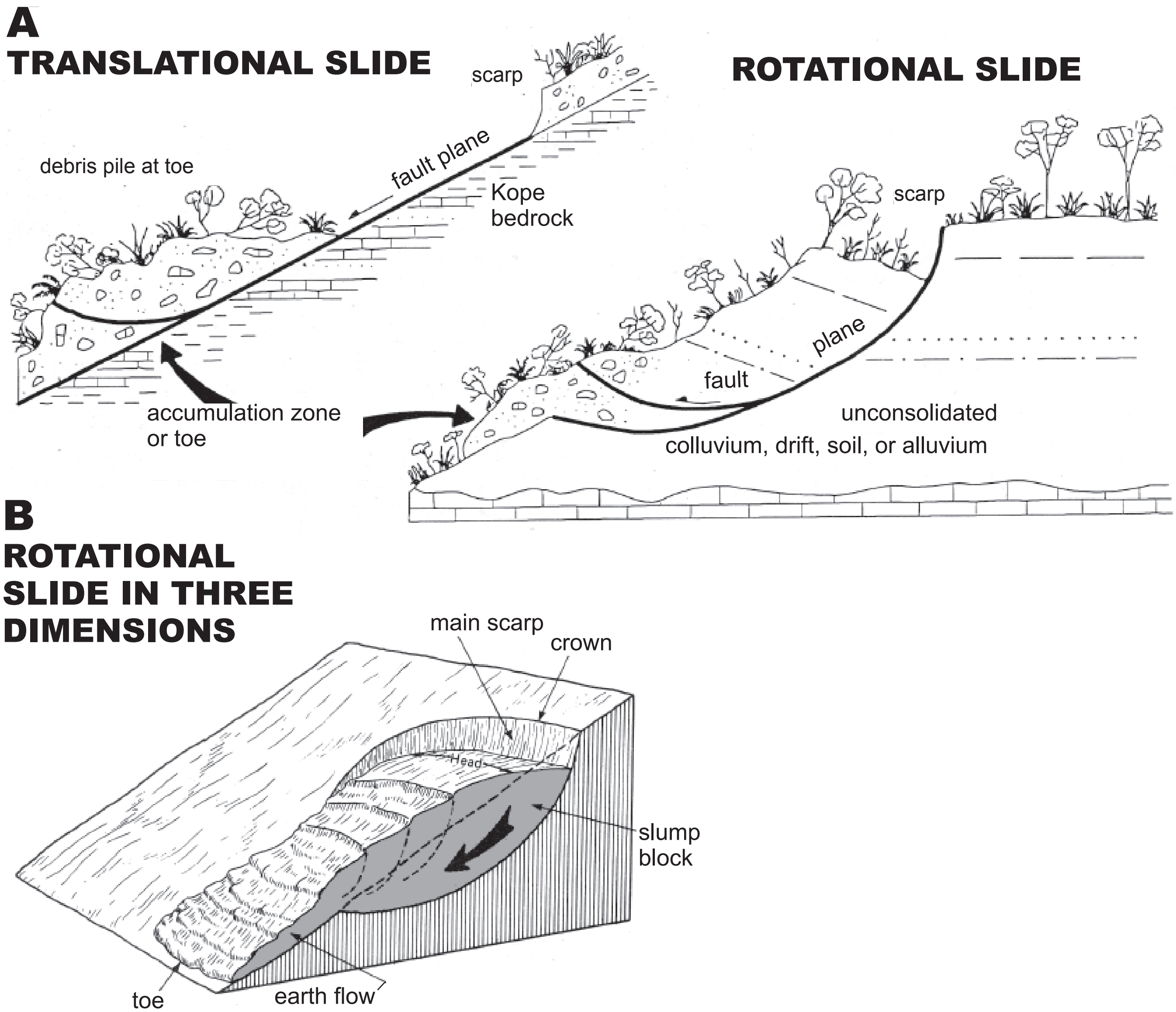


Figure 61. Definition diagrams for the principal types of landslides in the Cincinnati area. (A) Two principal types seen in cross section. (B) Block diagram of a rotational landslide (Bloom, 2004, Fig. 8-10). Reprinted with the permission of Waveland Press.

features of a floodplain are formed during high water. An informative study with much relevance for the Cincinnati region is that of Gray (1984), who reported on the floodplains near Louisville. Two regional studies are those by Walker (1957) and Gallaher and Price (1966).

To sum up, the floodplains of the Cincinnati region are its youngest natural features, and decrease in grain size upward in a well-defined sequence of basal gravel → sand → silt → clay cap plus soil. The fine-grained upper part of these deposits represents deposition from suspension during floods, whereas the coarser sand and gravel part represents traction transport along the bottom during floods. Floodplains and their ancestors, the bordering terraces, have played a key part in the development of the Greater Cincinnati region.

### *Urban Sedimentation*

What is urban sedimentation and why is it part of the geology of every urban area (Fig. 67)? Urban sedimentation is the study of the production, transportation, and deposition of both natural and manmade materials transported by air and water in and near cities. These materials include naturally occurring clays, silts, and sands plus bedrock debris from accel-

Figure 62. Floodplains such as this one near Elizabethtown in far western Hamilton County, Ohio, are highly valued for agriculture and, in addition, are underlain by valuable gravel deposits 60 or more feet thick, which yield prolific groundwater.

erated, man-made erosion and a legion of man-made debris: micron-size particles from smokestacks and car exhausts, fly ash, cans and bottles, plastic, concrete blocks, old TV tubes, abandoned washing machines, and much, much more diverse particulate debris, all in grand mixture (Fig. 68). To this should be added chemical compounds from factories plus fine dirt and chemicals that accumulate along highways, in parking lots, and on roofs, all of which are washed away to streams in a heavy rain. So, in a broad sense, urban sedimentation includes not only debris of all sizes but all chemical components as well. Thus, the materials of urban sedimentation are truly infinite: everything that nature and man working together can provide (Table 6). Urban sedimentation includes the study of erosion of soils, slopes, fields, and stream banks, as well as the deposition of all such eroded material. Accelerated run-off and erosion occur when the natural balance between rainfall, infiltration, and runoff of a landscape is suddenly altered by humans.

In every urban area, construction sites for new homes, streets, parking lots, highways, municipal buildings, or the bare surface of an unvegetated, sloping field all erode rapidly after heavy rains (Fig. 69). An immediate consequence is more turbid water in streams or clay, silt, and sand deposited in drains, sewers, and the channels of nearby creeks, causing them to flood and deposit sediment along their banks. Or reservoirs such as those in the suburbs of Winton and Sharon Woods may be almost totally filled by fine sediment, which greatly reduces storage capacity and recreational use (Fig. 70). Moreover, poorly designed highway cuts are a constant source of debris that fills their ditches so that cleaning is a constant problem. There are also consequences of urbanization well after initial construction and development. In much older, settled parts of a city, physical erosion is minimal, but roofs, sidewalks, parking lots, and highways all store fine dirt and chemicals from one rain to another and, because all these surfaces are impervious and impermeable, they greatly enhance stream discharge after a heavy rain. Such enhanced peak discharge leads to the accelerated erosion of stream banks, may overwhelm older culverts and undercut bridge abutments, and, perhaps of greatest importance, provides significantly less recharge to groundwater supplies, because rapid runoff replaces earlier longer intervals of infiltration. More frequent and larger floods result as fields are replaced by subdivisions and shopping centers—as permeable soil is replaced by roofs and concrete (Fig. 71).

What are the relevant processes? There are five principal ones. Consider first the smallest in size: the impact of raindrops on bare soil, called *splash erosion.* Impacts from raindrops disrupt the uppermost millimeters of the soil and thus make it available for transport by *sheet wash,* the flow of thin sheets of water across fairly uniform, sloping surfaces. Small, evenly spaced *rills* are the next to develop. Rills are the first step in concentrating or channeling the runoff, which greatly enhances the water's erosive power. Rills combine and lead to the development of *gullies,* deeper channels that only a bulldozer can modify. The last of these processes, called *mass movement,* occurs where water-saturated soil or colluvium becomes too heavy and moves either rapidly (landslide, mudflow, etc.) or slowly (creep) downslope, perhaps even directly into a stream. In most urban areas the majority of mass movements are man-made and thus clearly are part of urban sedimentation. This spectrum of processes is a universal one that operates everywhere, and understanding them is the key to minimizing the undesirable effects of urban sedimentation.

The keys to controlling physical erosion include vegetative cover during construction plus temporary check dams of straw bales or temporary plastic fences, and covering the ground with straw or planting grass. Vegetation is all-important (Fig. 72), because it helps absorb the kinetic energy of falling rain, slows the velocity of runoff, and catches fine sediment; in addition, its roots form an interlocking network that holds soil in place. Vegetation-induced slower runoff leads to more infiltration. Even better is a construction plan that includes permeable parking lots (Fig. 73), although these need a sandy or gravel-rich substrate. Terracing and temporary storage dams for runoff from parking lots are now standard. Stated differently, all the above procedures minimize urban sedimentation by working

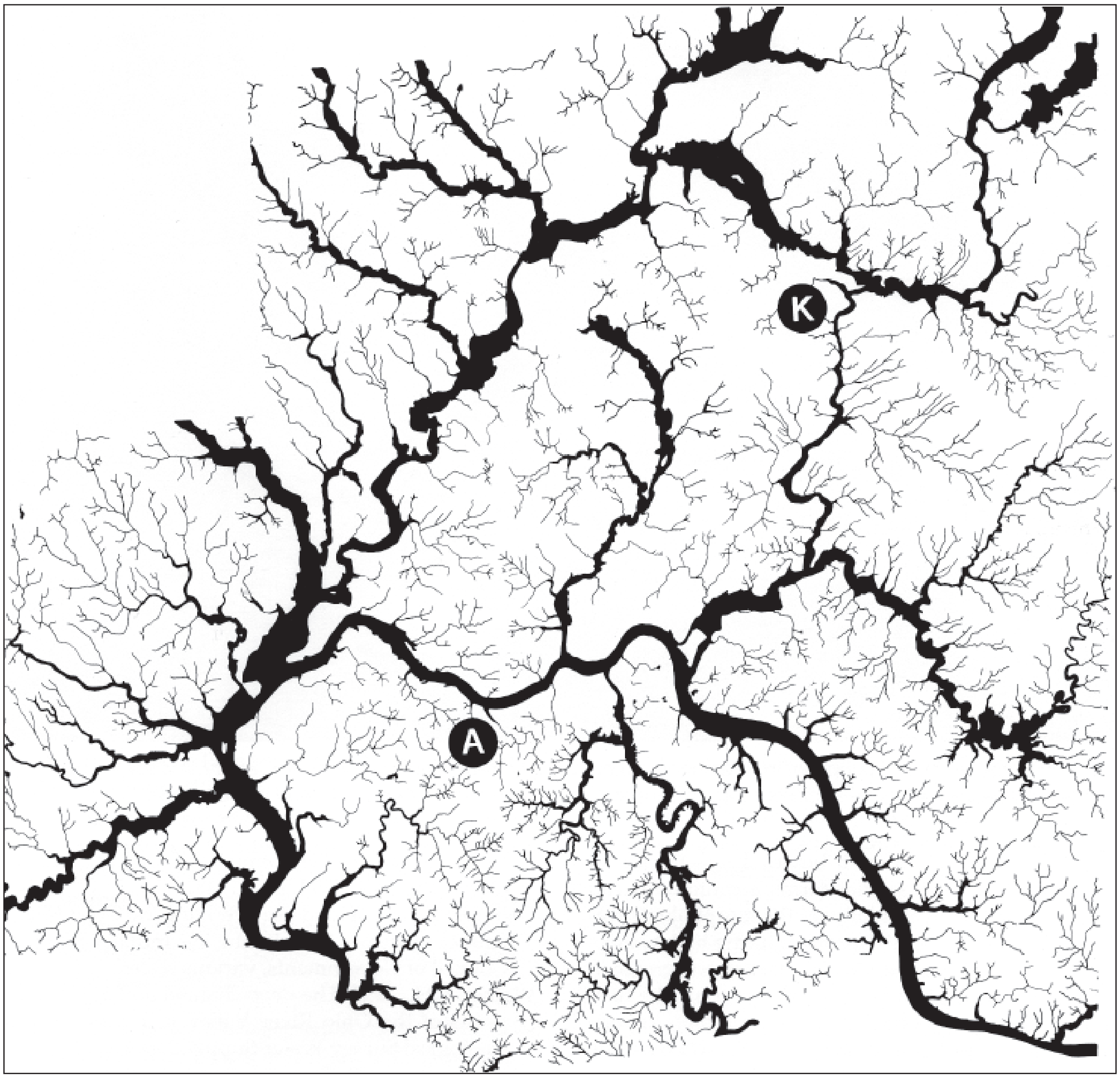


Figure 63. Floodplains and floodprone areas of the Greater Cincinnati region form a complex pattern. Adapted from Ohio, Kentucky, Indiana Regional Council of Governments (1989). All of these formed in response to late glacial and postglacial events. "A" represents the Greater Cincinnati International Airport and "K" represents Kings Island amusement park. Reprinted with the permission of the Ohio, Kentucky, Indiana Regional Council of Governments.

with nature rather than ignoring it. Each county and some municipalities of the Tri-State area have a set of erosion- and sediment-control procedures available from county commissioners and city authorities. In the widest sense, minimizing urban sedimentation calls for nothing more than application of the now well-established principles of soil conservation. The successful application of these principles needs constant reaffirmation by all of us.

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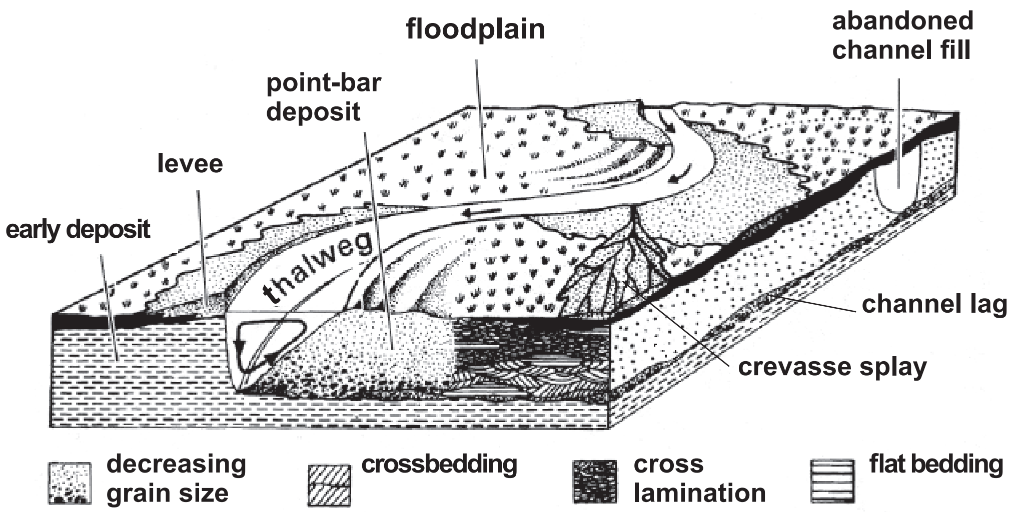


Figure 64. Definition diagram for floodplains with meanders (Collinson, 1996, Fig. 3.22). Reprinted with the permission of Blackwell Scientific Publications.


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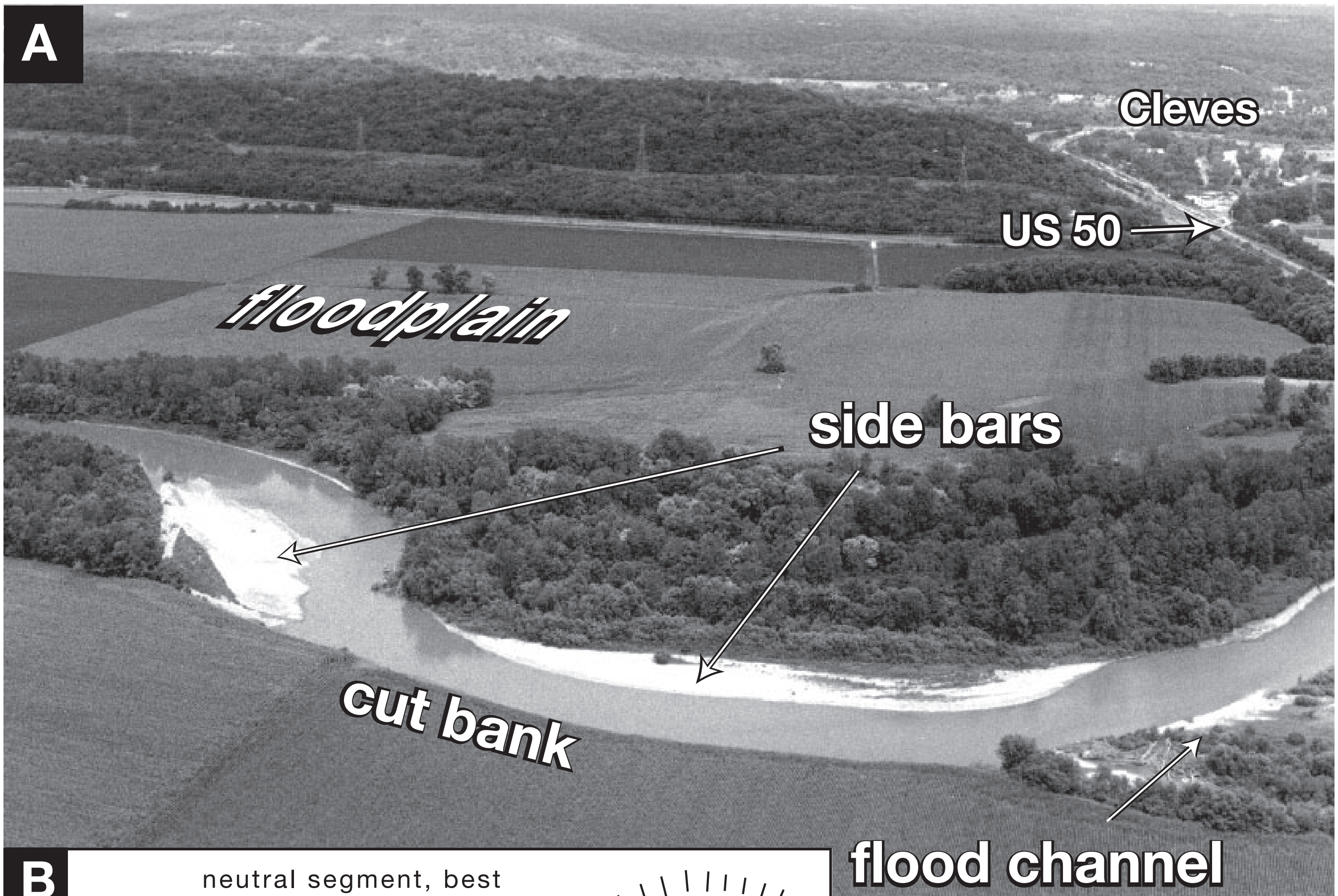


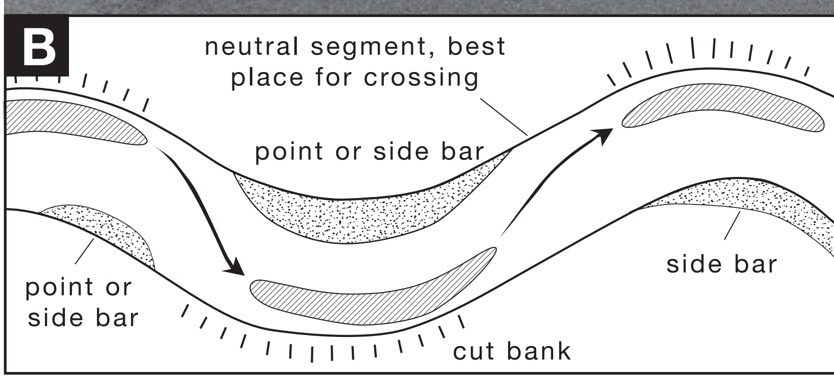


Figure 65. Classic floodplain and side bars. (A) Looking east across a meander bend of the Whitewater River toward Cleves in far western Hamilton County, Ohio. U.S. 50 is at far right. (B) Schematic diagram of a meandering river with cutbanks, side bars, and deep channels. Neutral crossing is the most stable reach (after Mecklenburg, 1996, Fig. 5.1). Reprinted with the permission of the Ohio Division of Soil and Water.

Figure 66. Origin of clay–fine silt cap of a floodplain. During high water (note mud line on trees), clay and fine silt settle from the *ponded quiet water* away from the main channel to form the clay cap of a floodplain.

Figure 67. Wood and trash jam on tributary to West Mill Creek in College Hill, Cincinnati—an aspect of urban sediment no one wishes to see.

Nuhfer, E.B., Procter, R.J., and Moser, P.H., 1993, The citizens' guide to geologic hazards: American Institute of Professional Geologists, 134 p.

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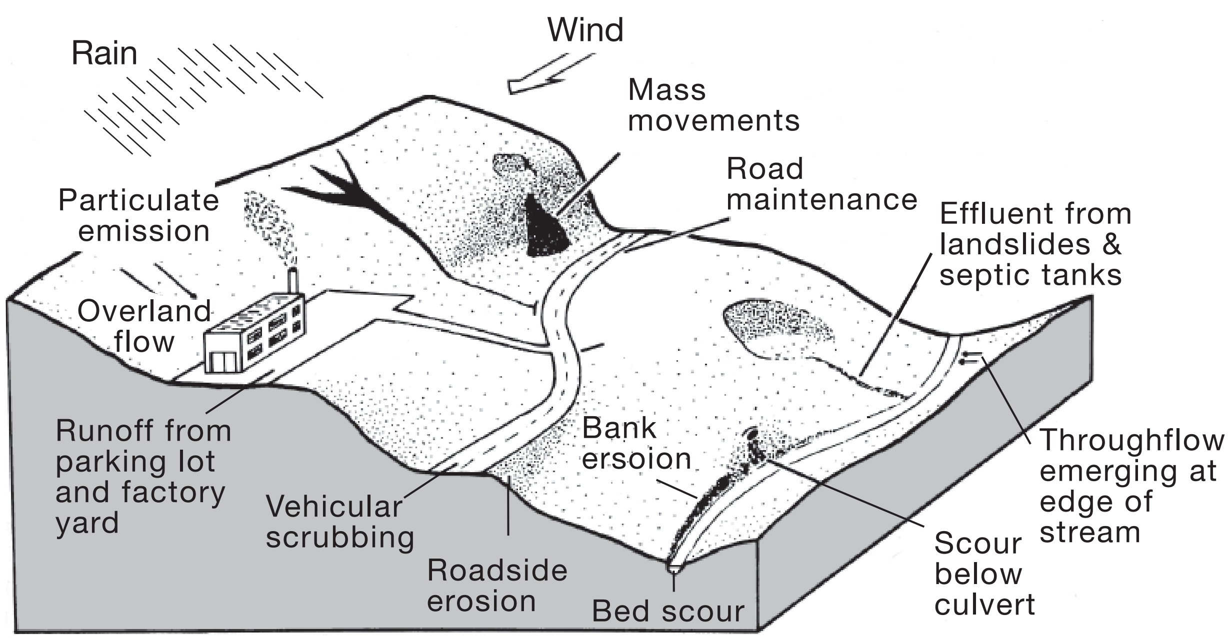


Figure 68. Definition diagram for urban sedimentation (Douglas, 1985, Fig. 1). Reprinted with the permission of Sage Publications.

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**Table 6.** Sources of urban sediment in the Tri-State region.

| | |
|---|---|
| *Natural* | |
| | Flood scour of channels and stream banks |
| | Mass wasting (creep, landslides, and slurries) |
| | Rill and gully erosion |
| | Splash and sheet erosion |
| *Man-made* | |
| | Construction—homes, highways, shopping centers, and industry |
| | Old highway cuts |
| | Dirt and chemicals from roads, roofs, etc. |
| | Trash from homes, cars, and factories |
| | Municipal and industrial effluents |

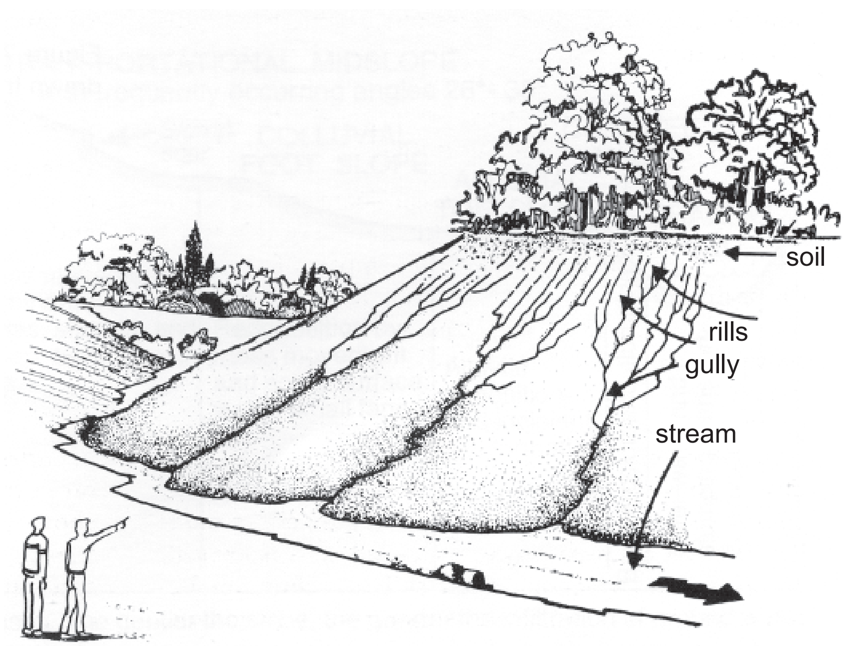


Figure 69. Rills and gulleys on a bare slope (redrawn from the Soil Conservation Service, undated, Fig. 3-1).

Figure 70. Silts and clays filled Sharon Lake in Sharon Woods Park before it was dredged. Most of this sedimentation occurred during initial urbanization of its watershed immediately after World War II, a time of maximum construction. Photograph courtesy of the Natural Resources Conservation Service and George Cummings.

Figure 71. Debris piled against the pier of a trestle of the CSX Railroad over Banklick Creek in Kenton County, Ky., after the flash flood of July 1996. Such floods become both more frequent and intense as impermeable roofs, roads, and parking lots replace fields and woods.

Counties: U.S. Department of Agriculture, Soil Conservation Service, and Kentucky Agricultural Experiment Station, 62 p.

Wiethe, J., 1970, Textural parameters of a modern point bar: The Compass, v. 47, p. 110–118.

### *Digging Deeper*

Alexander, C.S., and Prior, J.C., 1971, Holocene sedimentation rates in overbank deposits in Black Bottom of the Ohio River, southern Illinois: American Journal of Science, v. 270, p. 361–372.

This careful study of the microstratigraphy of an Ohio River floodplain plus radiocarbon dates of buried tree stumps provides a possible model for the floodplains of the Cincinnati/northern Kentucky region. Natural levee, swale, and ridge deposits are well described.

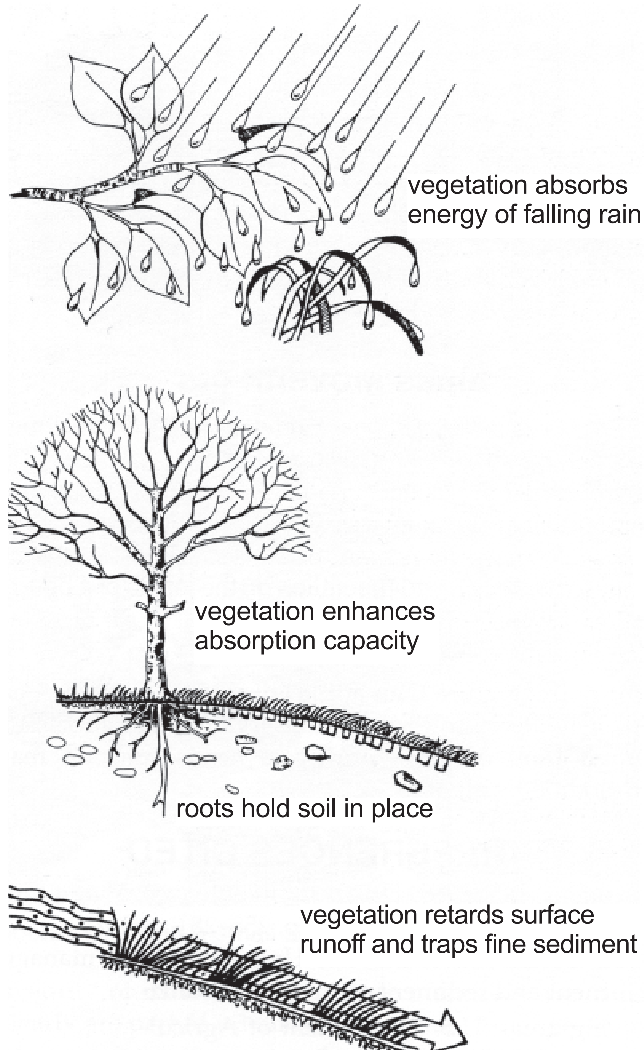


Figure 72. Roots, leaves, and grass retard runoff. Redrawn from the Soil Conservation Service (undated).

Alexander, D., 1989, Urban landslides: Progress in Physical Geography, v. 13, p. 157–191.

The causes and consequences of geologic mass movements in urban areas are discussed. Table 1 lists 45 sudden urban landslides that caused at least 286,000 deaths. It contains a useful section on hazard mapping and zonation plus intensity, scale, and complete list of symbols. It is highly recommended.

Bullock, P., and Gregory, P.J., eds., 1991, Soils in the urban environment: Oxford, Blackwell Scientific Publishers, 174 p.

Figure 73. This permeable parking lot still keeps you out of the mud. The open pattern of concrete blocks permits infiltration. These work best where placed above permable beds.

This book contains nine chapters, all for the professional, and all most relevant: "Soils, a Neglected Urban Resource," "Waste Materials in Urban Soils," "Soils and Vegetation in Urban Areas," etc. It also contains many references.

Craul, P.J., 1992, Urban soil in landscape design: New York, John Wiley and Sons, 396 p.
This book contains 10 useful chapters, ranging from "Basic Soil Properties" to "Description of Urban Soil" to "Roots" to "Fertility" to "Contamination" to "Compaction" to "Tree Planting," plus two appendices and almost 200 references.

Earth Surface Process Group, 1987, Report and recommendations on the maintenance and repair of deteriorating retaining walls and streets damaged by landslides, city of Cincinnati: University of Cincinnati Geology Department, 50 p.
This census of landslides from 1980 through 1987 gives an indication of the great magnitude of the problem. Its recommendations probably apply to many other cities.

Gunnerson, C.G., 1973, Debris accumulation in ancient and modern cities: American Society of Civil Engineers, Journal of Environmental Engineering Division, v. 99, Paper 971, p. 229–243.
The key idea is that archaeology sites and urban waste have much in common. This journal is a rich source of articles relevant to the Cincinnati region.

Haneburg, W.C., and Anderson, S.A., eds., 1995, Clay and shale slope instability: Geological Society of America, Reviews in Engineering Geology, v. 10, 160 p.
Ten papers, all written for the specialist, emphasize principles and case histories, which can be applied to the Tri-State region.

Haneburg, W.C., and Gökce, A.Ö., 1994, Rapid water-level fluctuations in a thin colluvium landslide west of Cincinnati, Ohio: U.S. Geological Survey Bulletin 2059-C, 16 p.
This advanced technical report about hydraulic conditions on hillsides—and their relation to landslides—also has a detailed map of a landslide.

Hodder, A.P., 1990, Practical weathering for geology students: Journal of Geological Education, v. 38, p. 306–310.
This is a useful starting reference for everyone.

Kibler, D.F., 1982, Urban storm water hydrology: American Geophysical Union, Water Resources Monograph Series 7, 271 p.
This work consists of nine articles written by civil engineers for civil engineers. The extended introduction of 34 pages provides an excellent, not-too-technical overview, however.

Leopold, L.B., 1968, Hydrology for urban land planning—A guidebook on the hydrologic effects of urban land use: U.S. Geological Survey Circular 554, 18 p.

This pioneering North American paper is by one of the world's leading authorities on riverine processes. It is classic, and still very much worth reading.

Lerch, N.K., LeMaster, D.D., and Hale, W.F., 1980, An inventory of Ohio soils, Hamilton County: Ohio Department of Natural Resources, Division of Lands and Soils, 67 p.

This is a simplified summary of the soils of Hamilton County. Figure 1 is good for teaching.

Mecklenburg, D., 1996, Rainwater and development [2d ed.]: Ohio Department of Natural Resources, Division of Soil and Water, 190 p.

The clear photographs and drawings with brief text make this an ideal handbook, with three parts and seven chapters plus a short glossary. It is absolutely essential reading for the developer, homeowner, and teacher of urban sedimentation.

Natural Resources Conservation Service, 2005, Urban soil primer: U.S. Department of Agriculture, Natural Resources Conservation Service, 74 p.

Eight easy-to-read chapters, all with many color photographs and illustrations, plus a glossary, is excellent for builders, planners, architects, geological engineers, geographers, and geologists working in cities.

Nuhfer, E.B., Procter, R.J., and Moser, P.H., 1993, The citizens' guide to geologic hazards: American Institute of Professional Geologists, 134 p.

The clear, informative text has many excellent color illustrations. Hazards are discussed under the broad headings of materials and processes. It contains many references.

Ohio, Kentucky, and Indiana Regional Council of Governments, undated, Soil associations in the OKI region: Cincinnati, OKI, scale 1:120,000.

This map shows the distribution of 27 major soil types, printed in black and white.

Singer, M.J., and Munns, D.N., 2006, Soils: An introduction [6th ed.]: Upper Saddle River, N.J., Prentice-Hall, 446 p.

A fairly advanced text of 16 chapters emphasizes plants, chemical fluxes, and flow of fluids.

Smale, J.G., 1988, What our hillsides do for us, and what we must do for them: Outlook, v. 6, p. 1–3.

This thoughtful article, published in the quarterly newsletter of the Hillside Trust, clearly sets forth the need for greater appreciation of our hillsides.

Smeck, N.E., and Ciolkosz, E.J., eds., 1989, Fragipans: Their occurrence, classification, and genesis: Madison, Wisc., Soil Science Society of America, 153 p.

This publication contains nine articles about fragipans, dense subsoil zones that restrict fluid flow, plus an informative summary. See especially chapter 6, which includes examples from southwestern Ohio.

Tong, S.T.Y., 1990, Roadside dusts and soils contamination in Cincinnati, Ohio, USA: Environmental Management, v. 14, p. 107–113.

Dusts and chemicals along roads—just as with cans, bottles, and paper—become concentrated with time.

U.S. Federal Interagency Stream Restoration Group, 1998, Stream corridor restoration, principles, and practices: U.S. Geological Survey, various pagination.

This wonderful document is about understanding, developing a plan for, and applying restoration principles, all gorgeously and profusely illustrated and concisely written. This impressive, how-to-do-it document comes in a thick three-ring binder. It is important!

Von Schlichten, O.C., 1935, Landslides in the vicinity of Cincinnati: The Compass, v. 15, p. 151–154.

A landslide that destroyed more than 40 houses in Riverside, a neighborhood along U.S. 50 (River Road), as well as others, is described and illustrated.

Way, D.S., 1978, Terrain analysis: Stroudsburg, Pa., Dowden, Hutchinson, and Ross, 438 p.

This book provides easy-to-read information on how to interpret aerial photographs and has a very good section on soils and geomorphology.

## Groundwater

Groundwater is the result of the downward movement of water, called *infiltration,* into pores, fractures, and cavities in rock (Fig. 74). The size and distribution of such pores, fractures, and cavities is directly controlled by geology. Hence, only now, after we have in hand an understanding of the bedrock and its unconsolidated mantle, can we profitably examine groundwater in the Cincinnati region. A fairly large number of easy-to-understand terms are associated with groundwater (see boxed text on p. 93).

Unconsolidated deposits (Table 7) are the principal source of groundwater in the 11 counties of the study area—wells in bedrock may supply enough water for a household, but rarely more than 5 to 10 gallons per minute. *Drawdown* (water table rapidly drops during pumping) is also rapid in bedrock wells, and even worse, there are many "dry holes." The plasticity of the near-surface, interbedded shales is the principal reason for this (few open fractures), followed by the lack of connected pores in the interbedded limestones. But, thanks to Illinoian and Wisconsinan ice sheets, there are thick and extensive sand and gravel deposits along the Ohio River and its major south-flowing tributaries, as well as some in buried valleys (Figs. 62, 75). In the four Ohio counties there are 34 community water fields (Fig. 76) in valley-train outwash and alluvial deposits, seven in the three Indiana counties bordering the Ohio River, and only two in the four counties of Kentucky. Why this distribution? In northern Kentucky, north-flowing tributaries are backfilled with fine silts and clays (glacial outwash ponded these streams) and, in addition, only Boone and Gallatin Counties have significant valley-train deposits along the Ohio River.

In terms of productivity, the best source of groundwater is the glacial sands and gravels along the Ohio, Great and Little Miami, and Whitewater Rivers—all thick and easily recharged by a river, and wells in them have yields of 500 to 1,000 gallons/minute (Fig. 77). Wells in buried valleys without major streams are also good, but typically have yields of less than 500 gallons per minute. In Ohio, these sands and gravels are collectively known as the Great and Little Miami Buried Valley Aquifer Systems. The thickness of this fill can locally approach 200 feet. Along the sides of a major valley, yields are 25 to 100 gallons/minute (less gravel and more clay-rich beds). Alluvial fills along smaller tributaries such as the East Fork of the Little Miami, Four Mile Creek in Butler County, and Todds Fork in Warren County are thinner and have much less sand and gravel and far less recharge, so are adequate only for small villages. Another source of groundwater is sand and gravel in end-moraine deposits. The least productive of the local aquifers are thin, isolated, interbedded sands and gravels on glaciated uplands (much of Clermont and parts of Warren, Butler, Ohio, and Dearborn Counties). In these areas, such reservoirs have little recharge, so supply to a modern home is likely to be marginal. Thus, it is recharge of glacial outwash and Holocene gravels by the larger streams that provides most of our groundwater. Without these accidents of late Tertiary and Pleistocene time, water supply would have long ago restricted the growth of the Cincinnati region. Sources for the preceding discussion are Spieker and Durrell (1961), Gallaher and Price (1966), Walker (1986), Indiana Division of Water (1988), Woodfield (1994), and Woodfield and Fenelon (1994); also see Krothe (1988), Rosenshein (1988), and Sharp (1988).

How does water quality vary from one formation to the other in the Cincinnati region? Groundwater from bedrock is hard and may also be high in iron and sulfates. Water from sands and gravels along a major stream is always less turbid than river water and is generally suitable for most uses, although it too may be hard.

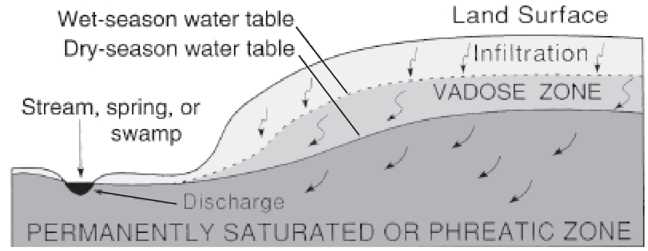


Figure 74. Definition diagram for infiltration and position of water table. Note how water table intersects the surface at a stream.

**Table 7.** Generalized well yields and reservoirs of the Tri-State region (adapted from Walker, 1986). Reprinted with the permission of the Ohio Division of Water Resources.

- Thick, continuous sand and gravel deposits formed chiefly as glacial outwash in Deep Stage valleys. Highest yields of 100 gallons/minute to more than 1,000 gallons/minute from coarse gravels recharged from nearby streams.
- Restricted sand and gravel deposits in Deep Stage valley-fill deposits; thicker deposits most productive. Yields of 25 to 100 gallons/minute.
- Small lenses of sand and gravel in valley fills and on end moraines. Yields of 10 to 25 gallons/minute.
- Clay-rich lacustrine deposits and tills with thin sand and gravel deposits. Yields of 3 to 10 gallons/minute.
- Bedrock of thin limestones interbedded with shales. Yields rarely exceed 3 gallons/minute, and are likely to be best from upper weathered zone.

## Groundwater

As with every subject, the study of groundwater has specific terms related to its origin and use. *Water table* (Fig. 74) refers to the uppermost surface of the saturated or phreatic zone, the *vadose zone* refers to the alternately saturated and unsaturated interval as the depth to the water table changes with the seasons or with pumping, and the zone above the highest level of the water table is called the *unsaturated zone.* The last named zone is thin and wetted by capillary action. Very roughly, as a first approximation, the top of the water table mimics the topography and intersects it in streams and springs.

Two rock properties determine the degree to which water can be produced from a well: its *porosity* or percentage of void or pore space, and its *permeability* or the degree to which these pores are interconnected so that water can flow from one pore to the other. Another factor is the flow of water through the rock. Flow rate, defined as volume per unit time per cross-sectional area of flow, is measured by hydraulic conductivity. When hydraulic conductivity is high, a rock or sediment is said to be permeable, and when it is low, it is said to be impermeable. A saturated deposit with high porosity and hydraulic conductivity is called an *aquifer,* and is a good source of groundwater; one with a low permeability is called an *aquiclude.* If an aquifer is capped by a low-permeability deposit, it is said to be confined, and if not, it is unconfined. A well drilled into a confined aquifer may be free-flowing, whereas one drilled into an unconfined aquifer cannot be free-flowing. The best aquifers of the Cincinnati region are its gravel- and sand-filled Deep Stage valleys with a large river for recharge (Table 7). The best examples of aquicludes in the Cincinnati region are the shales of the Kope and Waynesville Formations, lake beds, and clay-rich lodgment till deposited directly under the ice.

The fine pores of the soil, silt, and sand through which rainwater infiltrates to become groundwater effectively filter out particulate matter, so groundwater is nearly always clear. Even bacteria and some large viruses can be trapped by these same small pores. Chemicals in solution are not so trapped. Most chemicals in groundwater are naturally occurring, however, and result from the transformation of rainwater into groundwater; as rainwater infiltrates, it dissolves the materials through which it passes. In the Cincinnati region, the most easily dissolved and most abundant mineral is calcium carbonate, which forms the local limestones and much of the sand, gravel, and cobbles of the aquifer-forming glacial gravels as well. Thus, most of the groundwater of the Cincinnati region does not easily lather or make suds, and is considered hard, because it typically contains excessive dissolved calcium carbonate. Much of the local groundwater may also be high in iron and sulfates.

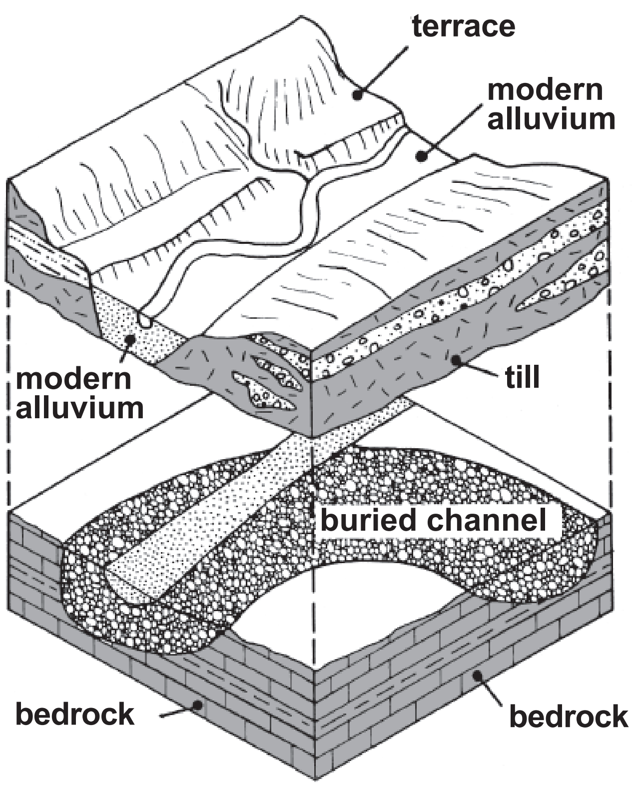


Figure 75. Idealized block diagram of recharge of gravel aquifer by a stream and gravel fill in an abandoned channel (Rosenshein, 1988, Fig. 4). Reprinted with the permission of the Geological Society of America.

Man-made chemicals from leaking chemical tanks, accidental spills along a highway or railroad, petroleum products from old gas stations, and the application of agricultural fertilizers and pesticides all have the potential to enter an aquifer—not to mention salt from the generous salting of roads in winter (in a typical year the city of Cincinnati applies 8,000 to 10,000 tons of salt to its roads). Today, we are more aware and more careful about the possibilities of man-made chemical contamination than in the past, and environmental protection agencies of Kentucky, Ohio, Indiana, and the federal government all have programs to control and, in some cases, clean up man-made contaminants, of which the most troublesome site in the Cincinnati region is the Fernald plant south of Ross in western Hamilton County. There are also some programs for preventive measures in addition to remedial

Figure 76. Pump housing and well on a low terrace along the Ohio River in Ohio County, Ind.

Figure 77. Highwall of a former glacial outwash gravel aquifer along the Great Miami River east of Elizabethtown in far western Hamilton County, Ohio. If it were below the water table, this gravel deposit would be a world-class glacial aquifer.

ones. But whatever the toxic waste and its location, knowledge of the surficial geology and the local flow path of the groundwater is vital to understanding and correcting the problem. An informative article on refined gasoline in the subsurface clearly illustrates this thought (Bruce, 1993).

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A standard methodology is used to assess pollution potential. It contains an excellent, concise summary of geology.

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This is a broad-scope, well-written text by two famous experts. If you can only buy one book, and are interested in water, buy this one. See especially chapter 11 on floodplains and chapter 15 on hillslope processes.

Heath, R.C., 1995, Basic ground-water hydrology: U.S. Geological Survey Water-Supply Paper 2220, 84 p.

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The floodplain and associated terraces of the Whitewater and Great Miami Rivers and all their major tributaries in Butler, Clermont, Hamilton, and Warren Counties are covered. Thirteen categories of land use over these aquifers are displayed. See OKI for many other groundwater-related publications.

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This report covers the part of Ohio that drains into the Ohio River and includes streamflow, groundwater levels and analyses, discussion of sampling networks, a glossary, and much more. It is a fundamental data source. See also the various issues of the National Water Summary for Ohio, also by the U.S. Geological Survey.

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Though moderately advanced, it is a most useful book.

## Geologic Hazards

The inhabitants of the southwestern Ohio/northern Kentucky/southeastern Indiana region are fortunate, because geologic hazards are few in number and consist chiefly of mass movements, rare minor to weak earthquakes, and minor exposure to radon gas. Mass movements are by far the most frequent and most costly, although not yet fatal. For all the topics below, the best path is always the same: early recognition and avoidance or proper planning and design when avoidance is not possible. For both possibilities, *geology and design always go hand in hand.* Geologic hazards—especially minimizing them and avoiding them—are one of the main themes of land-use planning (Smath and others, 2005a, b, c, 2006). A general reference to natural hazards of all types is Bryant (1991).

### *Identifying and Understanding Landslides*

Landslides in the Greater Cincinnati area affect construction on hillsides (crests, slopes, and toes) and in valleys with backwater fines, and along the cutbanks of rivers. Certainly, repair of roads and railroads, buildings, and underground cables and water pipes seems neverending and costs thousands of dollars each year.

Let us begin with hillside roads (Fig. 78). Virtually everyone in the 11 counties of Greater Cincinnati has driven hillside roads with many fresh patches, irregular dips and rises, retaining walls leaning into the road, and sunken guardrails. Pier walls are designed to stop landslides along highways and home sites (Fig. 79). Although expensive, these are by far the best solution. From 1974 through 2006, the city of Cincinnati has invested in 194 pier walls with a total length just short of 10 miles (Richard Pohana, personal communication) to prevent future landslides. Notable areas prone to landslide include Columbia Parkway in Cincinnati; Ky. 8 between Ludlow and Anderson Ferry in Kenton County and Ky. 8 east of Dayton in Campbell County; Mount Adams (whose specially designed retaining wall cost about $30 million in the early 1980's), as well as Hillside Avenue and Delhi Pike in western Hamilton County. A trained eye will soon discover many, many more landslides, however, and when buying hillside property, you would be prudent to have an inspection made for relic and active landslides (Tables 8–9). Technical studies of local landslides include Hough and Fleming (1974), Fleming (1975), Merritt (1975), Fleming and others (1981), Earth Surface Processes Group (1987), Pohana and Jamison (1993), and Fleming and Johnson (1994).

Three factors are chiefly responsible for most of today's landslides in the Greater Cincinnati region: entrenchment of Teays drainage (which formed most of the present landslide-prone relief), lacustrine deposits, and human activities. Although mass movements long predate humans, man-made modifications to hillsides and slopes have created many additional new landslides and reactivated older ones. Building a structure on a hillslope underlain by lake deposits invites landslides, as does dumping fill at the crest or on the side of a hill to widen a terrace, yard, or road (Fig. 80). All three destroy long-established hillside equilibrium. Undercutting-overloading a hillside for a road, parking lot, industrial site, or house disturbs long-term equilibrium by removing lateral support and by placing the cut material on colluvium. Heavy spring rains are always a catalyst. They add weight to colluvium and fill and increase water pressure in underlying permeable sediment or weathered bedrock, which reduces its shear strength. The result is a late winter–early spring landslide: thus the local term *slipping into spring.* Another factor that accelerates mass movements is cutting trees on hillsides. Trees on a hill reduce its water content by transpiration. In addition, tree root systems of all kinds, but especially those that are deep-seated, form a living, interpenetrating web that binds colluvium together and helps tie it to bedrock. When hillside trees are cut for a view, their root systems die, and 3 to 5 years later, downslope movement can be expected to accelerate (Reistenberg and Sovonick-Dunford, 1983). Landslides are also likely below an abandoned quarry in the Fairview Formation, caused by overloading by waste rock, as shown by Agnello (2005).

Drainage is critical to hillside stability. Any structure or activity (such as cutting trees) that adds water to a hillside will (through its added weight and higher pore pressures) lead to landslides. Thus, cutting trees on a hillside carries a double hazard: Root systems die and less water is returned to the atmosphere by transpiration. Another factor possibly related to drainage and thus landslides is slope orientation. South-facing slopes dry more quickly than north-facing slopes, and thus should be more stable, all other factors being equal. The possibility of water drainage into or away from a roadcut always deserves consideration: when gentle bedrock dip is toward the cut, flow will be greater into it than when gentle dip is away from the cut and water flows away from it.

A new, deep cut may also develop small-scale folding or faulting at its base, especially when the bedrock has gentle dip into the cut and consists of 50 percent or more shale. Such features are similar to the stream anticlines discussed earlier.

Figure 78. Embankment collapse on Interstate 74 in western Hamilton County, Ohio, undermined by a rotational slide. Highways parallel to hillslopes in the Greater Cincinnati area need special stepped benching or concrete piers in bedrock to minimize such failures (see Figures 79–80).

### *Earthquakes*

Earthquakes represent the sudden release of stored strain energy deep in the earth's crust. These releases take place constantly as many small tremors and less frequently as moderate to large and damaging earthquakes. Colliding continental and oceanic plates generate vast quantities of stored strain energy that periodically is released when failure occurs as the earth's crust is bent, broken, and faulted. Thus, many large earthquakes occur where an oceanic plate collides with a continental plate, whereas far fewer earthquakes occur in the interior of a large stable plate, such as much of the North American Plate (largely passive with less stored strain energy). When such energy is released deep in the crust, it is greatest at the surface just above the release point, called the *epicenter*. Damage from an earthquake depends on four factors: intensity or magnitude, distance from the epicenter (attenuation), geologic materials, and how buildings, bridges, cuts, etc., are constructed. Fortunately, the Cincinnati region has largely been free of damaging earthquakes, although the famous earthquakes near New Madrid, Mo., in 1811–1812 were felt here (Drake, 1815, p. 233–244).

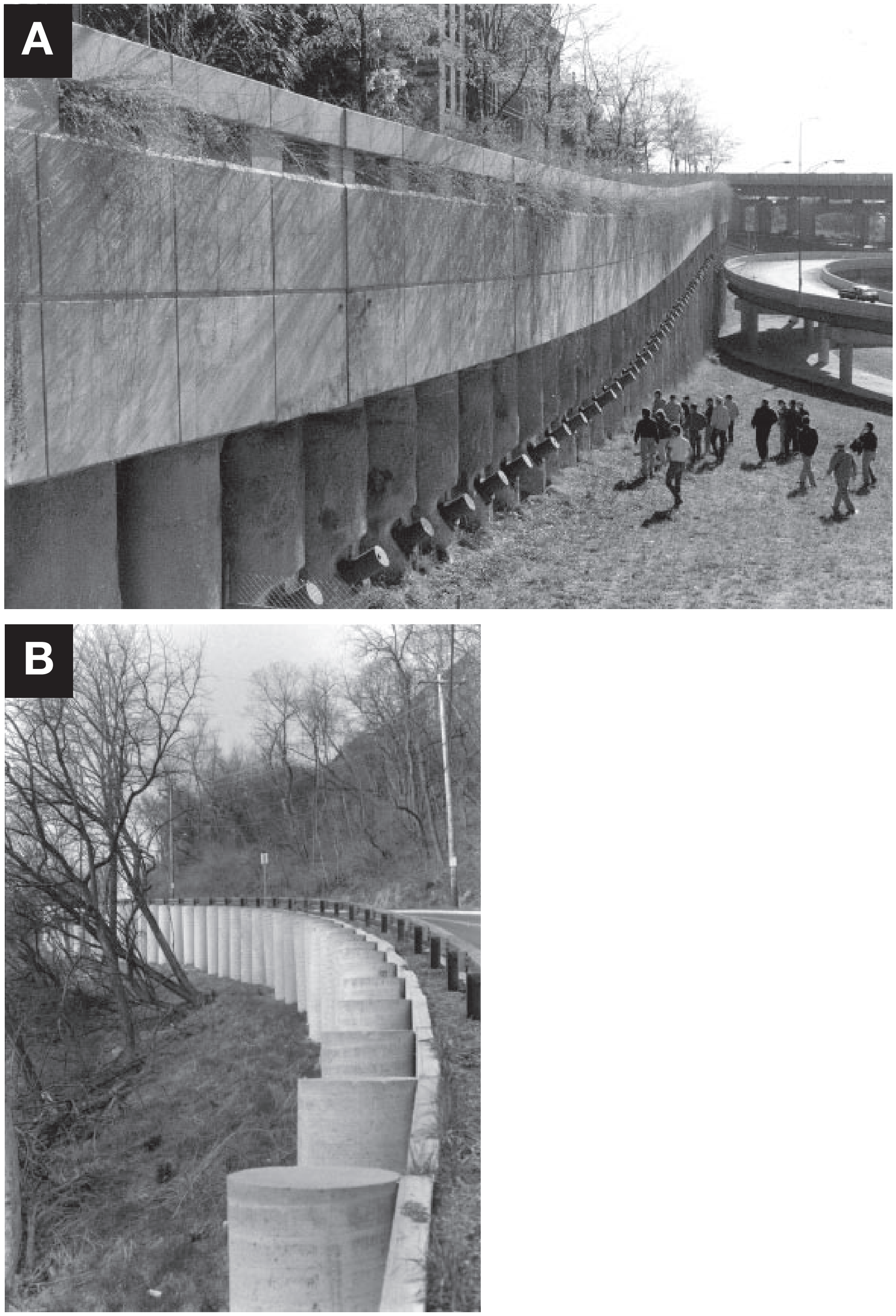


Figure 79. Pier walls. (A) Specially designed underground “corset” of concrete piers maintains the stability of Mount Adams in Cincinnati. (B) Closely spaced piers into bedrock tie a road (or also foundations) securely to a hillside, as seen here along Lehman Avenue in Price Hill, Cincinnati. (C) Here, in far eastern Hamilton County, Ohio, pipes securely hold a road to the hillside, but water collected from the inner roadside ditch continually feeds a landslide below the road (note exposure of the piers). Typically, piers are seated 10 to 15 feet into bedrock.

The intensity of an earthquake is measured in two ways: by calculation from the seismic record obtained from a seismograph or by inspecting and mapping the damage (Table 10). Effects in the Cincinnati region will vary markedly depending on the geologic substrate, topographic location, and, of course, construction. Level upland sites on either bedrock or clay-rich till would suffer the least damage, whereas

**Table 8.** Recognizing landslides.

*At the surface*

- Hummocky ground with 0.5 to 2 to 3 feet of irregular relief, especially below a low scarp or bare bedrock
- Trees randomly tilted or with trunks curved upslope
- Striations oriented downslope on thin clays above bedrock (translational slide)
- Long elongated areas (striations typical) stripped of soil and colluvium to bedrock (translational slides)
- Curved scarps of rotational slides (subtle to obvious and abrupt)
- Remolded textures (poorly sorted fragments in a massive, paste-like matrix) or deformed lake clays at creek level
- Tilted walls and utility poles (creep)
- Weakly concave cracks in pavements parallel to hillside (creep)
- Seepage at the base of a slope
- A closed depression on a low terrace underlain by lacustrine clays, especially where the valley drains northward (north of the Ohio River or on a former backwater lake), resulting from subsurface migration of plastic lake clays downslope toward a stream or new cut
- Cracks in basements and walls

*Below the surface*

- Sharp contact (possibly with slickensides and likely wet) of colluvium with bedrock
- Possible slickensides on clays (intercepted slip surfaces or fault planes) at several depths in the core
- Kinked roots intercepted by the core
- Leaking or broken gas or water lines
- Remolded clays (extruded “toothpaste” look but with clasts) or deformed lake clays
- Cracked and deformed basement floors or highways

**Table 9.** Landslide-prone soils (percent slope). Compiled from county reports of the Natural Resources Conservation Service.

| *Ohio* | *Indiana* | *Kentucky* |
|---|---|---|
| Butler County | Dearborn/Ohio Counties | Boone/Campbell/Kenton Counties |
| Eden, 15–50 | Carmel, 12–18 | Cynthiana, 12–50 |
| Clermont County | Eden, 15–50 | Eden, 12–35 |
| Eden, 18–50 | Pate, 18–25 | Gallatin County |
| Edenton, 18–50 | Switzerland, 12–18 | Eden, 12–30 |
| Fairmont, 18–50 | Switzerland County | Wheeling, 12–20 |
| Hickory, 18–15 | Eden, 15–50 | |
| Hamilton County | Pate, 18–25 | |
| Eden, 15–60 | | |
| Pate, 15–35 | | |
| Switzerland, 15–25 | | |
| Warren County | | |
| Eden, 15–60 | | |
| Hennepenn, 25–35 | | |
| Hicory-Fairmont, 25–50 | | |

Note: Each of these soils has subdivisions, some as many as four, based on differing slopes and textures.

sites constructed on artificial fill will suffer the greatest, especially if the fill is on a hillside. And the greater the difference in physical properties between the unconsolidated surface material and the bedrock, the stronger the seismic shaking. This is called *ground-motion amplification.* Water saturation is another factor. Differential settlement and subsidence will occur in soil, fill, and alluvium as the ground vibrates with each passing shock wave. *Liquefaction* may also occur below the water table in fine sands and silts and cause damage to construction (imagine a well-built bridge whose approaches of fine-grained fill collapsed because of liquefaction). When hillsides are saturated with water, as is typical in spring and late winter, earth tremors could reactivate old landslides as well as initiate new ones. Thus, areas of high landslide risk have the added disadvantage of having an even higher risk of earthquake-induced landslides.

How likely are major earthquakes in the Cincinnati region? Experts consider the greatest source of earthquake risk in our 11-county area to come from the New Madrid Seismic Zone, some 325 airline miles from the Cincinnati region (Fig. 81). This seismic zone is a major one and is related to an ancient, deep-seated rift whose boundary faults periodically release strain energy. Because the deep crust of the Midwest is very

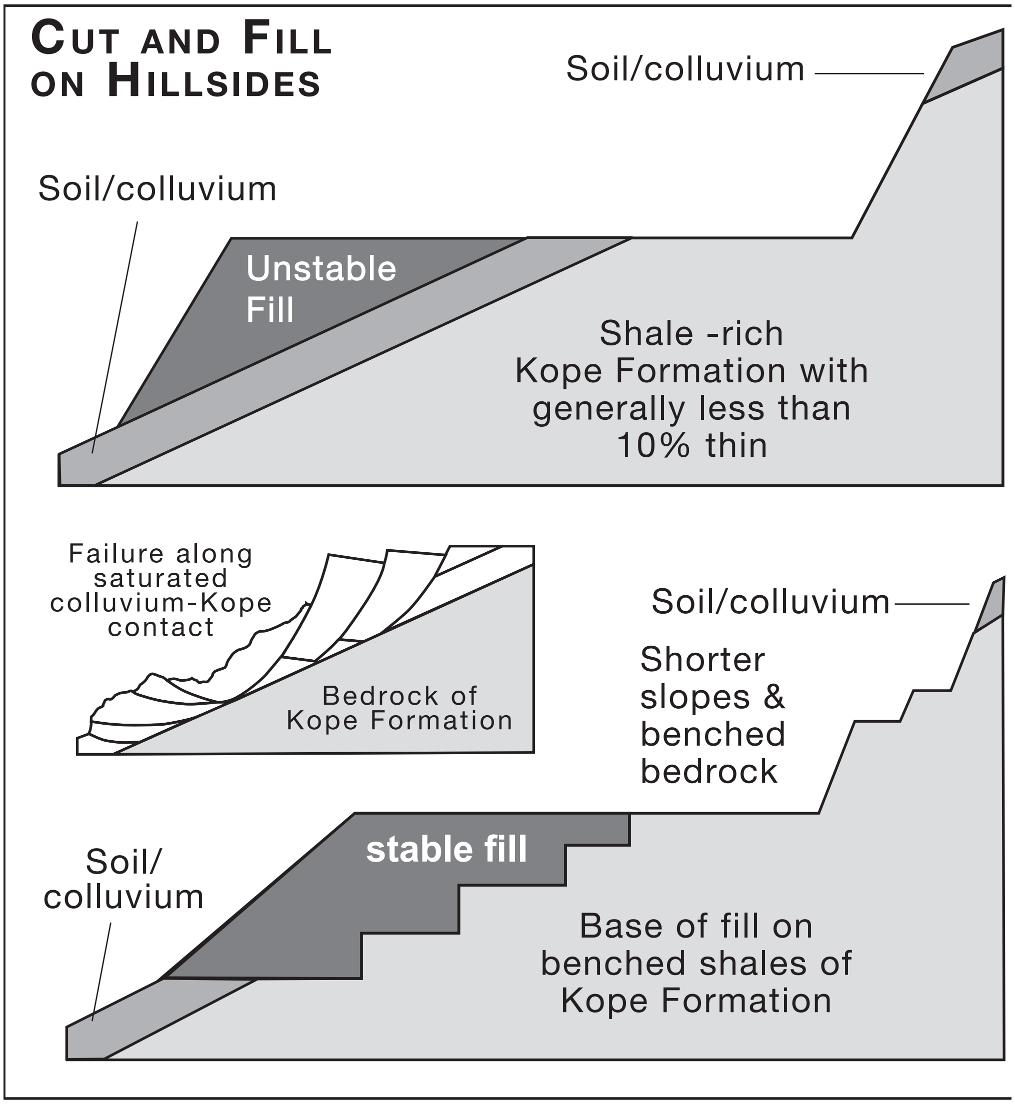


Figure 80. Benching a hillside underlain by shale needs special care, because shales readily generate colluvium in wet climates. Everywhere fill is placed on a hillside, failure is likely unless special precautions are taken.

uniform, the resulting shock waves travel far. The 1811–1812 earthquakes at New Madrid included three great ones estimated to measure 8.5 or more on the Richter scale, five measuring magnitude 7.8, 10 measuring magnitude 7.0, and at least 1,850 measuring less than magnitude 7.0 (Central United States Earthquake Consortium, 1985, p. 4). These earthquakes were well described for Cincinnati by Drake (1815, p. 233–234). If a moderate earthquake of magnitude 6.7 should occur at New Madrid, we would most definitely feel it, and probably it would be assigned a Mercalli intensity of VII (Table 10). Such an earthquake in the New Madrid Seismic Zone is estimated to occur about once every 200 to 300 years. In 1895, there was an earthquake of about this magnitude at Charleston, Mo., near the northern end of the New Madrid Seismic Zone. Fifty miles southeast of Cincinnati at Sharpsburg, Ky., there was a 5.2 earthquake in 1980, and 80 miles north of Cincinnati in the Anna-Sydney area there was a 4.5 earthquake in 1986. Felt by many in the Cincinnati region, its damage was negligible.

Beginning in the late 1980's, Kentucky, Ohio, and Indiana have each put in place a network of seismic stations: Kentucky has 22; Ohio, 26; and Indiana, 30. These modern, real-time seismic networks help us in two important ways. First, with these networks, each state can be subdivided into regions of different seismic risk so that appropriate construction codes can properly be put in place. Second, these networks help geologists locate, map, and understand the movements of deep, old faults that cause these earthquakes (better understanding equates to better planning). Although

**Table 10.** Simplified modified Mercalli scale of earthquake intensity and corresponding Richter magnitudes (from U.S. Geological Survey).

| | | |
|---|---|---|
| I. | Detected only by sensitive instruments/conditions | 1.5 |
| II. | Felt by a few persons at rest, especially on upper floors; delicately suspended objects may swing | 2.0 |
| III. | Felt noticeably indoors, but not always recognized as earthquake; standing autos rock slightly; vibrations like passing truck | 2.5 |
| IV. | Felt indoors by many, outdoors by few; at night, some awaken; dishes, windows, doors disturbed; standing autos rock noticeably | 3.0 |
| V. | Felt by most people; some breakage of dishes, windows, and plaster; disturbance of tall objects | 4.0 |
| VI. | Felt by all; many frightened and run outdoors; falling plaster and chimneys; damage small | 4.5 |
| VII. | Everybody runs outdoors; damage to buildings varies depending on quality of construction; noticed by drivers of autos | 5.0 |
| VIII. | Panel walls thrown out of frames; walls, monuments, chimneys fall; sand and mud ejected; drivers of autos disturbed | 5.5 |
| IX. | Buildings shifted off foundations, cracked, thrown out of plumb; ground cracked; underground pipes broken | 6.5 |
| X. | Most masonry and frame structures destroyed; ground cracked; rails bent; landslides | 7.0 |
| XI. | Few structures remain standing; bridges destroyed; fissures in ground; pipes broken; landslides; rails bent | 7.5 |
| XII. | Damage total; waves seen on ground surface; lines of sight and level distorted; objects thrown up into air | 8.0 |

### The Mercalli scale

The international standard of earthquake intensity is called the modified Mercalli scale and has 12 classes (Table 10). The Mercalli scale ranks *observable effects (intensities)* of an earthquake, whereas the Richter scale requires a seismograph and measures the *magnitude of energy released* from an earthquake. Because it can be quickly calculated from the seismic record, the Richter scale is calculated and reported shortly after an event, whereas the Mercalli scale requires an inventory in the field.

prediction of earthquakes is well into the future, by understanding the effects of earthquakes on different geologic materials and building properly, we can minimize the effects of a possible destructive earthquake rather than ignore earthquakes and maximize their effects. See the parallel with landslides?

We are far more likely to be seriously injured driving to work every day than by an earthquake once in a lifetime. Historic records since the New Madrid earthquakes seem to show that no one has ever been directly killed by an earthquake in the eastern Midwest. And property damage will always be very selective according to substrata topography and construction—quite unlike the case with tornadoes.

### *Sinkholes*

Sinkholes (Fig. 82) are closed circular to elliptical depressions with internal drainage that occur in soluble limestone formations such as are widespread around Lexington and across south-central Kentucky. Sinkholes and smaller solution-enlarged fractures require special attention under foundations of all kinds—dams, levees, roads, and buildings of all sizes—because they indicate open space underground. There are only a few sinkholes in our area, although there were doubtless many before they were filled and covered by the first ice sheets. Sinkholes can be seen in Mount Airy Forest in Cincinnati (Applegate, 2003), along Winton Road south of Greenhills, and in Miami Whitewater Forest (Bowles Woods) in northern and western Hamilton County (Pavey and others, 1999), and are shown by Fenneman (1916, Plate IV) in Devou Park in Covington. Also, a few scattered ones are present in Clermont County. In both western Switzerland and Dearborn Counties in Indiana, sinkholes are re-

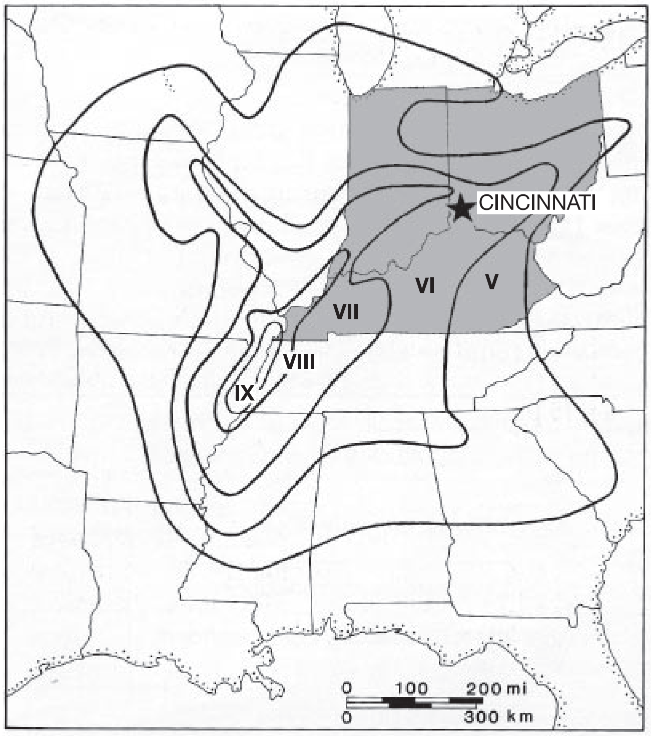


Figure 81. Vast areas are predicted to be affected by a moderate earthquake when its epicenter is at New Madrid, Mo., along the Mississippi River just opposite far western Kentucky. Damage in the Greater Cincinnati area would probably be between V and VII on the Mercalli scale. Redrawn from Algermissen and Hopper (1985).

ported (Powell and others, 2002). Diameters are generally small, although a few exceed 80 feet. All but the sinkholes in Winton Woods occur south of the limit of Illinoian glaciation, where glacial deposits are scattered and thin. Thus, more may be found in northern Kentucky and southeastern Indiana (Currens, 2001, 2002).

### *Radon*

Radon is an inert, odorless, colorless gas that is radioactive and part of a long chain of radioactive decay. Although discovered chemically almost 100 years ago, radon was recognized as a geologic hazard only in the mid-1980's. Fortunately, it is not a major geologic hazard in the Cincinnati region, and high concentrations in buildings are easily remedied by ventilation. Sources of information about remedies include the U.S. Environmental Protection Agency/Centers for Disease Control (1986), Otton (1992)—containing an excellent summary of additional sources of information—and Hansen (1993).

Radon is a gaseous daughter element of radium, which ultimately comes from uranium. There are several isotopes of radium, but only one, radium-222, has sufficient half-life to be dangerous. Radium-222 itself decays to polonium-218, which, when carried into the respiratory system by dust or smoke particles, can cause lung cancer. Its concentration is measured in picocuries or in working levels. One picocurie or 0.005 working level is an average indoor reading. Because

Figure 82. Three small sinkholes coalesce to form a larger one opposite the parking lot of Bowles Woods of the Miami-Whitewater County Park in far western Hamilton County.

of its short half-life, radon-222 is never a problem outdoors, only in closed spaces where its supply is continually being recharged from soil, air, open earth fractures, a sinkhole or cave, or even a fault. Because sinkholes are rare in the Cincinnati region and there are no mapped faults, then soil, glacial materials, and possible bedrock fractures are the chief sources. From any of these, radon gas can enter a basement through cracks in its walls, between slabs, or through utility pipes. Some radon can also enter from water derived from household wells—radon can escape into a house from water that comes directly from a well (this is not a problem after storage in a tank, because of its rapid radioactive decay). Thus, sealing leaks and adding ventilation reduce indoor concentrations of radon gas.

In the northern Kentucky/Cincinnati region, radon is not a major hazard, because geologic materials are only weakly to moderately radioactive, unlike with the Devonian black shale of Kentucky and central and northern Ohio.

### Contemporary Stress-Release Structures

The steep, narrow valleys of the Cincinnati/northern Kentucky region sometimes have small, ephemeral valley anticlines and compressional faults and shears in their stream bottoms. The thickness of such zones depends on the competence of the bedrock, especially the proportion of interbedded shale, but generally is only a few feet, say 3 to 7 feet, in the Cincinnati region. The term *stream valley anticline* has been broadly applied to such structures, which are considered the result of active lateral compression from valley sides (Ferguson, 1967, 1974). Such structures form in response to contemporary stress release. For example, in a new cut or in a deeply incised valley resulting from Wisconsinan river diversion, a shaly section in a creek or at the base of a cut may buckle, fold, or move laterally. Near-vertical joints parallel or subparallel to valley trend may also be present in and near valley walls and result from the same process. Descriptions of these local features are given by Hofmann (1966) and DeJong and others (1989). Stress-release features may develop during foundation excavation in narrow valleys when high cuts are made at the base of steep hills, especially when the water table is high and the geologic formation is the Kope.

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The causes and consequences of geologic mass movements in urban areas are discussed. Table 1 lists 45 sudden urban landslides that caused at least 286,000 deaths. It contains a useful section on hazard mapping and zonation, plus intensity, scale, and a complete list of symbols. It is highly recommended.

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This readable account in 12 chapters also includes nine appendices, an earthquake quiz, and a glossary. This is your starting text.

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This clear, informative text has many excellent color illustrations. Hazards are discussed under the broad headings of materials and processes. It contains many references.

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This thoughtful article, published in the quarterly newsletter of the Hillside Trust, clearly sets forth the need for greater appreciation of our hillsides.

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This careful review of historical documents clearly identifies four major shocks and quotes vivid descriptions by travelers. Mercalli intensities of VI and VII are estimated for the Cincinnati region, which experienced shocks for almost 2 months. It is fascinating reading.

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U.S. Environmental Protection Agency, 1988, Radon resistant residential new construction: U.S. Environmental Protection Agency, USEPA 600/8-88-087, 47 p.

Clear, straightforward text covers all the essentials.

Von Schlichten, O.C., 1935, Landslides in the vicinity of Cincinnati: The Compass, v. 15, p. 151–154.

A landslide that destroyed more than 40 houses in Riverside, a neighborhood along U.S. 50 (River Road), and disrupted nearby railroad tracks, is described and illustrated.

## Solid-Waste Landfills

All over the world, modern urban areas and landfills go hand in hand. Urban landfills are small areas where nontoxic solid waste—household garbage, metal, paper, shingles, old tires, scrap lumber, glass, etc.—is buried for final disposal according to a State-specified and approved procedure (Figs. 83–84). In 2006, the 11 counties of the Tri-State area had four active public landfills. Proper siting of landfills requires proper knowledge of local geology and groundwater hydrology. The requirements are simple: Find a site away from a stream or floodplain with as impermeable a geologic base as possible, such as a shale or shale-rich bedrock formation (e.g., the Kope or Waynesville), or either clay-rich lodgment till or clay-rich glacial lake beds. These materials serve to confine possible seepage into aquifers or potential aquifers. In short, clay-rich beds of any origin help the waste pile. When such beds are used, they are plowed and repacked to minimize possible leakage along joints or fractures and thus inhibit the flow of water into possible sand or gravel lenses or deeper aquifers. Plastic liners provide additional protection against leaks. As with landslides, water is the enemy.

In addition to minimizing flow away from the waste pile, the site should be above a floodplain and not have groundwater flowing into it. Thus, an upland site with an impermeable base or a site with an impermeable seal on a valley side prevents groundwater from entering the waste pile. Properly designed and filled, landfills ultimately provide good space for recreation.

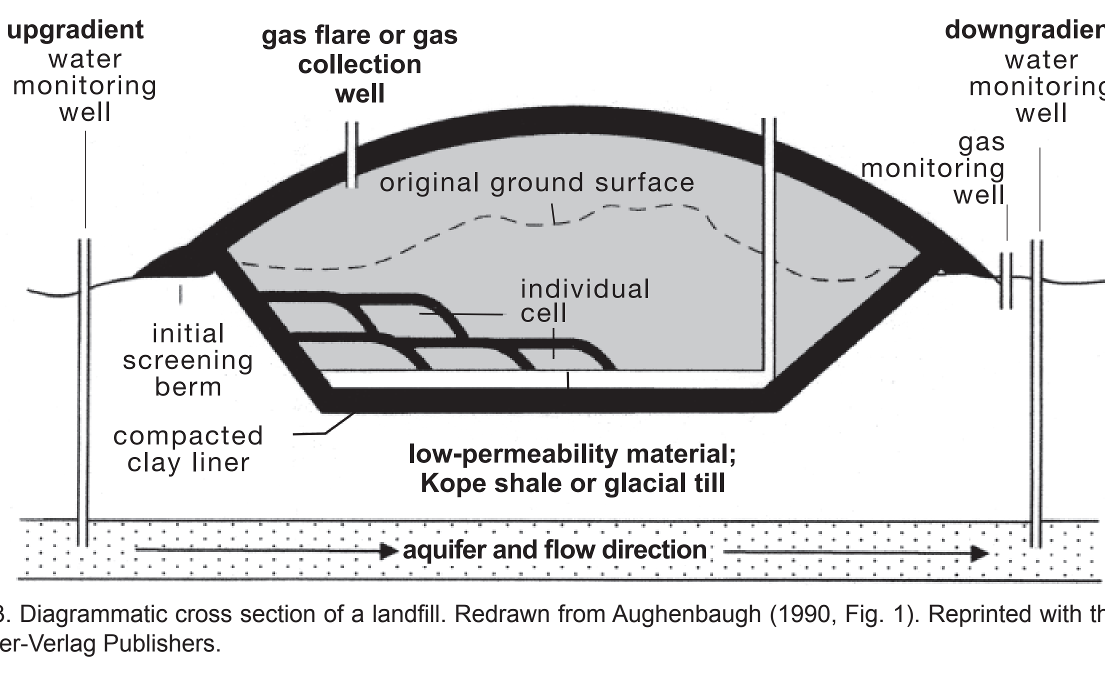


Figure 83. Diagrammatic cross section of a landfill. Redrawn from Aughenbaugh (1990, Fig. 1). Reprinted with the permission of Springer-Verlag Publishers.

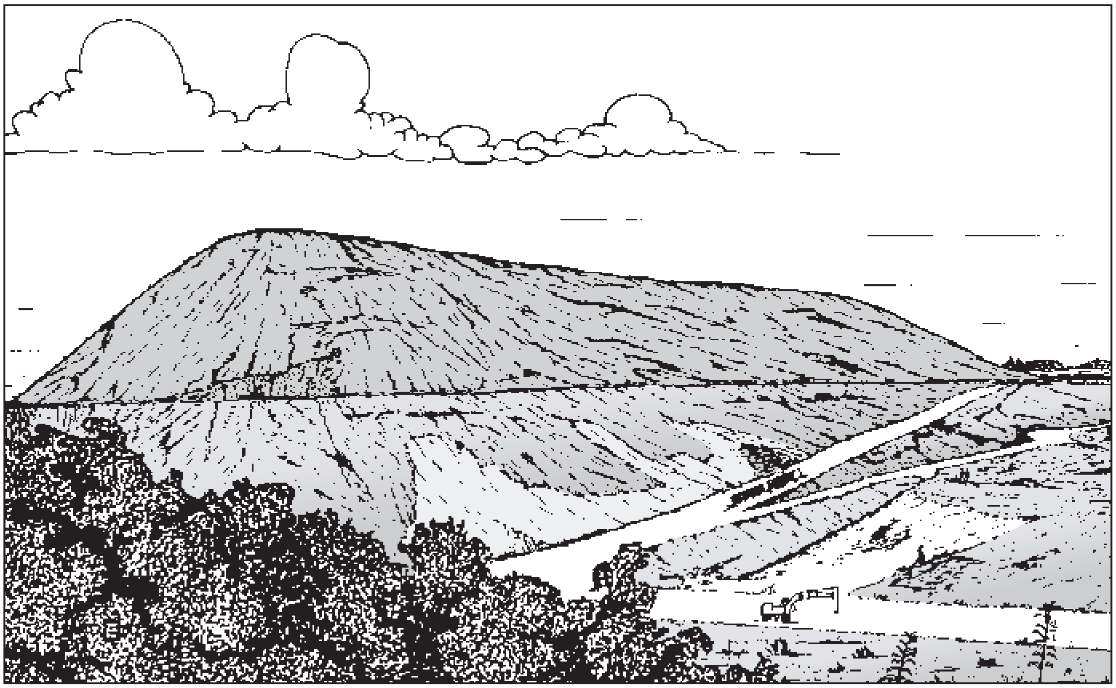

Figure 84. "Mount Rumpke," the largest landfill of the Greater Cincinnati area—and at 1,064 feet also the highest elevation in Hamilton County—as seen from U.S. 127. Drawn by Lila Messick from a photograph (1990).

There are also many rural sites, informally called *landfarms,* where Class B sewage sludge can be deposited on a field after proper authorization by State and county officials. Here sunlight and air oxidize the sludge, which adds nutrients to the soil.

Landfills generate considerable quantities of burnable methane, which must be either vented to the atmosphere or captured and used for combustion, as is done at several of the landfills in the Cincinnati region. The quantities of gas generated by a large landfill are enough to heat 10,000 to 20,000 homes per year in a climate such as Cincinnati's.

Fly and bottom ash from coal-fired power plants also "needs a home" and is typically stored on nearby floodplains and terraces or trucked nearby. Siting requirements for fly and bottom ash are broadly similar to those for ordinary urban solid waste, but less restrictive; both ashes have very low solubilities and only one substances is being stored—quite unlike urban solid waste, which can contain almost anything that is not radioactive.

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This objective, wide-ranging overview puts local problems in worldwide perspective.

Hull, D.N., 1992, The role of geology in the management of Ohio's solid waste: Ohio Geology, summer 1992, p. 3–5.

This is an excellent starting point for insight into the importance of geology for solid-waste disposal.

Indiana Solid Waste Management Board, Indiana Department of Environmental Management, Office of Land Quality, 100 North Senate Ave., Indianapolis, IN 46206-6015, (317) 232-8941.

Indiana's Administrative Code 329 gives complete legal requirements.

Kentucky Division of Waste Management, Kentucky Environmental and Public Protection Cabinet, 14 Reilly Rd., Frankfort, KY 40601, (502) 564-6716.

See www.waste.ky.gov for requirements.

Noger, M.C., 1990, Generalized geologic bedrock conditions as related to solid-waste landfills in

Kentucky: Kentucky Geological Survey, ser. 11, scale 1:500,000.

Based on the 1:24,000- and 1:250,000-scale geologic maps of Kentucky, this fine generalized map divides all of Kentucky's surface formations into 10 classes based on their suitability for a solid-waste site, the more impermeable the better. Conversely, the more permeable the formation, the greater the suitability for water wells.

Ohio Division of Solid and Infectious Waste Management, Ohio EPA, 401 East 5th St., Dayton, OH 45402, www.epa.state.oh.us/dswm.

Ohio Administrative Code Rule 3745-27-07 (paragraph H) and Guidance Document to Siting Criteria 0693 set forth details.

## Construction Materials

The bedrock and glacial sands and gravels of our area always have been and continue to be key economic contributors to the development of the 11 counties of the Greater Cincinnati region—local fieldstone (River Quarry and Hill Quarry Beds) in earlier times, followed by glacial sand and gravel and crushed stone from underground mines today. In addition, many rocks were brought from afar for ornamental building stones along with large blocks of sandstone from both southern and northern Ohio. Let us start first with what can be seen by a stroll along the sidewalks of Cincinnati and Covington.

### *Building and Dimension Stone*

The changing kinds and uses of building stones in every city reflect changes in the technology of quarrying and transportation, the cost and availability of labor, architectural tastes and styles, and the wealth of a city. In short, the evolution of the use of building stone in a city is a key part of the history of its growth and people. Cincinnati is no exception to these generalizations, because its center has over 20 different building stones within a few blocks (Table 11). Fortunately, there is now a building-stone guide for the city center (Hannibal and Davis, 1992). Along with it, consult "Cincinnati Observed," by John Clubbe (1991), for an understanding of the city's architecture.

Local Ordovician fieldstones were first used—mostly from the River Quarry Beds of the Point Pleasant Formation near river level and the Hill Quarry Beds of the Fairview Formation from the upper hillsides overlooking the city—for basement walls, piers, and early sidewalks. Later, the Mississippian Buena Vista Member of the Cuyahoga Formation, the Dayton Limestone, and the Berea Sandstone near Cleveland were widely used. In 1893, gray and pink Precambrian sandstone was imported from Wisconsin to build City Hall on Plum Street, whose interior also contains Italian marble. Much of the white and distinctive Dayton Limestone quarried near Dayton was probably first brought to the area in quantity when the Ohio-Erie Canal was opened. Granite and gneiss from the eastern United States and Canada began to be used with the advent of rail transport, which also made it possible to bring the Salem Limestone cheaply to Cincinnati from quarries near Bedford, Ind. To all of these should be added imported marbles and travertines from Europe. Today, most retaining walls are made of poured concrete or concrete blocks, and these older walls are rapidly disappearing.

What observations can be made about the weathering of local building stone in the Tri-State? Surprisingly, it has never been systematically studied, although it certainly would be most appropriate and timely. Of all the locally used building stones, limestone, because of its solubility to slightly acidified water, is the best indicator of urban weathering. Of these limestones, the Salem provides the best evidence of weathering because it is nearly always cut with smoothly sawed faces. After about 40 to 50 years, such faces generally acquire a relief of at least a millimeter or so, and are distinctly rough to the touch. Such etching in the urban environment highlights both small- and large-scale stratification in the Salem (well-sorted, fragmental lime sand that was washed back and forth by tidal currents on a shallow marine platform). Urban weathering also highlights the bioturbation and mottling of the Dayton Limestone and enhances its attractiveness manyfold. Thus, both the Salem and Dayton Limestones provide outdoor urban laboratories for sedimentology classes. Where abundant salt is used to control ice on sidewalks, both limestones and sandstones are exfoliated (Fig. 85), and even some of the feldspars in the polished granite rocks have a dull matte finish rather than a glossy appearance.

Stone fences and walls deserve special comment (Fig. 86). These fences were originally constructed chiefly from local fieldstone gathered from hillsides and creek beds. The fences are most common along the Ohio River and its dissected tributaries, where creeks choked with loose slabs crossed the Point Pleasant, Kope, and Fairview Formations. Today such a fence, gateway, or wall may be built with more distantly transported stone.

Have the styles of these walls built of local limestones changed through the years? The easiest to build was a dry wall stack where the slabs were simply laid

**Table 11.** Building and dimension stones.

*Gneiss*

A high-rank metamorphic crystalline rock that has pronounced flow structure; it is very spectacular when polished, used as an outside decorative stone, and wonderful to study. The best example is the Cincinnati Bell Telephone Building at Seventh and Elm, but also see the Woodward Building and Loan building at the southwestern corner of Main Street and Central Parkway.

*Granite*

A massive igneous rock that ranges widely in texture from fine to very coarse and in color from white to gray to shades of pink and red, it has many varieties. It is especially attractive as an *orbicular* granite with large, zone-grained crystals of pink feldspar called *porphyroblasts,* many of which are rimmed by quartz. See the Star Bank building and the Westin Hotel on Fountain Square (both faced with a coarse granite having fine, reflective feldspars and some large inclusions).

*Gabbro*

It is a dark-colored, coarsely crystalline, quartz-free igneous rock with many textural varieties, but all are black and have a dominance of plagioclase, its basic framework. Examples include the iridescent plagioclase in the facing of Bankhardt's Luggage on Fourth Street and the Seven Hills Savings and Loan office at Main and West Liberty Streets; other examples include the Society Bank building at Seventh and Walnut and the facing stone of the Omni Netherland at Race and West Fifth Streets. It is elegant formality.

*Marble*

A metamorphosed carbonate rock that ranges from massive and uniform to spectacular, multicolored angular breccias, it is used as both an interior decorative stone, as in the floor of Tower Place, and outside as at the Inglass Building at Fourth and Vine Streets, and the Federal Reserve Bank building at Fourth and Main Streets (a white, strongly deformed marble). Red marble is on the floor of Tower Place, and coarse, multicolored marble breccia is in the Omni Netherland Plaza.

*Serpentinite*

A black, basic rock derived from deep within the earth's crust, it is commonly brecciated and contains prominent white quartz veins; it may be fractured and is a spectacular ornamental stone. See it at 35 East Seventh Street, the Krippendorf Building at 628 Sycamore Street, and the entryway of the Huntington Bank Building at 101 West Fourth Ryder Street.

*Ordovician fieldstone*

This stone is mostly from the Quarry Hill Beds of the Fairview Formation, but also from the River Quarry Beds of the Point Pleasant Formation. It is commonly spectacularly fossiliferous—bring a fossil guide with you. Convenient, easily workable, and durable, this stone was used in some of the oldest basements, bridge abutments, and sidewalks in the city. See the Art Academy of Cincinnati and the Art Museum, both in Eden Park, and the Elsinore Tower on Gilbert Avenue, which is notable not only for its design but also for its workmanship. The piers of the Southern Railroad Bridge are also built of limestone from the Point Pleasant Formation.

*Dayton Limestone*

The whitest, most distinctive building stone in the city is fine to coarse grained, and has a noticeable nodular structure, bioturbation, and some stylolites. It is common as a trimstone on older buildings. Tracks, trails, and burrows are abundant, but body fossils are rare. See it at St. Peter in Chains Cathedral, Ninth and Plum Streets.

*Salem (Indiana) Limestone*

Gray, uniform, medium- to coarse-grained, and very homogeneous, this is the most common building stone of the 20th century in the eastern United States. Coarser blocks contain some small fragmented fossils, and weathered surfaces show abundant cross stratification after 30 to 50 years. Examples are found at the corporate headquarters of the Cincinnati Gas and Electric Co., the federal post office on Fifth Street, all the Procter and Gamble buildings, the Taft Theater, the masonic temple, and St. Louis Catholic Church at Eighth and Walnut Streets.

*Sandstone*

This was widely utilized in the Tri-State area in the 19th and early 20th centuries. The Buena Vista Sandstone from west of Portsmouth was the most widely used, followed by the Berea Sandstone from near Cleveland. City Hall at Ninth and Plum Streets is the most spectacular, however: red and gray Keweenawan Sandstone from the Lake Superior region. Three other examples of note include the towers of the Suspension Bridge and the piers of the L&N Railroad Bridge (both composed of the Buena Vista Sandstone), the facade of the old Second National Bank building at Ninth and Elm Streets, and the tower and steeple of St. Xavier Church on Sycamore Street.

*Travertine*

A handsome carbonate rock deposited from spring waters, it has crude stratification, is characteristically porous, and commonly has a brownish cast. It has been used as an interior decorative stone, as in the arcade of the Carew Tower, but also more recently as an exterior facing stone on the PNC Center at Fifth and Main Streets and the Mercantile Center at 120 East Fourth Street, plus the small facade at 35 East Seventh Street.

*Artificial stone*

Each week more common, walls and fireplaces built of artificial stone are more and more realistic. Recognize it by the uniformity of its rectangular and square cross sections and its textural uniformity.

Figure 85. Many winters of plentiful salt applied to a limestone entryway have taken their toll.

one upon the other and tied together by cement along their inner wall. A few of these early walls are still to be seen (Fig. 86). Near-perfect geometric regularity with thin, uniform, and regular cement between leveled limestone slabs is a later style, probably dating from 1900 through 1930. Still later is the use of unleveled slabs separated with wide cement. Many other possibilities are easy to find along the sidewalks of the older sections of Covington, Newport, and Cincinnati. Virtually all of the limestones on the older walls came from quarries in our local limestones.

### *Sand and Gravel*

All our sand and gravel comes from glacial outwash preserved in terraces or Holocene deposits along the larger rivers (see "Floodplains," p. 78), although earlier a few kames provided a minor source. Well washed and sorted by nature and easy to dig, these local deposits are fast disappearing as they are covered by houses and highways and as they are mined ever more rapidly by either floating dredges or by large cranes. Thicknesses of 60 to 100 or more feet of gravel above bedrock have been removed. The resultant pits have been utilized as lakes for recreation, to make housing developments more attractive, or have been filled with fly ash where a terrace deposit was mined. This mining of sand and gravel highlights the conflicting land-use demands of farming versus housing and industrial development versus preservation as a water field. As the reserves of outwash sands and gravels diminish, underground mining of the deeper Ordovician limestones will become necessary.

### *Bedrock*

There are two underground mines in the study area: one in Gallatin County and one in Clermont County. The Camp Nelson Formation is the principal unit mined for crushed stone, and large blocks are also used to stabilize roadcuts and stream banks. There is also a quarry near Butler, just south of Campbell County, that utilizes the Point Pleasant and Lexington Limestones; several quarries just outside the study area that supply fieldstone and crushed stone; and a large mine that produces lime for reduction of sulfur dioxide from coal-fired power plants at Carntown in Pendleton County, Ky.

Taken for granted by all too many of us, these gravel and sand pits, quarries, and underground mines supply limestone and dolomite for ornamental stone, concrete, and riprap, without which we could not have our modern society.

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Amaral, E.J., 1994, Sand and gravel resources along the Ohio River Valley: Kentucky Geological Survey, ser. 11, Report of Investigations 8, 59 p.

Distribution, stratigraphy, economic geology, and exceptionally detailed information on size, shape, roundness, and composition of these important deposits make this a most useful report for gravels on both sides of the Ohio River.

Ashurst, J., and Dimes, F.G., eds., 1998, Conservation of building and decorative stone: Oxford, Butterworth/Heinemann, 254 p.

This is a richly illustrated, easy-to-read, how-to-do-it book.

Bell, F.G., 1992, The durability of sandstone as building stone, especially in urban environments: Association of Engineering Geologists Bulletin, v. 29, p. 49–60.

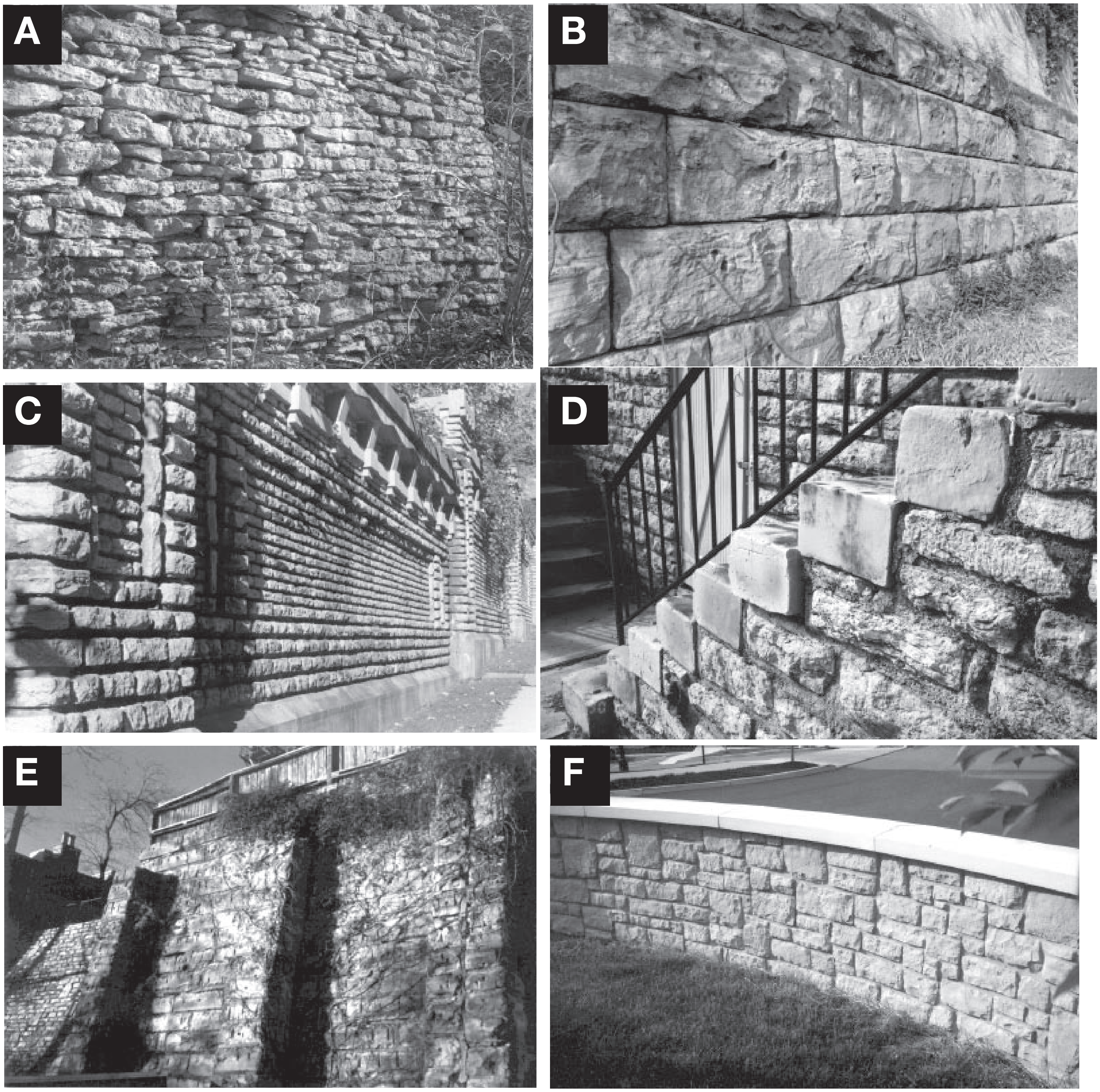


Figure 86. There are many, many styles of walls in the Greater Cincinnati region. These different styles reflect the lesser availability of local Ordovician limestones as the metropolitan area grew, the increasing cost of labor, the development of poured and precast concrete walls, and the use of fly ash in concrete blocks for walls. A few examples are shown above, all from the city of Cincinnati. (A) Old dry wall of local fieldstone still "doing its duty" in Walnut Hills. (B) Large blocks of coarse Pennsylvanian(?) stone support a railroad fill near the Ohio River. (C) A beautifully detailed wall of local limestone built by the stonemasons employed by the Works Progress Administration in Mount Echo Park in Price Hill in the late 1930's. (D-E) Stairway built of Mississippian Buena Vista Sandstone and local limestone and retaining wall of Berea Sandstone for former incline to Mount Auburn, both in the Prospect Hill National Historic District. (F) Modern wall of artificial stone capped by high-density concrete slab in University Heights.

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Fookes, P.G., Gourley, C.S., and Ohikere, C., 1988, Rock weathering in engineering time: Quarterly Journal of Engineering Geology, v. 21, p. 33–57.
This is a comprehensive review of in situ weathering of material used in Britain for construction. Expository text with many references includes 20 tables, one with rates of weathering starting 12,000 years ago. It is a starting point for the serious student.

Dever, G.R., Jr., 1974, High-carbonate rock in the High Bridge Group (Middle Ordovician), Boone County, Kentucky: Kentucky Geological Survey, ser. 10, Information Circular 22, 35 p.
This is a pioneering paper.

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This fine article is a starting place for studying urban weathering of building stone and sets forth the idea that the same processes that operate in nature also weather building stone in cities. It contains a summary of preservation methods as of 1978.

Hannibal, J.T., and Park, L.E., 1992, A guide to selected sources of information on stone used for buildings, monuments, and works of art: Journal of Geological Education, v. 40, p. 12–24.
The revival of interest in the use and preservation of dimension stone makes this article especially useful because it brings together general works, publications concerning specific states in the United States and provinces of Canada, city guides, and sources of trade names, lists of stone for sculpture, and much more. It is exceptionally well referenced.

Kemp, K.M., 1992, A walking tour of building stones for introductory geology courses: Journal of Geological Education, v. 40, p. 188–193.
This sets forth the learning possibilities of a field trip to city center.

Murray-Wooley, C., and Raitz, K., 1992, Rock fences of the Blue Grass: Lexington, University Press of Kentucky, 220 p.
Rich in color plates, but richer still in the scope of its six chapters, two appendices plus extended glossary, notes, reference list, and index, this beautiful book focuses on the Inner Bluegrass Region of Kentucky. It is also a great teaching guide to all those in the Tri-State area who admire stone fences.

Patton, J.B., 1974, Glossary of building stone and masonry terms: Indiana Geological Survey Occasional Paper 6, 15 p.
This paper defines over 400 trade and relevant geologic terms and is an important source of information by a long-time scholar of building stones.

Richey, H.G., 1951, Richey's reference handbook: New York, Simmons-Boardmen Publishing Co., various pagination.
Subtitled "For Builders, Architects, and Construction Engineers," this handbook has parts that are devoted to building stones. This classic contains many line drawings, along with discussion of stone finishes and directions on stone setting and pointing, and types of stone.

Siegesmud, S., Weiss, T., and Vollbrecht, A., 2002, Natural stone, weathering phenomena, conservation strategies, and case studies: Geological Society of London Special Publication 205, 448 p.
Thirty short technical articles are for the advanced reader.

Sims, I., 1991, Quality and durability of stone for construction: Quarterly Journal of Engineering Geology, v. 24, p. 67–74.
Strongly directed to the engineer, this paper provides insight into the European experience, especially with limestone. See other articles in the same volume.

Webster, R.G.M., ed., 1992, Stone cleaning: London, Donhead Publishing, 308 p.
This volume, subtitled "The Nature, Soiling, and Decay Mechanisms of Stone," contains 31 short papers

about an increasingly popular subject: Should a stone building be cleaned and, if so, how? The papers come from the proceedings of an international conference held in 1992 in Edinburgh, Scotland.

Winkler, E.M., 1975, Stone: Properties and durability in man's environment [2d ed.]: New York, Springer-Verlag, 230 p.

A famous European metamorphic petrologist turns his attention to the durability of stone in the modern world and produces a classic volume. It is fairly advanced reading, rich in illustrations.

Wunder, J.M., 1979, Sand and gravel resources of the lower Great Miami River Valley, Ohio: University of Cincinnati, Department of Geology, 95 p.

This little-known study has 61 pages of appendices—described sections, size data, and pebble counts—plus a plate. It is a most valuable reference.

# Field Work in the Greater Cincinnati Region

Among metropolitan areas in the eastern Midwest and upper South, ours is unusually favored by an abundance of outcrops of fascinating Cincinnatian bedrock, drainage diversions with "narrows," large abandoned misfit valleys, diverse glacial features, opportunities to study the mass wasting of hillsides, and wide, imposing floodplains bordering the Ohio River, itself a complex ice-margin stream. Hence, opportunities for short field trips are numerous everywhere in the Greater Cincinnati region.

The best sources for bedrock localities are Davis and Cuffey (1998) plus Algeo and Brett (2001) and McLaughlin and others (in press). Davis and Cuffey (1998) has an appendix with locations of more than 130 Cincinnatian outcrops, whereas Algeo and Brett (2001) and McLaughlin and others (in press) provide roadlogs with sequence-stratigraphic interpretations. Other guidebooks emphasizing bedrock geology include Pope and Martin (1977), Meyer and others (1981), Davis (1986), Kepferle and others (1987), Haneberg and others (1992), and Shrake (1992). Guidebooks have been written for both Interstates 71 and 75 in Kentucky (Haney and Noger, 1992a, b). Field trips farther afield are provided by Biggs (1986) and Neathery (1986). The two statewide highway guides by Camp and Richardson (1999) and Camp (2006) are also worthy of attention. The trips described in Table 12 are only a small start for many informative outings.

Four useful books for study of fossils in Cincinnatian outcrops are "Cincinnati Fossils," by Davis (1992), "Ohio Fossils," by LaRocque and Marple (1985), "Fossils of Ohio," by Feldman and Hackathorn (1996), and "Fossils in the Field," by Goldring (1991), a general text on how to collect and interpret fossils. The study of fossil concentrations in the field, on bedding planes, and in single beds yields much useful information (Table 13), especially when a standard classification of limestones is used (Table 14). Two books on fossil hunting in Indiana are those by Perry (1959) and Shaver (1959). Greb (1989) provided an accessible overview of evolution in a single handsome publication.

The glacial deposits of the Cincinnati region are largely summarized by Goldthwait and others (1961, 1981) and engineering geology by Fleming and others (1981). A guidebook written for high-school teachers is also available (Haneberg and others, 1992). Use Durrell (1977) for drainage history.

Needed equipment includes a notebook, shovel or hammer, possibly a hand lens, marking pen, sample sacks, and, most important of all, permission to cross private property. The serious amateur will always want to take notes in the field and draw a picture of the outcrop and its section of exposed rock or glacial drift. A standard set of symbols is available and should always be used (Fig. 87). Careful determination of the geographic and stratigraphic position of your samples

**Table 12.** Five field trips.

*Mount Echo Park:* Located in Price Hill off Elbron Avenue and directly overlooking the Ohio River, this park provides two splendid, contrasting views of the valley of the Ohio River. Stop at the first overlook and look upstream to see the wide central bottoms (Fig. 2) and the city center of Cincinnati at the mouth of misfit Mill Creek Valley, then go to the second overlook, look downstream, and see the narrows (Figs. 9, 11, 13) that were formed when Illinoian ice blocked Mill Creek Valley. Note also the beautiful stone wall built of local limestones as you enter the park and observe its many tempestite beds. From downtown, reach Elbron Avenue by following the Sixth Street Viaduct across misfit Mill Creek Valley.

*Trammel Fossil Park:* Follow Reading Road to Sharonville in northern Hamilton County, and after you pass under I-275 turn right on Hauck Road and then left onto Tramway Drive and follow it to the fossil park of some 7 acres. Here you will find a large, accessible outcrop complete with informational signs, and you can collect from all of the Miamitown Shale, the Bellevue, and part of the Fairview Formation. From the parking lot, look southwest and observe the wide-open abandoned valley of the Ohio River as it looped around western Hamilton County. Here, valley depth is much less than seen at Mount Echo Park, because the valley is largely filled with both Wisconsinan and Illinoian glacial deposits.

*Ky. 8 and 445:* If shale is your principal interest, this fine outcrop of Kope shale is a must to see. Access is easiest by taking Ky. 8 from Bellevue or by taking I-471 south across the Ohio River to U.S. 27 and following it north to Ky. 445; turn left and follow Ky. 445 to the outcrop. This section contains most of the members and submembers proposed by McLaughlin and others (in press) and illustrated in Figure 27. Notable are the graptolites low in the section. There is ample parking.

*I-275:* From the Ohio River follow I-275 west to Ky. 17 and see many fine roadcuts. Although you cannot stop and collect, driving back and forth will give you a good idea of the Fairview (about 60 percent limestone) in the upper parts of these cuts and the Kope (about 70 percent plus of blue-gray shale) in their lower parts. North and south of the junction of I-275 and Ky. 17 are many accessible cuts of the Kope Formation in the preglacial valley of Banklick Creek in Kenton County.

*Mason Road:* At the junction of Ky. 16 and I-275 turn north toward Cincinnati and *immediately* turn right onto Mason Road, where you can easily park and examine units from the uppermost Kope (base of section) into the Bellevue.

**Table 13.** Study of fossil concentrations (adapted from Kidwell, 1991; Kidwell and Holland, 1991). Reprinted with the permission of the Society for Sedimentary Geology.

| | |
|---|---|
| *Diversity* | One or many types present? Provides some measure of degree to which organisms can exploit a habitat. |
| *Packing* | Matrix or bioclastic (framework) support? Matrix support implies "dumping," whereas little or no matrix implies well-washed conditions. |
| *External geometry* | Stringers, pavements, pods, clumps, lenses, wedges, or uniform beds? External shape of deposit depends on many factors—paleohydraulics, microtopography of sea bottom, and also ecology of organisms—and is an important aspect of field study. |
| *Internal structure of fossil-bearing bed* | Graded (tempestite), nonstratified, laminated, random or oriented fossils or clasts, or bioturbated? Paleohydraulics and bed history. |

is always a good idea. Use of a practical classification of limestones is also helpful (Table 14). See Tucker (2000) for many insights into field work.

Nature centers in the area, nearby State and county parks, the Cincinnati Natural History Museum, local university geology departments, and the geological surveys of the three states have information about geology and personnel to explain it.

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**Table 14.** Practical classification of limestones (adapted from Embry and Klovan, 1971, Fig. 2). Reprinted with the permission of the Canadian Society of Petroleum Geologists.

| Detrital limestones (original components not organically bound during deposition) | | | | | | In situ limestones (original components organically bound during deposition) | | |
|---|---|---|---|---|---|---|---|---|
| Less than 10% of components > 2 mm | | | | More than 10% of components > 2 mm | | Organisms acted as baffles | Organisms encrusted and cemented particles | Organisms built rigid frameworks |
| Contains lime mud (< 0.3 mm) | | | No lime mud | | | | | |
| Mud supported | | Grain supported | | Matrix supported | > 2 mm component-supported | | | |
| Less than 10% grains (> 0.03 mm < 2 mm) | More than 10% grains | | | | | | | |
| Micstone | Wackestone | Packstone | Grainstone | Floatstone | Rudstone | Bafflestone | Bindstone | Framestone |

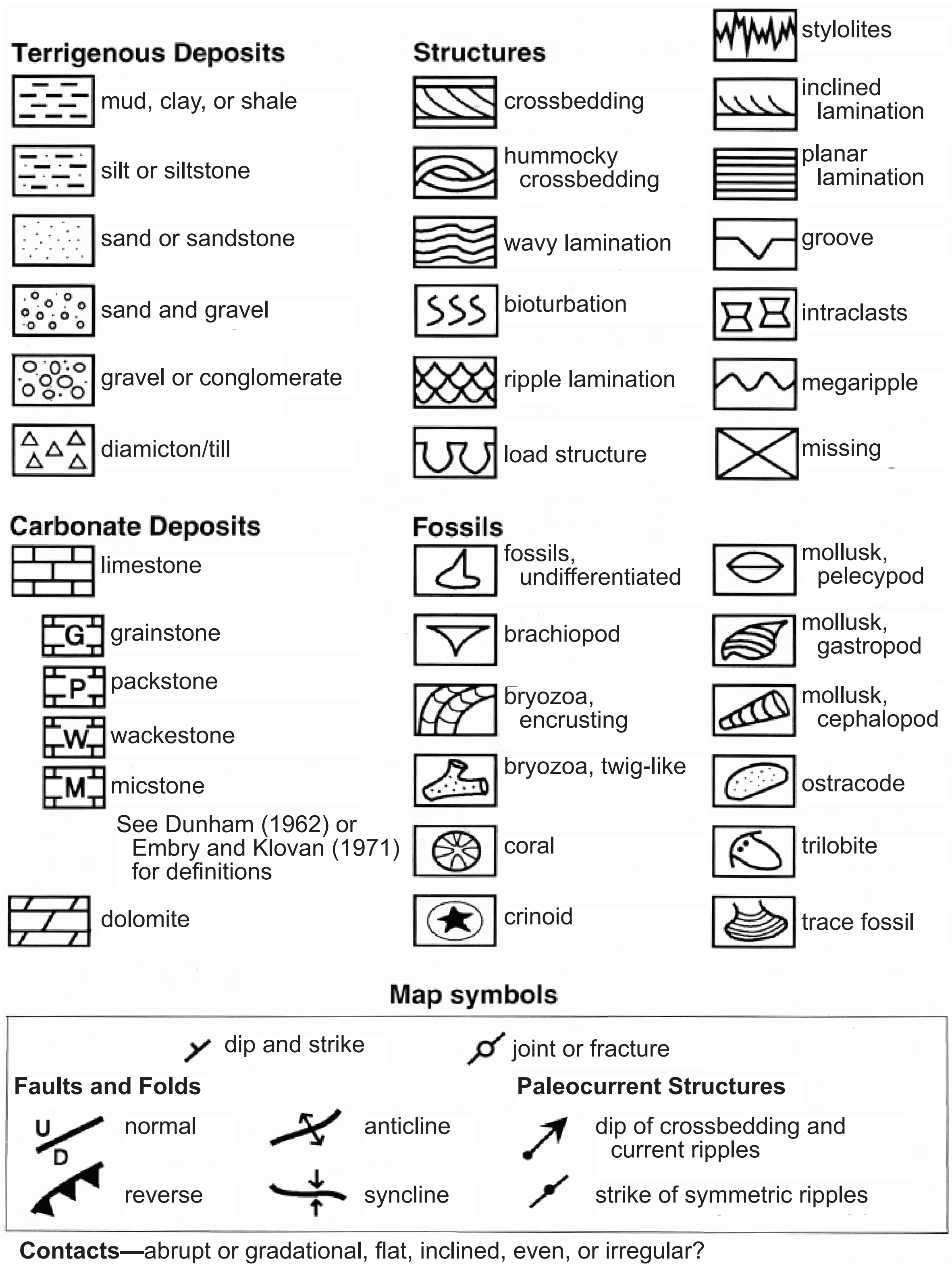


Figure 87. Symbols for bedrock description.

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### *Digging Deeper*

Camp, M.J., 2006, Roadside geology of Ohio: Missoula, Mont., Mountain Press Publishing, 410 p.

Easy-to-read, well-illustrated, handy volume gives the big picture of Ohio. See especially "Western Ohio—The Till Plains," "The Teays Drainage," and "The Ohio Valley." Also see the companion volume for Indiana.

Camp, M.J., and Richardson, G.T., 1999, Roadside geology of Indiana: Missoula, Mont., Mountain Press Publishing, 315 p.

This informative, easily accessible volume has a special section on southeastern Indiana (p. 17–72) that provides a good introduction to the geology of Dearborn, Ohio, and Switzerland Counties.

Tucker, M.E., 2000, Sedimentary rocks in the field [3d ed.]: New York, John Wiley, 234 p.

Eight to-the-point, well-illustrated chapters start with tools and end with big ideas that go beyond outcrops. It contains many helpful tables plus a short section on GPS.

# Sources of Information

Counties, states, independent agencies, and the federal government all have organizations that can help with the geology, water resources, and surface environment of the Greater Cincinnati region. Commonly, a good place to start is with the county or regional planning commission. Most are listed below.

## Counties and Cities

Each county has an engineer, county commissioners, and offices of the Natural Resources Conservation Service and a soil and water conservation district to offer technical assistance on soils, erosion, drainage, and landslides. Each county has a soil survey available at no cost from the local soil and water conservation district. All are most helpful and can direct you to engineering, soil, and geological information. Many cities of the Tri-State also have a Division of Engineering or City Engineer, prime sources of information for surficial deposits and depth to rock. For the city of Cincinnati, contact Division of Engineering, (513) 352-3427, where there are engineers and a geologist.

## Kentucky

Kentucky Environmental Quality Commission, 14 Reilly Rd., Frankfort, KY 40601-1132, (502) 564-2150, ext. 194, www.eqc.ky.gov.

This commission has information about and produces documents on the condition of Kentucky's environment.

Kentucky Geological Survey, 228 Mining and Mineral Resources Building, University of Kentucky, Lexington, KY 40506-0107, (859) 257-5500, www.uky.edu/kgs.

This is your source for all kinds of geologic and topographic maps, guidebooks, and publications for all of Kentucky. If you are planning a geologic trip to northern Kentucky, call the Survey, or better yet, visit them on the campus of the University of Kentucky. All subsurface records are online.

Kentucky Transportation Cabinet, Department of Highways, Division of Materials, Wilkinson Dr., Frankfort, KY 40622, (502) 564-3160, transportation.ky.gov/materials.

A wide variety of geologic support activities are carried out by this group: geotechnical studies, analysis of aggregates, design of rock cuts, and foundation design for bridges. Consider also their District 6 Headquarters at Buttermilk Pike and I-75, Crescent Springs, KY 41017, (859) 341-2700.

Department for Environmental Protection, 14 Reilly Rd., Frankfort, KY 40601, (502) 564-2225, www.dep.ky.gov.

This department deals with waste storage and water supplies, and is attended to by the Division of Water—(502) 564-3410.

Northern Kentucky University, Division of Geology, Highland Heights, KY 41076, (859) 572-5309, www.nku.edu.

This undergraduate department is a resource for northern Kentucky.

## Indiana

Department of Environmental Management, 100 N. Senate Ave., Indianapolis, IN 46204, (317) 232-8603, www.in.gov/idem.

This is an information source for environmental regulations, problems, and solutions.

Department of Transportation, Room 1105, State Office Building, 100 North Seventh Ave., Indianapolis, IN 46204, www.in.gov/dot.

Ask for the Public Information Office. The Southeastern Indiana District is located at Box 5450, Seymour, IN 47274, (812) 522-5649.

Department of Natural Resources, Division of Water, 2475 Directors Row, Indianapolis, IN 46241, (317) 232-4165, www.in.gov/dnr/water.

The primary responsibility of the division is the planning, regulation, and managing of groundwater and surface water in Indiana.

Indiana Geological Survey, Indiana University, 611 North Walnut Grove Ave., Bloomington, IN 47405, (812) 855-5067, igs.indiana.edu.

A research institute of Indiana University, it is the best single source of geologic information and topographic and geologic maps plus many publications on the geology of Indiana. Start here, if you are new to Indiana.

Indiana State Museum, 650 West Washington St., Indianapolis, IN 46204, (317) 232-1637, www.in.gov/ism.

Indiana's pioneer and later history, including development of its present landscape, is on display here.

## Ohio

Cincinnati Museum of Natural History and Science, 1301 Western Ave., Cincinnati, OH 45203, (513) 287-7000, www.cincymuseum.org/explore_our_sites/natural_history.

Just a short distance from the business district, the new home of the museum in the former Union Station is an excellent place to take a class or visit. Purchase "The Natural History of Cincinnati and Vicinity" and other geology-related literature. The museum has plenty of parking.

Cincinnati Nature Center, 4949 Tealtown Rd., Cincinnati, OH 45150, (513) 831-1711, www.cincynature.org.

Consult with their naturalists before planning a group trip. Hamilton County has an active natural history program.

College of Mount St. Joseph, 5701 Delhi Rd., Cincinnati, OH 45051, (513) 244-4200, www.msj.edu/academics/departments/chemphyssci.

There are several geologists in the Chemistry Department.

Department of Transportation, Central Office, 1980 W. Broad St., Columbus, OH 43223, (614) 466-7170, www.dot.state.oh.us.

Call the public information officer at the above number to find how you can be helped. District 8 includes the Tri-State area and is located on Ohio 741 west of Lebanon, OH 45036, (513) 932-3030.

Hillside Trust, French Park, 710 Tusculum Ave., Cincinnati, OH 45226, (513) 321-3886, www.hillsidetrust.org.

The trust is a rich source of information on hillsides, of which there are many on both sides of the river.

Miami Conservancy District, 38 East Monument Ave., Dayton, OH 45402, (937) 223-1271, www.miamiconservancy.org.

The district's primary objective is flooding on the Great Miami River. It was formed in response to the 1913 flood on the Miami River.

Cincinnati Preservation Association, 217 West Ninth St., Cincinnati, OH 45202, (513) 721-4506, www.cincinnatipreservation.org.

Contact this association if you encounter evidence of human artifacts in shallow digging on floodplains or elsewhere.

Miami Valley Regional Planning Commission, 1 Danton Center/South Main St., Ste. 260, Dayton, OH 45402, (937) 223-6323, www.mvrpc.org.

The commission compiles and provides data on demographics, land use, and summaries of natural resources, especially groundwater and land use. It covers the counties of the Greater Dayton area.

Miami University, Department of Geology, Oxford, OH 45056, (513) 529-3216, www.miami.muohio.edu/academics/majorsminors/majors/geology.cfm.

A fine faculty and good geological library provide important geologic resources.

Ohio Division of Geological Survey, 2045 Morse Rd., Fountain Square, Building C1, Columbus, OH 43229-6693, (614) 265-6576, www.dnr.state.oh.us/geosurvey.

Start here to study field or subsurface geology in southwestern Ohio. Begin with a trip to Columbus to the Survey to see what is available and talk with some of their helpful staff.

Ohio Division of Water, Fountain Square, Buildings B1 and B2, Columbus, OH 43229, (614) 265-6717, www.dnr.state.oh.us/water.

The mission of the Division of Water is to define the groundwater resources of each county. Hence, they have many water-well logs and reports, all online. It is an important resource. See also the U.S. Geological Survey's Water Resources Division in Columbus.

Ohio Department of Natural Resources, Division of Soil and Water Conservation, 2045 Morse Rd., Fountain Square, Building B3, (614) 265-6610, www.dnr.state.oh.us/soilandwater.

The division collaborates with personnel of the federal Natural Resources Conservation Service.

Ohio Environmental Protection Agency, 50 W. Town St., Ste. 700, Columbus, OH 44315, (614) 644-3020, www.epa.state.oh.us.

A regulatory agency that touches on many of the practical applications of geology, its regional office is in Dayton ((937) 285-6357).

Ohio, Kentucky, Indiana Regional Council of Governments, 720 E. Pete Rose Way, Cincinnati, OH 45202, (513) 621-6300, www.oki.org.

This is a good place to start your investigation, because their interests are broad, ranging from water quality to parks to industrial development. Aerial photographs and many other maps of the 11 counties of the Tri-State area can be seen here. It is excellent for help and information.

Ohio River Valley Water Sanitation Commission, 181 Renslar Ave., California, OH 45228, (513) 231-7719, www.orsanco.org.

Clean, safe drinking water and a healthy environment for the Ohio River is the goal of ORSANCO.

Hamilton County Planning and Zoning, 138 Court St., Cincinnati, OH 45202, www.hamilton-co.org/hcrpc.

This is a key group for information about the city of Cincinnati.

University of Cincinnati, Departments of Geology, Geography, and Civil and Environmental Engineering, Cincinnati, OH 45221, (513) 556-3732, 556-3421, 556-3648, respectively; www.uc.edu.

All three departments have information about geology, water resources, and geographic background of the Cincinnati region and do some work on local problems. The Geology/Mathematics/Physics Library and the Engineering Library contain much useful material.

## U.S. Government

U.S. Army Corps of Engineers, Great Lakes and Ohio River Division, Ohio River, P.O. Box 1159, 550 Main St., Cincinnati, OH 45202, (513) 684-3010, www.lrd.usace.army.mil.

This is a source for river and floodplain studies plus evaluation of geologic materials for engineering and construction utilization. They have an excellent technical library of geotechnical publications, foundation design, and evaluation of design criteria. The mission of the Corps of Engineers is flood protection and maintenance of navigation on the Ohio River.

U.S. Department of Agriculture, Natural Resources Conservation Service, www.nrcs.usda.gov.

Each county has a conservation officer and staff and much helpful literature.

U.S. Environmental Protection Agency, 26 West Martin Luther King Dr., Cincinnati, OH 45219, (513) 569-7931, www.epa.gov.

A regional center, this subunit includes both a research facility at Center Hill in Cincinnati and diverse administrative functions.

U.S. Geological Survey

The USGS has an office in each state: Ohio Water Science Center, 6480 Doubletree Ave., Columbus, OH 43229, (614) 430-7700; Indiana Water Science Center, 5957 Lakeside Rd., Indianapolis, IN 46278, (317) 290-3333; Kentucky Water Science Center, 9818 Bluegrass Pkwy., Louisville, KY, 40299-1906, (502) 493-1930; www.usgs.gov. All requests for maps and publications should be addressed to Western Distribution Branch, Box 25286, Denver Federal Center, Denver, CO 80225, (303) 236-7477.

Stream gaging and river water quality are the principal activities, but they also work on groundwater supplies and pollution, as well as special problems such as karst, the southern shores of Lake Michigan, etc.

## Local Geotechnical and Environmental Firms

There are a number of well-established, well-qualified geotechnical firms and consultants in the northern Kentucky/Cincinnati region, whose addresses can be found in the telephone book.

# Glossary

Every subject has its terminology, and the fascinating geology of the Cincinnati region is no exception. Fortunately, the most commonly used terms needed for understanding the geology of the Greater Cincinnati area are neither excessive nor complex. See also "Glossary of Geology," by Jackson and others (2005), for many more terms.

**Accelerated erosion**—Erosion several orders of magnitude greater than natural or geologic erosion; in the Tri-State area it is nearly always the result of human activity (e.g., heavy rain on a newly plowed field or construction site).

**Aggrading stream**—A stream or river that is depositing more sediment than it carries away.

**Alluvium**—General, broad term for the deposits of a stream or river. Such deposits range from large, overlapping slabs of the local bedrock to gravel to fine silts and muds, and may also incorporate wood and organic debris. Understanding alluvium is fundamental to understanding rivers, agriculture, groundwater, and sand and gravel.

**Aquiclude**—Sedimentary deposit such as shale or till that has low permeability and therefore retards flow. It is important for waste disposal of all kinds because an aquiclude retards dispersion from the site.

**Aquifer**—Sedimentary deposit that has good permeability and therefore transmits fluids effectively. In the Cincinnati region the best aquifers are the coarse gravels and sands of the glacial valley trains and outwash that partially fill old valleys.

**Barbed tributary**—A tributary that joins the main stream at an acute angle pointing upstream and indicates reversal of flow of the main stream. Two local examples are Pleasant Run Creek in Kenton County, Ky., and West Fork of Mill Creek in Hamilton County, Ohio.

**Basement**—Refers to the old Precambrian rocks, mostly granites and metamorphic rocks, but includes the newly discovered red metasandstone called the Middle Run Formation that locally underlies Paleozoic sedimentary rocks. Basement in the Cincinnati region is about 3,300 to 4,100 feet below the surface. Basement is always harder, denser, and older than the sedimentary rocks above it.

**Bed**—Name for a distinct layer of sedimentary rock or unconsolidated sediment that differs from its neighbors in one or more of the following ways: thickness, composition, continuity, texture, or homogeneity. It is the fundamental unit for geology, geologic engineering, and hydrology. In the Tri-State area, streams contain many loose slabs of Ordovician limestone, each of which represents a bed or stratum, even though it is now detached from the bedrock.

**Bedding plane**—Top or bottom of a bed; a former surface of sedimentation. It is important to engineers because sedimentary rocks will fall more readily parallel to a bedding plane than perpendicular to it. It also may influence local fluid flow. Fossil collecting is generally best on bedding planes.

**Bedrock**—A general term for the first consolidated, hard, coherent material underlying soils, alluvium, or other loose, unconsolidated deposits. In the Cincinnati area, bedrock consists entirely of interbedded limestone and shale of Ordovician age.

**Bentonite**—Altered volcanic ash; also called K-bentonite, because of its high potassium content. Bentonites on a craton indicate volcanism along its margins.

**Best management practice**—Lessening the impact of construction on the natural environment (and later, lessening ongoing maintenance too).

**Bioturbation**—The disruption of bedding and lamination by animals that bored through, rested on, or ate soft sediment. Bioturbation is readily seen in the local limestones.

**Body fossil**—A fossil formed by the shell, skeleton, or other hard body parts of an organism. Body fossils are very abundant in local Ordovician outcrops.

**Boulder**—A large rock whose diameter exceeds 10 inches. In the Cincinnati area, many exotic boulders have been introduced by ancient ice sheets and are commonly seen along driveways.

**Brachiopod**—A solitary, bivalved marine invertebrate with a calcareous skeleton. They range from the Early Cambrian to the present (phylum Brachiopoda). Many types are present in the limestones of the Cincinnati region. See Davis (1992, p. 23–24) for details.

**Braided stream**—A shallow stream with a shifting bed, many ephemeral islands, and a bed load of mostly gravel and sand. Most of the local glacial outwash of the Cincinnati region was deposited by now-vanished braided streams derived from melting glaciers.

**Bryozoa**—Marine invertebrate, usually with calcareous skeleton, that has occurred in colonies from the Early Cambrian to the present (phylum Bryozoa). They are abundant in local limestones. See Davis (1992, p. 23) for details.

**Buried valley**—A valley either partially or wholly filled by later alluvium or glacial deposits. In the

Cincinnati region, buried valleys are restricted to areas of glaciation.

**Cambrian Period**—The oldest period of the Phanerozoic Era, extending from 570 to 500 million years ago. Cambrian rocks occur in the deeper subsurface of the Cincinnati region, where they overlie Precambrian basement. Cambrian rocks are known only from wells. A Cambrian sandstone, the Mount Simon, is important for liquid waste disposal.

**Cephalopod**—A marine organism with a calcareous shell, which may be straight, curved, or coiled (phylum Cephalopoda). Hollow, straight cones with internal chambers are common in the local Ordovician limestones. This group ranges from the Cambrian to the present, and occurs in local limestones. See Davis (1992, p. 25–26) for details.

**Channel**—A low elongate area that conveys water; may be natural and have movable boundaries or may be man-made. Ancient buried channels are common.

**Clast**—A detrital particle, usually taken to be a pebble or larger.

**Clay**—Material finer than 1/256 millimeter, which consists mostly of clay minerals and fine silt. Its lithified equivalent is called shale. Plastic when wet.

**Clay minerals**—A broad family of platy, fine-grained, siliceous minerals of diverse chemistry and crystal structure, which together give them different physical properties. Illite and lesser quantities of kaolinite and chlorite predominate locally.

**Col**—A low divide between two watersheds.

**Colluvium**—Slope material on a hillside. Such material is loose, poorly sorted, and heterogeneous, and is composed of locally derived debris that moves downhill, propelled by gravity. Recognizing it on hillsides is important, because it is unstable. In the Cincinnati/northern Kentucky region, the lower slopes of the Kope are commonly thickly mantled with colluvium.

**Conodont**—A small, phosphatic, toothlike fossil element produced by small marine animals of uncertain origin. They range from the Cambrian to the Late Triassic, are abundant and widespread, and therefore are useful biostratigraphic markers.

**Craton**—The stable, passive core of a continent, commonly Precambrian in age and in part covered by Paleozoic or younger rocks. Cincinnati's interior location on the North American craton is a major factor in its geology.

**Creep**—The slow downhill movement of the colluvium and soil on a hillside. Creep is too slow to observe directly, but its effects are easy to see: tilted fence posts and telephone poles, stone walls leaning downhill, etc. It is a form of mass wasting.

**Crinoid**—A marine echinoderm (class Crinoidea) that is fairly common in local limestones and ranges from the Ordovician to the present. Calcareous segments of the stalk are the easiest part to recognize. See Davis (1992, p. 29) for details.

**Cross section**—A vertical representation slicing across either the topography or the bedrock of a region. It is commonly used by geologists, engineers, and planners to show spatial relations graphically.

**Cross stratification**—An inclined arrangement of layering. If the unit is thicker than 10 centimeters, it is called crossbedding, and if it is less than 10 centimeters, it is called cross lamination. Cross stratification is used to infer conditions of paleoflow and its direction. It is present in the limestones of the Cincinnati region and very abundant in its glacial outwash. See also **Hummocky stratification.**

**Debris flow**—A type of generally rapid, downslope mass movement consisting of loose, unconsolidated debris; includes mud flows and earth flows. It may have a basal scour surface.

**Deep Stage**—Used to describe the pre-Illinoian entrenchment of the major streams and valleys of the Cincinnati region, including the Whitewater River, the Great Miami River, Mill Creek, and the Norwood Trough.

**Depositional system**—A group of sedimentary deposits closely associated in space and linked one to the other in origin. A local example is provided by the channel, levee, and overbank deposits of the Tri-State region. See also **Land system.**

**Detrital**—Used to describe a particle transported by water, air, or ice.

**Diamicton**—An unlithified, poorly sorted, pebbly, or clast-rich muddy sediment. Common origins for such deposits in the Cincinnati/northern Kentucky region are glacial till or a debris flow.

**Downcutting**—Channel deepening commonly the result of increased flow or steeper stream gradients. Applies equally to a large river (Ohio and its Deep Stage) or a small gulley. Produces deposition downstream.

**Drift**—Broad, older name used for deposits of glacial origin such as till, lake clays, silt, sand, gravel, and windblown loess.

**Drawdown**—How fast the water level in a well (top of water table) falls as it is pumped. A measure of the size or capacity of the aquifer.

**Eluviation—**Movement of fine material into another solid, such as fine clays into the B horizon of a soil.

**Epibole—**Unusual concentration of a fossil group that is usually rare.

**Erratic—**Cobble or boulder of nonlocal composition transported into a region. In the Cincinnati region, glacial ice introduced many large crystalline rocks derived from Canada.

**Floodplain—**The part of a valley adjacent to a stream and flooded by it. Alluvium underlies the floodplain. Abandoned floodplains form terrace surfaces.

**Formation—**A mappable geologic unit that is distinct lithologically from its neighbors and has a definite stratigraphic position. It is the fundamental unit of stratigraphy and geologic history. Local examples are the Bull Fork Formation, Fairview Formation, and Kope Formation. See also **Member.**

**Fracture—**A break in a rock. Fractures may be widely or closely spaced, may be open or closed, and nearly always form a system, although a few have random orientation. Fractures include cracks and joints, and are vital for the flow of fluids through a rock.

**Fragipan—**Soil layer low in permeability and organic material, and moderately high in clay. Dense and usually hard, it impedes root growth and water flow. Occurs below the A horizon.

**Gastropod—**A mollusk (class Gastropoda) with a single calcareous shell, which may be spiraled. Local gastropods in the Ordovician lack chambers. They range from the Early Cambrian to the present. See Davis (1992, p. 26) for details.

**Geologic system—**Refers to rocks deposited during a major subdivision of geologic time. Rocks of the Cambrian and Ordovician Systems underlie the Cincinnati region.

**Geotechnical—**Refers to combined engineering/geologic study of rocks and soils for construction.

**Glauconite—**A greenish, fine-grained mineral that may occur as distinct pellets or be disseminated. It is abundant only in the deeply buried Eau Claire Formation in the Cincinnati region.

**Graded bed—**An individual bed that has an internal, vertical gradation of grain size from coarse at its base to fine near its top. It is fairly common in local limestones.

**Grainstone—**Well-washed, fossil-bearing limestone. See Table 14.

**Graptolite—**A marine colonial animal whose colony forms a rhabdosome, which is small and dark and has a linear, serrated shape in local Ordovician shales (phylum Hemichordata). It is a good indicator of paleocurrents. See Davis (1992, p. 30) for details.

**Groundwater—**Water that fills the open spaces in rock or sediment. Where such water permanently saturates a rock or sediment, it is called *phreatic,* but where saturation is partial, the term *vadose* is used.

**Gutter cast—**A conspicuous, sediment-filled, linear groove at the base of a bed.

**Hardground—**A knobby, irregular surface with bioturbation and perhaps pyrite that formed on the sea bottom during slow sedimentation. It is fairly common in the local Ordovician limestones.

**Hard water—**Ground or river water containing sufficient magnesium and calcium to produce a carbonate scale when boiled or prevent sudsing of soap.

**Hummocky stratification—**A type of stratification characteristic of tempestites (rocks formed during a storm whose waves touched the sea bottom); common in the local Ordovician limestones.

**Hydraulic conductivity—**A parameter that quantitatively specifies the water-transmitting characteristics of sediment or rock. Materials with high hydraulic conductivities are called permeable and those with low conductivity are called impermeable.

**Hydrogeology—**The branch of geology that deals with the distribution, properties, and management of groundwater. The term *geohydrology* is broadly equivalent.

**Hydrograph—**A frequency graph showing the volume of flow of a stream plotted against time. Good hydrographs are constructed by careful record-keeping over many years and are a vital part of floodplain management.

**Hydrologic unit—**A rock unit, generally a sediment or sedimentary rock, that behaves as a single hydrologic entity. This is an important concept for groundwater development and resources.

**Ice-margin stream—**One located at the side or in front of an ice lobe. The Ohio River is a classic example of an ice-margin stream.

**Imbrication—**The preferred orientation of disk-like clasts; in a stream deposit such clasts dip upstream. It is very common in the coarse debris carried by the streams of the present Cincinnati region and also apparent in most of the glacial outwash of the area.

**Infiltration—**Seepage of surface water into the soil or deeper into the water table. Desirable for rainwater (cuts peak flow during and after a storm), but not for, say, gasoline or cleaning fluid.

**Internal mold—**Preserved infill of a shell now dissolved.

**Joint—**See **Fracture.**

**Kame—**A low mound or hill, generally isolated, composed mostly of glacial sand and gravel.

**K-bentonite—**An altered volcanic ash, rich in potassium. Two local examples are the Millbrig and Diekie.

**Karst—**Complex solution networks in limestones: surface sinkholes, caves, and solution channels. Karst features are not common in the Cincinnati region.

**Lacustrine deposits—**Mostly clay and silt but possibly some sand deposited in a lake. They are common in many of the preglacial valleys in the Cincinnati region, and are very landslide prone.

**Lamination—**The smallest unit of stratification; it never exceeds 1 centimeter, and commonly is only a few millimeters thick. It may be parallel or inclined to under- and overlying beds. Also cross lamination.

**Land system—**A collection of landforms of similar origin that characterize a region. Understanding the origin of the type of landform is a useful guide to predicting what underlies it.

**Landfarm—**A surface waste-disposal site used for treatment of biological waste; an open field where biological waste is oxidized by air, bacteria, or both.

**Landform—**A specific, distinctive element of the landscape. In the Cincinnati/northern Kentucky/southeastern Indiana region, terraces, kames, landslide scarps or scars, abandoned stream meanders, and natural levees are all examples of landform elements. See also **Land system.**

**Landslide—**General term for the rapid downslope movement of a mass of rock or soil. Landslides may be rotational or translational, active or inactive. Most landslides in the Greater Cincinnati area occur in unconsolidated material.

**Lateral accretion deposit—**Any deposit formed on the inside of a stream bend; such deposits become younger toward the stream channel.

**Leaching—**Removal of calcium carbonate and other soluble components from a soil or rock. One of the most important weathering processes.

**Limestone—**A sedimentary rock consisting of more than 50 percent calcium carbonate. Many subtypes are recognized (e.g., fossiliferous limestone, brachiopod limestone, argillaceous limestone, high-calcium limestone, etc.), as well as scientific names (see Table 14). The limestones of the Cincinnati region are world famous for their fossils.

**Lithification—**The process, consisting mostly of cementation and compaction, that converts unconsolidated sediment into an indurated and consolidated rock.

**Liquefaction—**The sudden transformation of loose, but coherent sediment into a weak, quasi-fluid mixture of sediment and water.

**Loess—**Fine windblown silt and clay derived from braided outwash valley trains in front of glacial ice. In the Cincinnati region there are thin, widespread deposits of late Wisconsinan loess on the uplands, especially near major glacial sluiceways such as the Great Miami River Valley.

**Mass movement—**The slow or sudden downslope movement of a large mass of rock, colluvium, or soil, chiefly under the influence of gravity. Mass movements are of several types and are common on the slopes of the Cincinnati/northern Kentucky region, especially in colluvium derived from the Kope Formation. See also **Rockfall** and **Landslide.**

**Member—**A body of rock of less importance than a formation, but sufficient to deserve recognition and a geographic name; alternatively, a subdivision of a formation.

**Micstone—**A fine-grained limestone. See Table 14.

**Milankovitch cycles—**Name given to variations in solar energy intercepted by the earth, with average periods of about 20,000, 40,000, 100,000, and 400,000 years. Such astronomical cycles are linked to sedimentary deposits through variations in the earth's climate, which directly affects rainfall and temperature, and thus sedimentation rates and types of sedimentary deposits. Global variations in temperature and climate also are important factors in the growth and melting of glaciers.

**Misfit valley—**A valley such as Mill Creek, whose present stream is much smaller than its valley. It indicates diminution of stream flow.

**Moraine—**A deposit of unsorted glacial material (diamictons, gravel, sand, and silt) deposited in front of, at the side of, or beneath a glacier. In the Cincinnati/northern Kentucky/southeastern Indiana region, moraines of Wisconsinan age are fairly easy to recognize as low, elongate, rolling hills and slopes not cut by streams. Good examples of moraines can be seen in Butler and Warren Counties and northern Hamilton County.

**Mudstone—**A fine-grained, argillaceous rock lacking lamination. If it is fine-grained and calcareous, the term *micstone* is used. See Table 14.

**Mudflow—**See **Mass movement.**

**Openwork gravel—**Gravel lacking interstitial sand or silt. It is seen in local gravel pits.

**Ordovician Period—**Second oldest period of the Phanerozoic Era. Bedrock of the Cincinnati region is mostly Ordovician in age and was deposited in an ancient sea 440 to 500 million years ago.

**Outwash—**Clay, silt, sand, and gravel transported downstream in a valley train beyond the ice by the meltwater of a glacier. It is an important local resource for sand and gravel, groundwater, and agriculture. Notable examples are in Butler, Clermont, Hamilton, and Dearborn Counties.

**Overburden—**Unconsolidated material found above bedrock. Maps of the thickness of overburden are useful for groundwater and engineering geology.

**Packstone—**A limestone with abundant fossil debris and some interstitial carbonate mud. See Table 14.

**Paleoecology—**The study of ancient organisms and their relations to one another and to their environment. The richly fossiliferous limestones of the Tri-State region provide many opportunities for paleoecologic study of the Cincinnatian Series.

**Paleosoil—**A soil buried by alluvium, loess, or even glacial till. It is commonly oxidized and may also be leached and zoned. The most prominent paleosoil of the Tri-State region is the Sangamon soil, formed after the Illinoian ice sheet withdrew.

**Paleozoic Era—**Spans the time from about 575 to about 250 million years ago and is represented locally by sedimentary rocks of the Cambrian and Ordovician Periods.

**Pelecypod—**A bottom-living mollusk (class Pelecypoda) with a calcareous bivalve shell in which each valve generally is the symmetrical mirror image of the other. It ranges from the Ordovician to the present. See Davis (1992, p. 27) for details.

**Percent slope—**The ratio of vertical decrease of elevation divided by horizontal distance times 100. Slope is the key factor for runoff and erosion. Same as grade.

**Permeability—**The ability of a porous rock or sediment to transmit fluid (i.e., how fast water can move through a rock). See also **Hydraulic conductivity.**

**pH—**Quantitative measure of hydrogen-ion concentration in a solution on a scale of 14; less than 7 is acidic, 7 is neutral, and more than 7 is alkaline.

**Pleistocene Epoch—**Interval of time from about 7,000 to 1.65 million years ago marked by glaciation, especially in the Northern Hemisphere. Glacial deposits are well developed in the Cincinnati region, because at least three ice sheets covered the region.

**Piping—**Field term for underground flow through irregular channels or a more systematic fracture system.

**Plume—**A term used to describe the downcurrent (downflow) train of particles or chemicals from a point (or single) source. The term is used in studies of air, surface-water, or groundwater problems.

**Point bar—**A deposit of gravel, sand, and silt, collectively called riverwash, that occurs on the inside curve of a stream.

**Point source—**Flow from a single pipe, chimney, or creek or river.

**Porosity—**The percentage of free space in a rock or sediment; the ratio of void space to all rock volume. Effective porosity is the percentage of the total porosity that transmits fluid.

**Precambrian—**A term for events and rocks deposited prior to the Cambrian Period of the Phanerozoic Era. The basement rocks in the Cincinnati region are late Precambrian in age.

**Recharge—**The downward movement of water from the ground surface by infiltration into an aquifer.

**Regolith—**Weathered bedrock; in situ material overlying bedrock.

**Ripple mark—**A sedimentary structure with an undulatory surface consisting of small ridges and swales formed by the transport of silt and sand by water or air. It is a primary structure formed by the interaction of a fluid and its boundary. It has many varieties, but especially notable are the large ones found on bedding planes of the Fairview Formation and upper part of the Kope Formation.

**Riverwash—**The sand, gravel, and small boulders carried by a modern stream.

**Rock—**A coherent, hard material composed of grains or crystals that does not weaken when saturated with water. Joint spacing and clay partings are key determinants of rock strength. See also **Soil.**

**Rockfall—**A catastrophic type of mass movement that is dominantly vertical rather than horizontal or subhorizontal. It is rare in the Cincinnati region. Detrital grains are between 1/16 and 2 millimeters in diameter; loose granular material is of sand size.

**Sediment pond—**A dam or catchment specifically designed to trap muddy stormwater (settling pond).

**Series—**A formal stratigraphic unit smaller than a geologic system and larger than a formation (for example, the Cincinnatian Series).

**Seismic image—**Also called a seismic cross section, constructed from seismic profiles. A seismic image provides an image in time of the underlying rocks, stratified or not. Seismic images are essential to understanding the deeply buried geology of the Cincinnati region because so few deep wells are available.

**Shale—**A fine-grained sedimentary rock consisting mostly of clay and some silt. It may or may not be calcareous, but is finely laminated; if not laminated, the term *mudstone* or *claystone* is used.

**Shear plane—**Plane of failure of a solid; the contact surface between two moving solids.

**Sheet wash—**The uniform erosion of a roughly planar surface such as a newly graded slope or field; roughly the same as slope wash.

**Shrink-swell index—**Relative change of volume with change in moisture. High values are unsuitable for construction.

**Silt—**Granular material between 1/16 and 1/256 millimeters in diameter. Loess is composed chiefly of silt.

**Silurian Period—**A period of the Phanerozoic Era between 440 and 400 million years ago; the third oldest period of the Phanerozoic Era. Some Silurian rocks crop out on the margins of the Cincinnati Arch.

**Sinkhole—**Circular to ovate solution-collapse depression formed in limestones. These are uncommon in the Tri-State area, where there are deposits of glacial till, although some are present where glacial drift is old and thin.

**Slackwater terrace—**Common name for a terrace formed in a tributary to an aggrading stream, which in the Cincinnati region was a braided, glacial, outwash stream. Silt, clay, and fine sand form almost all of the material underlying a slackwater terrace. Well developed along the lower reaches of the Licking River.

**Slickenside—**A smooth, shiny, inclined surface in soils, clays, colluvium, and shales that indicates movement.

**Slide—**Informal, general term for a landslide.

**Slope—**Controls runoff rate of rainfall. Same as grade. See **Percent slope.**

**Slope wash—**Clay, silt, sand, and even possibly small pebbles washed down a slope.

**Soil—**A three-dimensional layer at the earth's surface capable of supporting plants. It is formed by a combination of physical and chemical weathering. Soil types vary with parent material, slope, and time. See your U.S. Department of Agriculture county soil survey report for more information. As used by engineers, soil is any solid material that weakens when saturated by water. Soils are classified into orders (large groups) and series (smaller groups), and named after a location of best development (just as geologists name rock formations).

**Soil horizon—**A layer of soil parallel to the surface, with distinct characteristics: A–organic rich, B–infiltration of clay, and C–weathered parent material.

**Sole marks—**Broad term for all the marks, both physical and biological, preserved on the bottom surface of a bed. Sole marks are made by currents, animals, and compaction, and are of many different types. They are used by sedimentologists and paleoecologists to infer processes of sedimentation and paleoecology.

**Solum—**The A and B horizons of the soil profile, where the processes of soil formation are the most active. See the county U.S. Department of Agriculture soil surveys for details.

**Stratification—**Layering produced by deposition from air or water. Bedding is stratification thicker than 1 centimeter and lamination is stratification less than 1 centimeter thick. Stratification is the prime characteristic of most sedimentary rocks, and because it has much interpretive and practical significance, is given careful attention by geologists and engineers. See also **Bedding plane.**

**Stratigraphy—**The study of the age, layering, sequence, and continuity of any sedimentary accumulation, large or small. It is vital to both engineering geology and all geologic studies.

**Stratum—**Latin for a single layer; plural is strata.

**Stylolite—**An irregular solution surface subparallel to bedding, most common in carbonate rocks. Stylolites are not abundant in the local limestones, but are easily seen in some limestones brought to the region.

**Taphonomy—**The study of organisms after death; their preservation or destruction, mineralogical changes, disarticulation, etc. It is fundamental for understanding ancient fossiliferous limestones and dolomites.

**Tempestite—**An individual bed believed to be formed in a lake or ocean during a storm and identified by its characteristic internal sequence of sedimentary structures, especially hummocky bedding and upward vertical decrease in grain size.

**Terrace—**A long, generally narrow, flat area bordering a stream. The terrace may be bounded by one or two scarps or an upland. A terrace represents the former floodplain of a stream. The Tri-State area has many terraces in its valleys, and downtown Cincinnati and adjacent Newport and Covington are built on a terrace of glacial outwash.

**Tertiary Period—**Unit of time from about 65 million years to 1.6 million years ago. Some deposits associated with the preglacial drainage in Kentucky are of probable Tertiary age.

**Texture**—The size and sorting of sediment; alternatively, the proportions of clay (less than 4 microns), silt (4 to 62 microns), sand (62 to 2,000 microns), or coarser debris.

**Till**—Unsorted and unstratified material deposited by ice. In the Cincinnati region, till is commonly a hard, pebbly to boulder-rich, bluish-gray deposit when fresh. Its pebbles and larger clasts commonly are faceted, and may have striations. See also **Diamicton.**

**Tilth**—The physical condition (porosity and permeability) of a soil relative to a plant's needs.

**Toe of slope**—The base of a slope and a point of importance for both engineering and geology, because types of surficial deposits and processes change at the toe of the slope.

**Top-of-rock map**—A map showing the elevation above sea level of the buried bedrock. From such a map the thickness of the overburden can be calculated. Also called a bedrock-topography map.

**Trace fossil**—A structure (track, trail, burrow) formed by an organism living on the top of or within a bed during deposition or shortly thereafter. Very abundant in the bedrock outcrops of the Cincinnati region.

**Transmissivity**—The rate at which water is transmitted through a cross-sectional area in response to a unit hydraulic gradient.

**Trilobite**—A marine organism (phylum Arthropoda, class Trilobita) characteristic of lower Paleozoic rocks. Dark-colored trilobite fragments can commonly be seen on the surfaces of local limestone slabs. Entire specimens are less common and are highly prized. See Davis (1992, p. 28) for details.

**Type section**—A place where a distinctive geologic rock unit—a formation, member, or bed—is well exposed and shows its typical characteristics, including upper and lower contacts. The type section takes the name of a nearby town, creek, or distinctive topographic feature (e.g., the Fairview Formation is named after a neighborhood in Cincinnati).

**Unconformity**—A major break in the geologic record such as that between the Precambrian basement and the Cambrian System in the Cincinnati region or between the Ordovician rocks and the overburden; a buried erosion surface.

**Vadose zone**—The upper, fluctuating limits of the water table.

**Valley train**—The deposits of sand and gravel that were formed by the meltwater from former glaciers. Valley trains can be thought of as giant sluices in which cold, glacial meltwater effectively washed, rounded, and sorted debris transported by meltwater. The meltwater chiefly followed preexisting valleys. Valley trains are an important economic resource for the Tri-State.

**Wackestone**—See Table 14.

**Water table**—A surface in the bedrock or unconsolidated deposits below which there is groundwater. The surface elevation of the water table varies with the seasons and with pumping or natural recharge.

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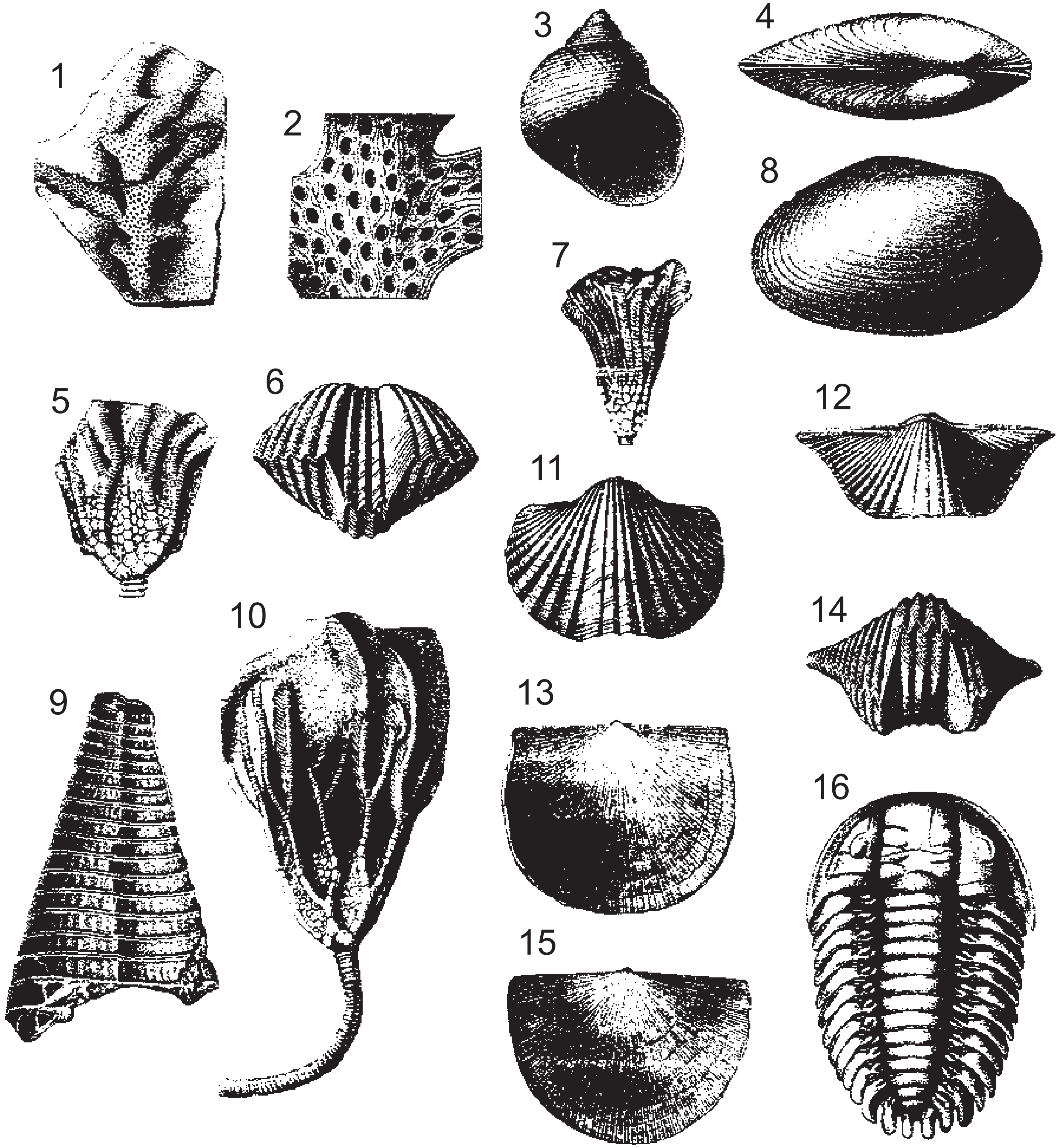
# On the Back Cover

The habitats of each of these fossils were quite different. The crinoids, although animals, were rooted to the bottom like plants and obtained food by filtering microorganisms from seawater (filter feeders). The brachiopods, pelecypods, and gastropods were also filter feeders and lived on the bottom, but had some limited mobility. In contrast, the cephalopods were free-swimming. The trilobites were also free-swimming, and obtained most of their food by scavenging muddy bottoms. The richly fossiliferous outcrops of the Cincinnatian Series in the Greater Cincinnati region offer amateurs and professionals alike many opportunities to explore the relations between fossil communities and their habitats (paleoecology) and to study evolution.

## Key to Fossils Illustrated on Back Cover

| | |
|---|---|
| 1, 2. | Branching bryozoan colony, *Graptodictya shafferi*. Drawing 2 provides details of drawing 1: Dark areas represent former living chambers of the individual colonial animals of the bryozoan colony |
| 3. | Spiraled gastropod, *Cyclonema bilix* |
| 4, 8. | Pelecypod with hinge, *Cuneamya neglecta* |
| 5. | Crinoid calyx (echinoderm), *Pycnocrinus dyeri* |
| 6, 11. | Two valves of brachiopod, *Platystrophia ponderosa* |
| 7. | Crinoid calyx (echinoderm), *Ptychocrinus parvus* |
| 9. | Small fragment of straight nautiloid cephalopod |
| 10. | Crinoid calyx and part of once-flexible stem, *Gaurocrinus nealli* |
| 12, 14. | Brachiopod with profile of hinge line and two valves, *Platystrophia acutilirata* |
| 13, 15. | Two views of same brachiopod and profile of its hinge line, *Strophomena filitexta* |
| 16. | Top view of trilobite, *Ceraurinus icarus* |

Drawings from various plates from F.B. Meek, 1873, Descriptions of invertebrate fossils of the Silurian and Devonian Systems: Ohio Division of Geological Survey, v. 1, pt. 2, p. 291–343 (modern names courtesy of David L. Meyer, University of Cincinnati). Also see the always-instructive Web site of the very active local fossil club, the Dry Dredgers, at drydredger.org, about fossils in the Greater Cincinnati region, as well as the Web site of Professor Stephen Holland of the University of Georgia, at www.uga.edu/strata/cincy (click on fossils for an ongoing compilation of named Ordovician fossils of the Cincinnati Arch region).




# Examples of World-Famous Upper Ordovician Fossils of the Cincinnati/ Northern Kentucky Region

See last page of booklet for identification of fossils.

Potter—Exploring the Geology of the Cincinnati/Northern Kentucky Region (second revised edition)—Kentucky Geological Survey, ser. XII, 2007, Special Publication 8