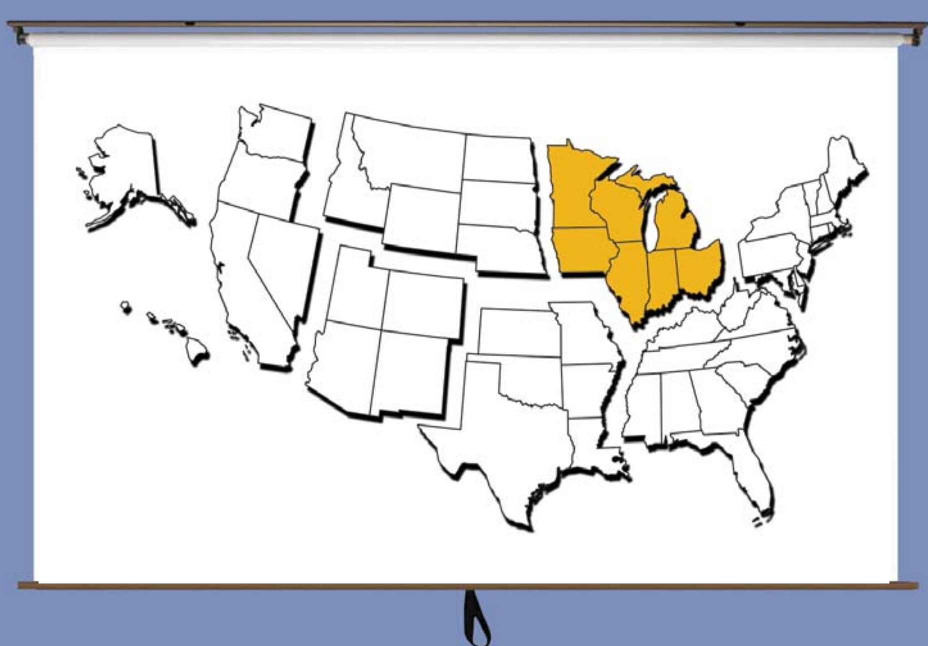
The *Teacher-Friendly* Guide™

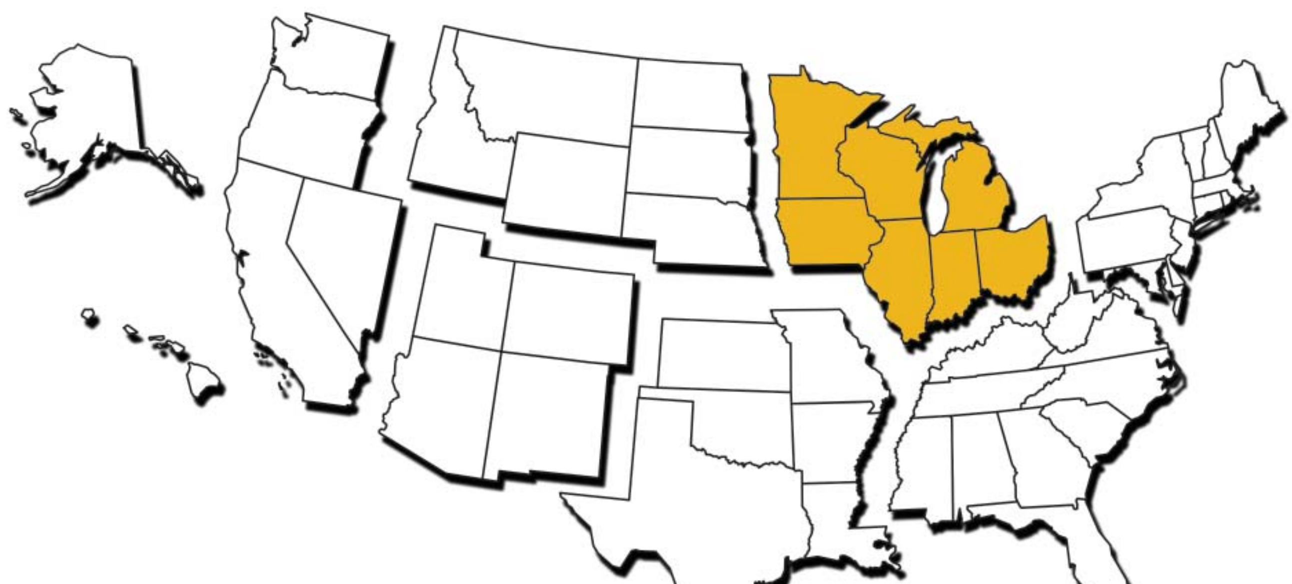
to the Earth Science of the Midwestern US



Edited by Mark D. Lucas, Robert M. Ross, & Andrielle N. Swaby

The **Teacher-Friendly** Guide™

to the Earth Science of the Midwestern US



Edited by Mark D. Lucas, Robert M. Ross, & Andrielle N. Swaby

Paleontological Research Institution
2014

ISBN 978-0-87710-507-7
Library of Congress no. 2014953666
PRI Special Publication no. 46

1259 Trumansburg Road
Ithaca, New York 14850 USA
priweb.org

First printing October 2014
Second printing, revised January 2015

This material is based upon work supported by the National Science Foundation under grant DRL-0733303. Any opinions, findings, and conclusions or recommendations are those of the author(s) and do not necessarily reflect the views of the National Science Foundation. The publication also draws from work funded by the Arthur Vining Davis Foundations and The Atlantic Philanthropies.

The interactive online version of this *Teacher-Friendly Guide*™ (including downloadable pdfs) can be found at http://teacherfriendlyguide.org. Web version by Brian Gollands.

The Teacher-Friendly Guide™ series was originally conceived by Robert M. Ross and Warren D. Allmon. Original illustrations in this volume are mostly by Jim Houghton (The Graphic Touch, Ithaca), Wade Greenberg-Brand, and Christi A. Sobel.

Layout and design by Paula M. Mikkelsen, Elizabeth Stricker, Wade Greenberg-Brand, and Katherine Peck.

Cite this book as:
Lucas, M. D., R. M. Ross, & A. N. Swaby (eds.), 2014, *The Teacher-Friendly Guide to the Earth Science of the Midwestern US.* Paleontological Research Institution, Ithaca, New York, 316 pp.

Cite one chapter as (example):
Wall, A. F., and W. D. Allmon, 2014, Fossils of the Midwestern US. Pages 57–83, in: M. D. Lucas, R. M. Ross, & A. N. Swaby (eds.). *The Teacher-Friendly Guide to the Earth Science of the Midwestern US.* Paleontological Research Institution, Ithaca, New York.

On the back cover: Blended geologic and digital elevation map of the Midwest. Each color represents the age of the bedrock at the surface. Adapted from Barton, K.E., Howell, D.G., Vigil, J.F., *The North America Tapestry of Time and Terrain*, US Geological Survey Geologic Investigations Series I-2781, http://pubs.usgs.gov/imap/i2781.

Preface

Earth science is an inherently local subject. No two places share exactly the same sequence of events that led to the way they are today. In this sense, Earth science is a subject to be explored in one's own neighborhood, examining the detailed sequence of rocks for the history that has gone on under our feet. What is not possible from only one location is making sense of why this particular sequence of events took place when and where it did, particularly relative to sequences in other places around it.

The distribution of rocks and landforms can be explained by processes that shape areas covering thousands of kilometers, such as the volcanism, mountain building, and sedimentary basins that accompany converging plates. These processes link widely separated sequences in a common history.

Earth science educators at the Paleontological Research Institution, in working with teachers, have noted that no single source for educators exists that attempts to make sense of the disparate local features of the Midwestern United States in terms of a basic sequence of historical events and processes. Nationally distributed textbooks make few references specifically to the Midwest region. While a number of reasonably good resources exist for individual states, these do not take enough geographic scope into account to show how, say, the coals of Illinois are related to the Late Ordovician marine sedimentary rocks of southwestern Ohio, or why fossil fuels are found in some states and iron mining occurs in other nearby states. Further, these resources are not necessarily "teacher-friendly," or written with an eye toward the kind of information and graphics that a secondary school teacher might need in their classroom. This *Teacher-Friendly Guide*™ is intended to fill this need for teachers.

Explaining why (for example, certain kinds of rocks and their mineral resources are found where they are) is the most effective way of providing students with a tool to remember and predict the nature of local Earth science. The Midwest (though, like states, an artificial political area), is of the right scale to discuss the evolution of significant portions of sedimentary basins, but also includes ancient igneous and metamorphic rocks. This means most Earth processes are illustrated by rocks present within a day's drive, and that Earth phenomena can be illustrated with examples in areas students and teachers are likely to have been to or at least heard of. Since the rocks and landforms are relatively accessible, regional Earth science is an excellent subject for hands-on, inquiry-based teaching using, for example, real rocks and landforms. A transect across the Midwest in several places will reveal most major rock types that students should know and will come into contact with over the course of their lifetimes.

The chapters chosen are by no means an exhaustive list, but reflect especially the historical side of "solid Earth" geosciences. Each chapter starts with a brief review, then (in most chapters) describes the Earth science of three natural regions with the Midwest. There is a resource list at the end of each chapter. There is a chapter on field work, not only on suggestions for how to do it, but how to integrate the field into your curriculum through "virtual fieldwork experiences." There are chapters on Big Ideas in Earth system science—a few major conceptual ideas that run throughout the subject—and on using real-world regional Earth science in the context of the Next Generation Science Standards (NGSS).

This volume is part of a national series of seven *Teacher-Friendly Guides™* to regional Earth science, covering all 50 states. We also have two *Teacher-Friendly Guides™* to evolution, and other Guides in development.

We would hope for our students that, years from now, they will be able to make sense of the place they live and the places they visit, through a comprehension of a few Big Ideas and a basic grasp of the "big picture" story of geological history of their area. It is our hope that this book might help teachers, and their students, grasp such a coherent understanding of their regional and local Earth system science.

Robert M. Ross, Associate Director for Outreach
Don Duggan-Haas, Director of Teacher Programs
Paleontological Research Institution
September 2014

Table of Contents

Contributors

Warren D. Allmon
Paleontological Research Institution
Ithaca, New York

Carlyn S. Buckler
Cooperstown Graduate Program
Cooperstown, New York

Don Duggan-Haas
Paleontological Research Institution
Ithaca, New York

William F. Kean
University of Wisconsin-Milwaukee
Milwaukee, Wisconsin

Richard A. Kissel
Yale University
New Haven, Connecticut

Nicole D. LaDue
Northern Illinois University
DeKalb, Illinois

Judith T. Parrish
University of Idaho
Moscow, Idaho

Alex F. Wall
University of Cincinnati
Cincinnati, Ohio

How to Use this Guide

General philosophy of the Teacher-Friendly Guides™

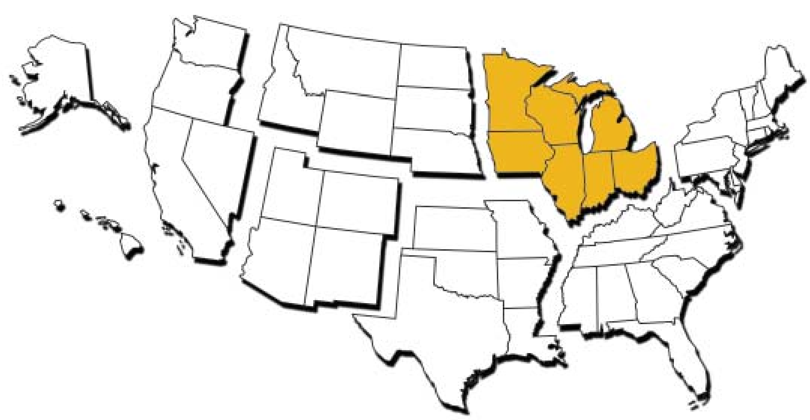
This Guide is organized by regional geologic history because it helps make sense of local Earth science—*Why does this place look the way it does? Why is this particular set of rocks, soil, landforms, water bodies, and local climate here?* We recommend introducing geologic history into your curriculum early.

The idea of systems also runs through the Guide. Through systems we understand, for example, why geologic history controls where different types of rocks occur, helping us make sense of landforms and water bodies. Landforms and water bodies in turn influence local climate, and all of it influences life. Understanding a few essentials of geologic history and Earth systems allows us to make sense of the world around us.

Please incorporate ideas from the Guide into your existing curriculum. This Guide is a resource rather than a curriculum itself.

Understanding real-world Earth science is a lifelong learning experience. Don't be intimidated by rocks that you don't recognize, fossils with long names, or complicated weather patterns. Enjoy learning alongside your students and show that enjoyment.

A National Series of Guides



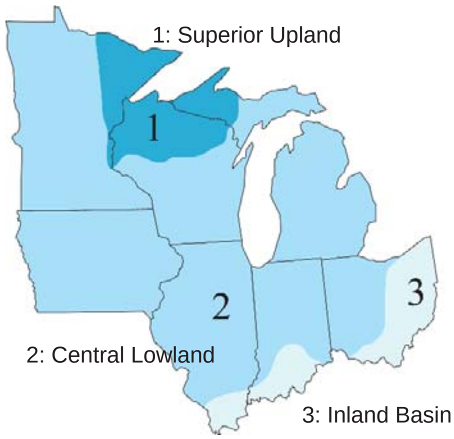
This Guide is one of seven covering the United States. There are also two *Teacher-Friendly Guides™* to evolution, one focused upon bivalves and another focused on maize genetics. To learn more, visit www.teacherfriendlyguide.org, a website of the Paleontological Research Institution.

For the interactive website version of this Guide, visit www.teacherfriendlyguide.org. To download individual chapters for printing, visit the website for the Midwest Guide and click "Downloads" on the chapter menu to the left.

To purchase a printed grayscale copy, visit "Publications" at the Paleontological Research Institution website. Images in the printed version, which are in grayscale, are available in color in the digital versions.

Design of the Guides

Most chapters in this guide divide the Midwest into three broad regions, each of which has a different geologic history and thus varies in rocks, fossils, topography, mineral resources, soils, and Earth hazards. The Geologic History chapter explains the history of all three within the context of Earth history. Chapters on climate and glaciers are not divided by region because these tend to be driven by processes at broader geographic scales.



Each Guide begins with five cross-cutting Big Ideas of Earth science. These have applications across the curriculum. Deep study of specific Earth science sites gives context and meaning to these most fundamental ideas, and in turn understanding these ideas facilitates a lifetime of making sense of Earth processes anywhere.

Each Guide ends with a chapter on fieldwork— even from the classroom. You and your students can begin to interpret the Earth science in your area, and bring back photos and data to re-visit your field sites—using "virtual fieldwork"—throughout the year. More information is available at www.virtualfieldwork.org.

Use the color geologic map as a reference tool while you read this Guide. The map is on the back cover of the printed Guides and available as a downloadable graphic on the website.

Cross-referencing

You do not have to read this Guide from front to back! Each chapter is written to stand alone. Main concepts are repeated in more than one chapter. In this way you can use read just what you need, in any order, as you approach particular units through the school year.

The chapters are cross-referenced, should you need to find more information about a particular concept or region. Bold-faced words are defined in a separate glossary, with selected words defined in chapter side bars.

For Further Information…

At the end of each chapter are lists of resources specific to that topic. There are lists of national and state-based resources, many of which cover multiple topics, at the end of the Guide.

Earth System Science: The Big Ideas

Like all scientific disciplines, the Earth sciences continually evolve over time. New discoveries fuel new ideas, providing an ever-increasing understanding of the planet. But of the overwhelming number of observations, theories, and principles that form the foundation of Earth system science, what is essential for every American to understand? All too often, curricula are too ambitious and, as a result, may fail to cover topics in any substantial depth. An alternative approach is to build one's curriculum upon a foundation of focused, interconnected big ideas. A well-designed set of big ideas can provide an all-encompassing conceptual framework for any discipline, including Earth system science. Developed alongside scientists and Earth science teachers, this coherent set of big ideas illuminates what is fundamental to the Earth sciences:

1. The Earth is a system of systems.
2. The flow of energy drives the cycling of matter.
3. Life, including human life, influences and is influenced by the environment.
4. Physical and chemical principles are unchanging and drive both gradual and rapid changes in the Earth system.
5. To understand (deep) time and the scale of space, models and maps are necessary.

These ideas are designed to cover the breadth of any Earth science curriculum, but they must be dissected to build deep understanding. Each idea is essentially bottomless; that is, while a meaningful understanding of these ideas is readily attainable, the details contained within are endless. Each of the ideas can be understood, but the depth of understanding can vary greatly.

Introduction of these ideas also invites discussion of the nature of science. As curricula are designed and implemented, the traditional topics of Earth system science should be complemented with ideas on how we have come to know what we know about the natural world. Within our big ideas framework, we draw attention to the nature of science with two overarching questions:

1. How do we know what we know?
2. How does what we know inform our decision making?

These questions, when addressed in concert with the big ideas, provide a gateway into the nature and utility of the range of scientific ideas.

CHAPTER AUTHORS

Don Duggan-Haas
Richard A. Kissel

Big Ideas

plate tectonics • _the way by which the plates of the Earth's crust move and interact with one another at their boundaries._

weathering • _the breakdown of rocks by physical or chemical means._

erosion • _the transport of weathered materials._

uplift • _upward movement of the crust due to compression, subduction, or mountain building._

metamorphism • _when pre-existing sedimentary, igneous, and metamorphic rocks are exposed to high enough temperature and/or pressure that minerals within the rock recrystallize and realign._

igneous rocks • _rocks derived from the cooling of magma underground or molten lava on the Earth's surface._

glacier • _a body of dense ice on land that does not melt away annually and has sufficient mass to move under its own weight._

Big Idea 1:
The Earth is a system of systems

The Earth is composed of many systems, which cycle and interact in both space and time. It is also part of a multitude of systems, nested in larger systems such as the solar system and the universe. Systems are composed of an untold number of interacting parts that follow simple rules; they can and do evolve. For example:

Outlining the geologic history of any region demonstrates the concept of the Earth as a system of systems. **Plate tectonics** drives the formation of mountains. Subsequent **weathering** and **erosion** of the **uplifted** mountains leads to the formation of deltas in the adjacent shallow seas. And with uplifted continents, shorelines change and the distribution of marine communities are altered.

The planet's systems are intimately connected: the forces of one system affect other systems nested within it. As plates collide, systems that drive plate tectonics are obviously linked to the formation of mountains, but they are ultimately linked to and influence much smaller systems. The intense **heat** and pressure resulting from collisions can lead to the **metamorphism** of existing strata, or it can melt existing rocks to later form **igneous rocks**.

As **glaciers** extended down from the north, they cut into river valleys in the upper portion of the Midwest. This glacial system shaped the landscape, deepening and widening the river valleys and, after the glaciers' retreat, triggering the formation of the **Great Lakes**. Had the glaciers never advanced so far south, the erosional forces that led to the formation of these lakes would have never been set in motion.

See Chapter 4: Topography for more on how glaciers shaped the Midwestern landscape.

Each of the remaining ideas operates across multiple systems within the larger Earth system.

Big Idea 2:
The flow of energy drives the cycling of matter

The Earth is an open system. Energy flows and cycles through the system; matter cycles within it. This cycling is largely driven by the interaction of the differential distribution of solar radiation and internal heat: the constant flow of solar radiation powers much of Earth's ocean and **atmospheric** processes on the surface of the system, while the flow of heat from **radioactivity** within the Earth drives plate tectonics. For example:

One of the fundamental processes known to Earth system scientists is the rock cycle. The rock cycle illustrates the steps involved in the formation of one type of rock from another. It is a system that has operated since the Earth's origin, and it continues today. The energy that drives weathering and erosion, melting, or an increase in heat or pressure, drives the continuation of the rock cycle.

See Chapter 1: Geologic History for more on the formation of the Midwest.

The landscape of the Midwest that we see today has been shaped by the geologic forces of the past. Evidence littered throughout the terrain tells a story that began over two billion years ago with the formation of the **Canadian Shield**, which is an accumulation of smaller plates as well as plate fragments that **sutured** themselves to another plate (forming what is known as a **terrane**). The movement of Earth's plates is driven by plate tectonics, illustrating how the flow of energy drives the cycling of matter—the flow of heat from radioactivity within the Earth drives plate tectonics.

See Chapter 6: Glaciers to learn more about the Midwest during the ice age.

During the most recent **ice age**, glaciers advanced and retreated many times during the past two million years. One of the great questions in the Earth sciences revolves around the causes of these glacial cycles, with the general consensus pointing toward cyclic variations in the planet's tilt, movement about its axis, and its orbital shape around the sun. These variations lead to changes in the amount of solar radiation that reaches the Earth, which in turn affect global **climate**.

The rock cycle, plate tectonics, and the water cycle are all **convection**-driven. Without convection, Earth would be extraordinarily different.

atmosphere • *a layer of gases surrounding a planet.*

radioactive • *when an unstable atom loses energy by emitting radiation.*

Canadian Shield • *the stable core of the North American continental landmass, containing some of the oldest rocks on Earth.*

suture • *the area where two continental plates have joined together through continental collision.*

ice age • *a period of global cooling of the Earth's surface and atmosphere, resulting in the presence or expansion of ice sheets and glaciers.*

climate • *description of the average temperature, range of temperature, humidity, precipitation, and other atmospheric/hydrospheric conditions a region experiences over a period of many years.*

convection • *the rise of buoyant material and the sinking of denser material.*

greenhouse gas • *a gas in the atmosphere that absorbs and emits heat.*

global warming • *the current increase in the average temperature worldwide, caused by the buildup of greenhouse gases in the atmosphere.*

Big Idea 3: Life—including human life—influences and is influenced by the environment

Across its four-billion-year history, the course of life's evolution has been intimately tied to the Earth's physical environment. Global cooling led to the relatively recent spread of grasslands, which then triggered an evolutionary shift in many herbivorous mammals from browsing to grazing. Conversely, the evolution of life has altered the physical environment. Photosynthetic bacteria released free oxygen into the early oceans and atmosphere, making Earth habitable for later types of organisms. Humans, with their increasing population and expanding technology, have altered the landscape and the distribution of flora and fauna, and they are changing atmospheric chemistry in ways that affect the climate. Earth system processes also influence where and how humans live. For example:

With human populations increasing the world over, the emission of **greenhouse gases** has also increased dramatically. These gases alter the chemical composition of the atmosphere and directly influence the planet's climate. It is generally agreed that the rapid and immense pouring of carbon dioxide into the atmosphere will lead to **global warming**, which will have incredible impacts throughout the world.

See Chapter 9: Climate to learn more about the effect of greenhouse gases.

Around three million years ago, a land bridge formed between North and South America. For the first time in more than 150 million years, the two continents were linked, and the mammals inhabiting both lands migrated across the bridge. Horses, mastodons, cats, and dogs moved south, while opossums, porcupines, ground sloths, and armadillos moved north (to name a few). Today, half the mammal species in South America are descended from North American migrants.

Big Idea 4:
Physical and chemical principles are unchanging and drive both gradual and rapid changes in the Earth system

The Earth processes operating today, everything from local erosion to plate tectonics, are the same as those operating since they first arose in Earth history, and these processes are obedient to the laws of chemistry and physics. While the processes that constantly change the planet are essentially fixed, their rates are not. Tipping points are reached that can result in rapid changes cascading through Earth systems. For example:

> During the **Precambrian**, the evolution of photosynthetic organisms led to significant changes in the planet's atmosphere. Prior to this event, there was little free oxygen in the atmosphere, but with photosynthesis producing oxygen as a waste product, the very existence of these organisms flooded the seas and atmosphere with free oxygen, changing the planet forever. But life's evolution represents just one of the processes working upon Earth systems.
>
> Extending from the eastern edge of modern-day Lake Superior to Kansas, a **rift** valley began to split North America apart around 1.1 billion years ago. Intense **volcanism** along the rift produced 7.6-kilometer-thick (4.7-mile-thick) igneous deposits. This rift zone continued to spread for about 20 million years, after which it began to sink and eventually become filled with sediment.
>
> Today, the **ice sheets** of Greenland and Antarctica make up some 95% of all the current glacial ice on Earth. The study of these modern glaciers and their influences on the environment, such as through the formation of U-shaped valleys, is key to interpreting glacial deposits of the past, which are thought to have formed under the same processes as those operating today.

See Chapter 1: Geologic History for more information about rifting.

Precambrian • *a geologic time period that spans from the formation of Earth (4.6 billion years ago) to the beginning of the Cambrian (541 million years ago).*

rift • *a break or crack in the crust that can be caused by tensional stress as a landmass breaks apart into separate plates.*

volcanism • *the eruption of molten rock onto the surface of the crust.*

ice sheet • *a mass of glacial ice that covers part of a continent and has an area greater than 50,000 square kilometers (19,000 square miles).*

Big Idea 5: To understand (deep) time and the scale of space, models and maps are necessary

The use of models is fundamental to all of the Earth sciences. Maps and models:

1. Aid in the understanding of aspects of the Earth system that are too big or small for direct observation, or where observation is not possible; and
2. Help make complex systems comprehensible through strategic simplification.

When compared to the size and age of the universe, humanity is a speck in space and a blip in time; models assist in the comprehension of time and space at both sub-microscopic and immense scales. For example:

> Much of scientists' understanding of the inner workings of our planet is derived from mathematical modeling. It is not possible to directly measure the movement below Earth's surface, but modeling of convection currents brings us closer to the true nature of these monumental geologic phenomena.
>
> The observation of natural phenomena today, such as deposition along a streambed, is critical for interpreting the geologic record. But for processes that operate on much larger, slower scales, modeling within the lab is required. The formation of mountain ranges, such as the Appalachians, is better understood by examining the effects of stress and strain in the laboratory.
>
> What is the effect of a two-kilometer-thick (1.2-mile-thick) glacier on the terrain? In addition to changes related to deposition, the shear weight of such an object depresses the continental mass. Understanding this compression—and the rebound that occurs upon the glaciers retreat—is improved through modeling in the laboratory.

In Conclusion

Taken individually, these big ideas and overarching questions represent important aspects of Earth system science, but together they are more significant. Keeping these ideas in mind—and considering how they arose through scientific methods and investigation—is invaluable as one proceeds throughout his or her curriculum, and it can provide a conceptual framework upon which to build an enduring understanding of the discipline.

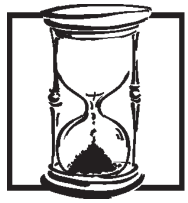
Resources

Donovan, S., & Bransford, J., 2005. *How Students Learn: Science in the Classroom*. Washington, D.C: National Academies Press. Retrieved from http://books.nap.edu/catalog.php?record_id=10126.

Wiggins, G.P., & McTighe, J., 2005. *Understanding by Design* (2nd ed.), Association for Supervision and Curriculum Development: Alexandria, VA.

Wiske, M.S. (ed.), 1998, *Teaching for Understanding: Linking Research with Practice*. Jossey-Bass: San Francisco.

Exploring Geoscience Methods with Secondary Education Students, by Ebert, J., Linneman, S., Thomas, J. http://serc.carleton.edu/integrate/teaching_materials/geosci_methods/index.html.



Chapter 1: Geologic History of the Midwestern US: The Big Picture

Geologic history is the key to this Guide and to understanding the story recorded in the rocks of the Midwest. By knowing more about the geologic history of our area, you can better understand the type of rocks that are in your own backyard and why they are there. We will look at the history of the Midwest as it unfolds: as a series of major events over the past one billion years that created and shaped the area. These events will act as the framework for the topics to follow and will shed light on why our region looks the way it does!

Geologic Time

How did geologists come up with the timeline for the history of the Earth? Over the course of many years and through the combined work of geologists around the world, the geologic time scale was developed (*Figure 1.1*). No rock record in any one place contains the complete sequence of rocks from Precambrian to present. Geology as a science grew as geologists studied individual sections of rock. Gradually, geologists discovered evolutionary successions of fossils that helped them determine the relative ages of groups of rocks. Rock units were then correlated with similarly aged rock units from around the world. The names you see for the different periods on the geologic time scale have diverse origins. Time periods were named after dominant rock types, geography, mountain ranges, and even ancient tribes like the Silurese of England and Wales, from which the "Silurian period" was derived.

The **geologic time scale** is an important tool used to portray the history of the Earth—a standard timeline used to describe the age of rocks and **fossils**, and the events that formed them. It spans Earth's entire history and is separated into four principle divisions.

geologic time scale • *a standard timeline used to describe the age of rocks and fossils, and the events that formed them.*

fossil • *preserved evidence of ancient life, including, for example, preserved skeletal or tissue material, molds or casts, and traces of behavior.*

CHAPTER AUTHORS

Richard A. Kissel
Alex F. Wall

1 Geologic History

Geologic Time

About the Time Scale:
The time scale in The Teacher-Friendly Guides™ *follows that of the International Commission on Stratigraphy (ICS). The Tertiary period, though it was officially phased out in 2008 by the ICS, remains on the scale in the Guides, since "Tertiary" is present extensively in past literature. In contrast, the Carboniferous and Pennsylvanian & Mississippian periods all enjoy official status, with the latter pair being more commonly used in the US.*

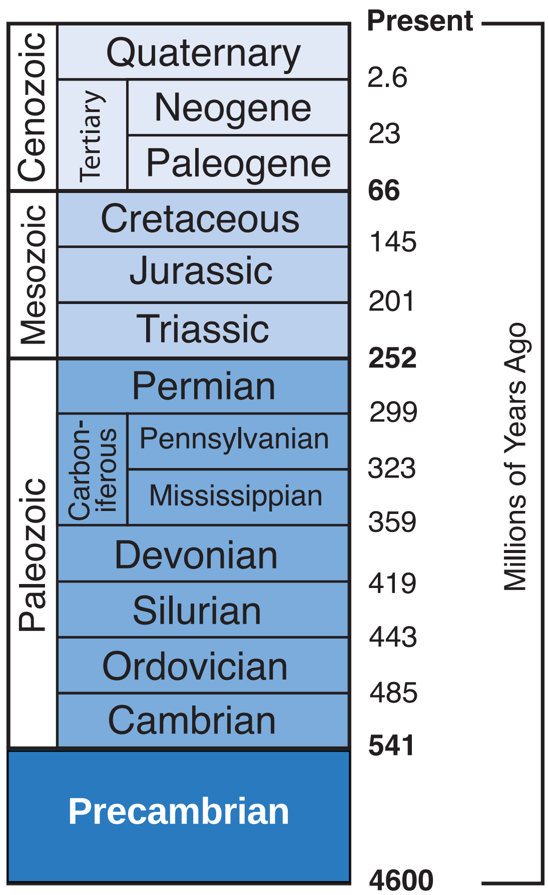


Figure 1.1: The Geologic Time Scale (spacing of units not to scale).

The first of these, the **Precambrian**, extends from about 4.6 billion years ago to 541 million years ago. Little is known about this time period since very few fossils or unaltered rocks have survived. What few clues exist indicate that life first appeared on the planet some 3.9 billion years ago in the form of single-celled organisms.

The second division, the **Paleozoic**, extends from 541 to 252 million years ago. Fossil evidence shows that during this time period, life evolved in the oceans and gradually colonized the land.

The third division, the **Mesozoic** (from 252 to 66 million years ago), is also called the "age of reptiles" since dinosaurs and other reptiles dominated both marine and terrestrial ecosystems. It is also noteworthy that during this time the last of the Earth's major supercontinents, **Pangaea**, formed and later broke up, producing the Earth's current geography.

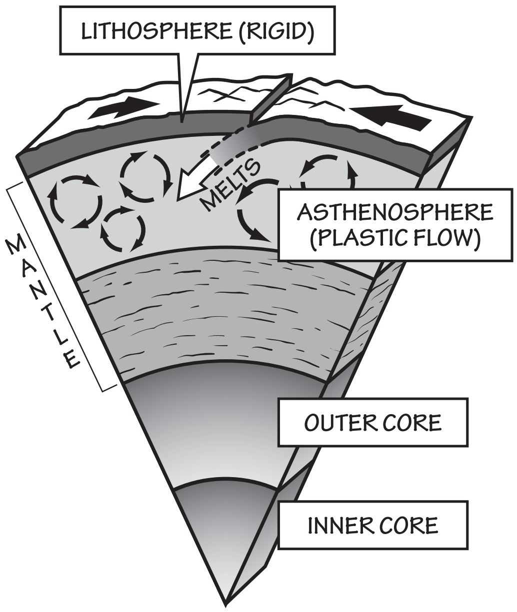
The last and current division, the **Cenozoic**, extends from the **extinction** of the dinosaurs, nearly 66 million years ago, to the present. With the demise of the dinosaurs, mammals became dominant and, subsequently, more diverse and highly developed. We humans don't come into the picture until the last 2 million years. To get some perspective on this, if the entire geologic time scale were reduced to 24 hours, we wouldn't come onto the stage until 2 seconds before midnight!

The Earth is dynamic, consisting of constantly moving **plates** that are made of rigid continental and oceanic **lithosphere** overlying a churning, plastically flowing **asthenosphere** (*Figure 1.2*). These plates are slowly pulling apart, colliding, or sliding past one another with great force, creating strings of **volcanic islands**, new ocean floor, **earthquakes**, and mountains. The continents are likewise continuously shifting position relative to each other. This not only shapes

extinction • *the end of species or other taxonomic groups, marked by death of the last living individual.*

lithosphere • *the outermost layer of the Earth, comprising a rigid crust and upper mantle broken up into many plates.*

asthenosphere • *a thin semifluid layer of the Earth, below the outer rigid lithosphere, forming the upper part of the mantle.*

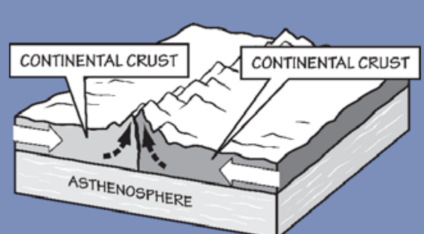


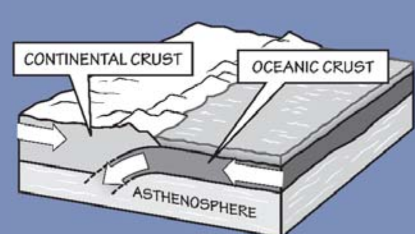
the land, but also affects the distribution of rocks and **minerals**, natural resources, **climate**, and life. Scientists can reconstruct what the ancient Earth might have looked like by studying rocks, fossils, and other geologic features.

Figure 1.2: The layers of the Earth include the rigid crust of the lithosphere, which is constantly moving over the plastically flowing asthenosphere.

Continental and Oceanic Crust

The lithosphere has two types of crust: continental and oceanic. Continental crust is less dense but significantly thicker than oceanic crust. The higher density of the oceanic crust means that when continental crust collides with oceanic crust, the more dense oceanic crust will be dragged (or subducted) under the buoyant continental crust. Although mountains are created at these oceanic/continental crust collisions due to the compression of the two plates, much taller ranges are produced by continental/continental collisions. When two buoyant continental crusts collide, there is nowhere for the crust to go but up! The modern Himalayas, at the collision site of the Asian and Indian plates, are a good example of very tall mountains formed by a collision between two continental crusts.





Geologic Time

plates • *large, rigid pieces of the Earth's crust and upper mantle, which move and interact with one another at their boundaries.*

volcanic islands • *a string of islands created when molten rock rises upwards through oceanic crust.*

earthquake • *a sudden release of energy in the Earth's crust that creates seismic waves.*

mineral • *a naturally occurring solid with a specific chemical composition and crystalline structure.*

climate • *description of the average temperature, range of temperature, humidity, precipitation, and other atmospheric/hydrospheric conditions a region experiences over a period of many years.*

1 Geologic History

Canadian Shield

terrane • *a piece of crustal material that has broken off from its parent continent and become attached to another plate.*

gneiss • *a metamorphic rock that forms from granite or layered sedimentary rock, and is characterized by a striated appearance.*

Archean • *a geologic time period that extends from 4 billion to 2.5 billion years ago.*

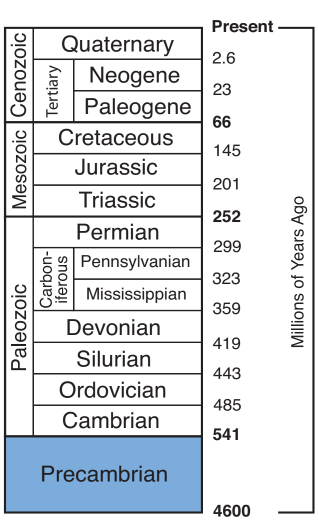
The Canadian Shield: Foundation of a Continent

The shape and position of North America has changed dramatically over the last few billion years, and geologic processes continue these changes today. The Earth is estimated to be approximately 4.6 billion years old. The oldest rocks known are located in northern Quebec and date to 4.3 billion years ago. Rocks dating to 4 billion years old are found on almost every continent. In North America they are found exposed at the surface in parts of Canada, composing the **Canadian Shield**, a stable core of the North American continental landmass.

The oldest rocks found on Earth are 4.3-billion-year-old greenstone beds found along the eastern shore of Hudson Bay in northern Quebec. The oldest known materials are 4.4-billion-year-old zircons from Western Australia.

The Canadian Shield is the original core, or **craton**, of the North American continent. It includes much of Greenland, more than half of Canada, and it extends into the Adirondack Mountains of New York and the Superior Upland region of the Midwest. It is an accumulation of smaller plates and **terranes** that formed over a period of hundreds of millions of years, between 2.5 and 1.25 billion years ago. The shield was the first section of the North American continent to emerge above sea level, and it remains the largest exposure of Precambrian-aged rock in the world.

Seven distinct provinces compose the nucleus that is the Canadian Shield. The Superior Province is found in south central Canada, and it extends into northeastern Minnesota, northern Wisconsin, and the Upper Peninsula of Michigan. Metamorphic **gneisses** exposed within the Minnesota River Valley represent the oldest rocks found in the Midwest, dating back 3.5 billion years. The oldest rocks from Wisconsin are represented by 2.8-billion-year-old gneiss, while Precambrian outcrops in a small area of northwestern Iowa—the Sioux Quartzite in Gitchie Manitou State Preserve—date to 1.7 billion years ago. No Precambrian rocks are exposed in Indiana, Illinois, or Ohio (*Figure 1.3*).



Mountain Building 1:
The Proterozoic Record

Following the formation of the Superior Province around 2.7 billion years ago during the late **Archean**, the **Proterozoic** of the Midwest was characterized by the deposition and presence of **banded iron formations**. With the evolution of photosynthetic organisms (still single-celled at this time), their waste product, oxygen, was released into the oceans and ultimately the **atmosphere**. The

Mtn Building 1

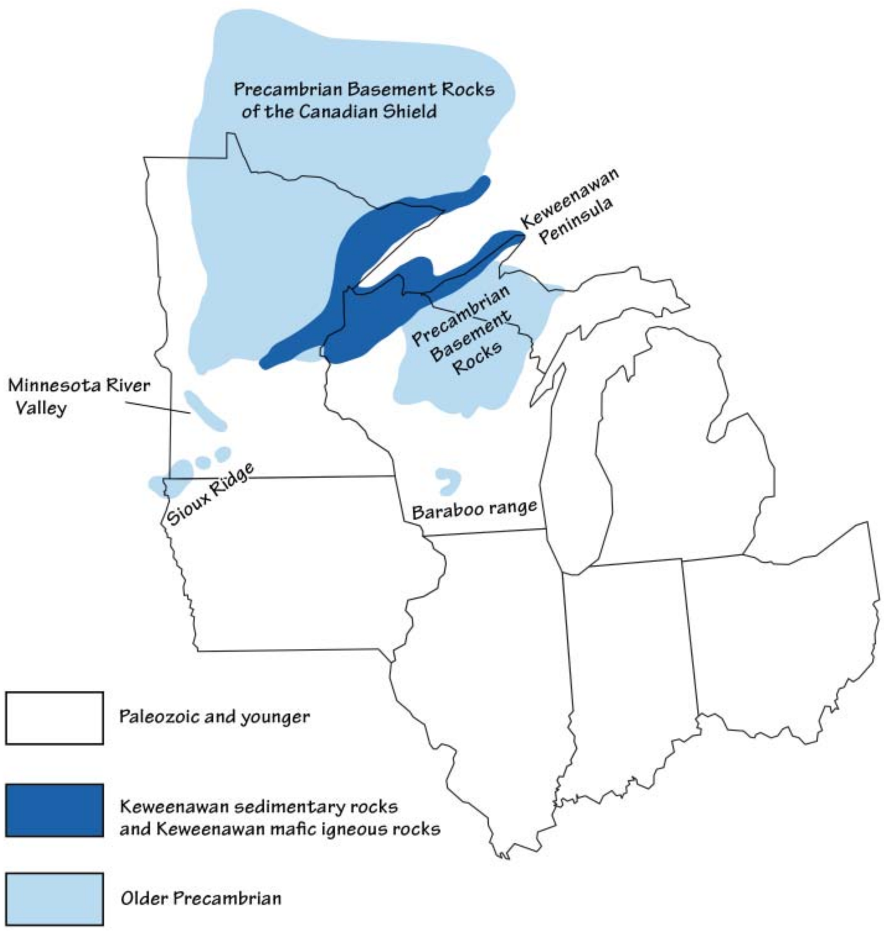


Figure 1.3: Precambrian outcrops within the Midwest.

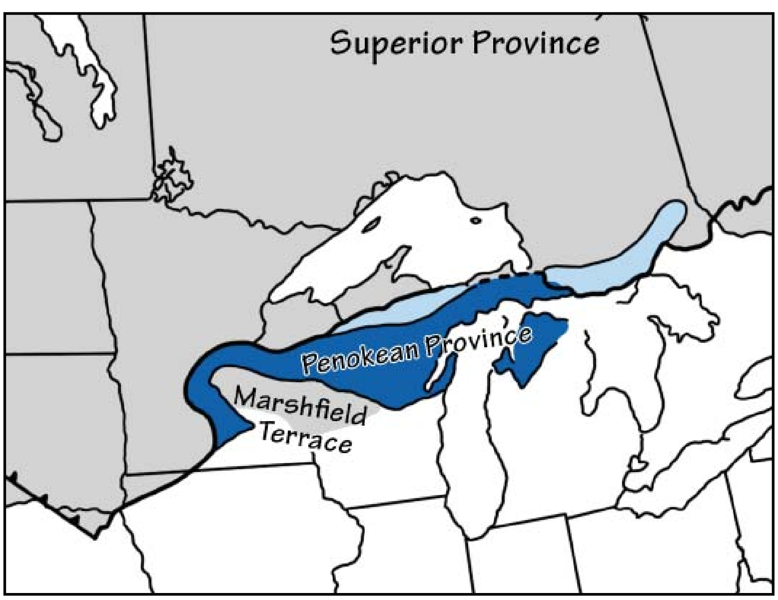


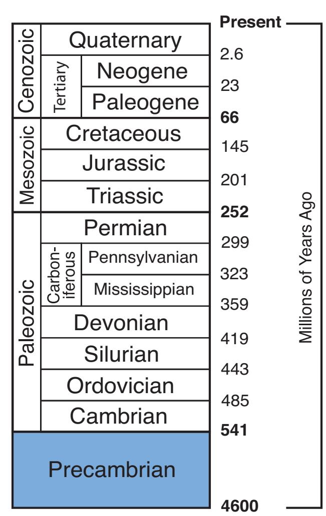
Figure 1.4: The accretion of the Pembine-Wausau island arc and the Marshfield terrane led to the Penokean Orogeny of the Proterozoic.

basement rocks • *the foundation that underlies the surface geology of an area, generally composed of igneous or metamorphic crystalline rock.*

banded iron formation • *rocks with regular, alternating thin layers of iron oxides and either shale or silicate minerals.*

Proterozoic • *a geologic time interval that extends from 2.5 billion to 541 million years ago.*

atmosphere • *a layer of gases surrounding a planet.*



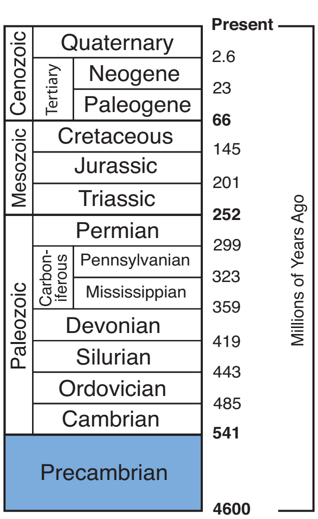
Mtn Building 1

orogeny • *a mountain-building event generally caused by colliding plates and compression of the edge of the continents.*

metamorphism • *when pre-existing sedimentary, igneous, and metamorphic rocks are exposed to high enough temperature and/or pressure that minerals within the rock recrystallize and realign.*

rift • *a break or crack in the crust that can be caused by tensional stress as a landmass breaks apart into separate plates.*

volcanism • *the eruption of molten rock onto the surface of the crust.*



oxygen reacted and combined with dissolved iron particles to produce bands of iron oxides such as **hematite** and **magnetite**.

Between 1.8 and 1.9 billion years ago, an **orogenic** event produced the Penokean Mountains, which extended from Minnesota into northern Wisconsin and Michigan. The Penokean Orogeny occurred as the Pembine-Wausau island arc and Marshfield terrane collided from the south, increasing the size of the Superior landmass (*Figure 1.4*). Erosion of the Penokean Mountains led to deposits of **sandstone** along the margin of a shallow sea. Around 1.7 billion years ago, after millions of years of heat and pressure, this sandstone produced the **metamorphic** Sioux Quartzite of Minnesota and Iowa. The Baraboo Quartzite of the Devil's Lake area in central Wisconsin also dates to this time.

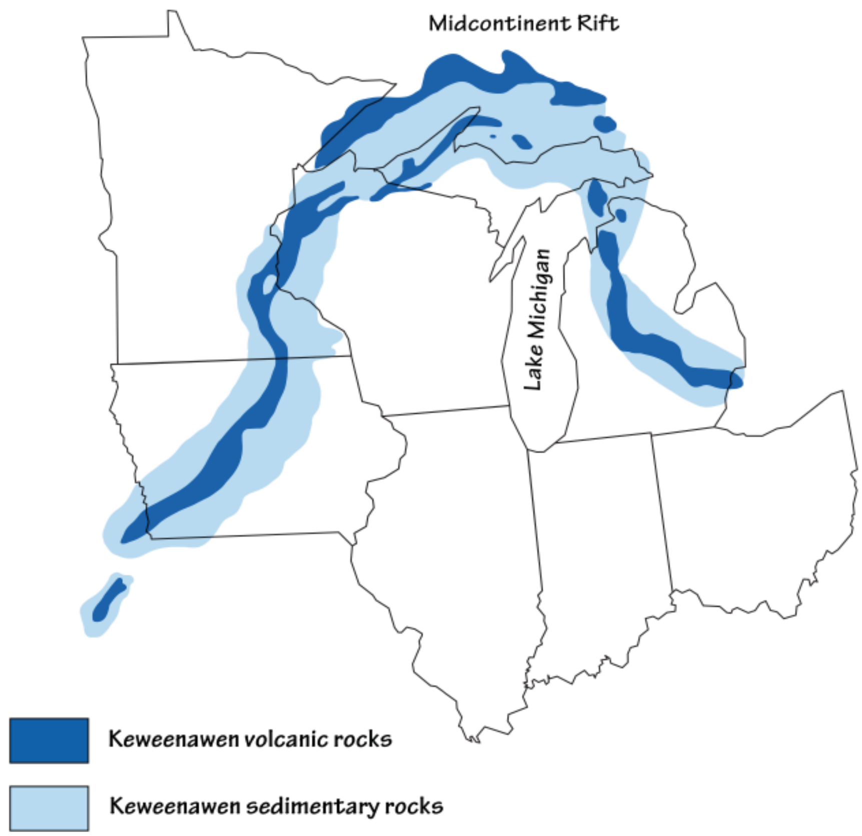


Figure 1.5: Active for 20 million years, a great rift valley extended through the Midwest from today's Lake Superior to Kansas.

Around 1.1 billion years ago, a **rift** valley called the Midcontinental Rift—extending from the eastern edge of modern-day Lake Superior to Kansas—began to split North America apart (*Figure 1.5*). Intense **volcanism** occurred along the rift, producing **igneous** deposits with a thickness of some 7.6 kilometers (25,000 feet). The spreading occurred for 20 million years, after which the rift zone began to sink and was gradually filled with sediment.

Mountain Building 2: the Paleozoic

Overlying the older rock of the Canadian Shield, much of the remaining geologic history of the Midwest records the presence of shallow seas, the formation of the supercontinent Pangaea, and—most recently—the modern **ice age**.

Cambrian deposits are recorded in Wisconsin, Illinois, Minnesota, and Iowa. During this time, shallow seas covered much of the Midwest, with several **transgression** and **regression** episodes recorded as well. Nearly all of what would become North America was located just *south* of the equator at the dawn of the Cambrian, and it drifted within the tropics for most of its existence.

During the middle of the **Ordovician** period, about 470 million years ago, the **Iapetus Ocean** began to close as **Baltica** (proto-Europe) approached the North American plate from the southeast (*Figure 1.6*). The intense pressure of the colliding plates and islands smashing into the side of North America caused its edge to crumple, crushing and folding it into mountains. This mountain-building event is called the Taconic Orogeny, and the resulting Taconic Mountains stretched from Newfoundland to Georgia, sharing roughly the same location and orientation of the Appalachian Mountains today, but with towering peaks in eastern Canada and New England.

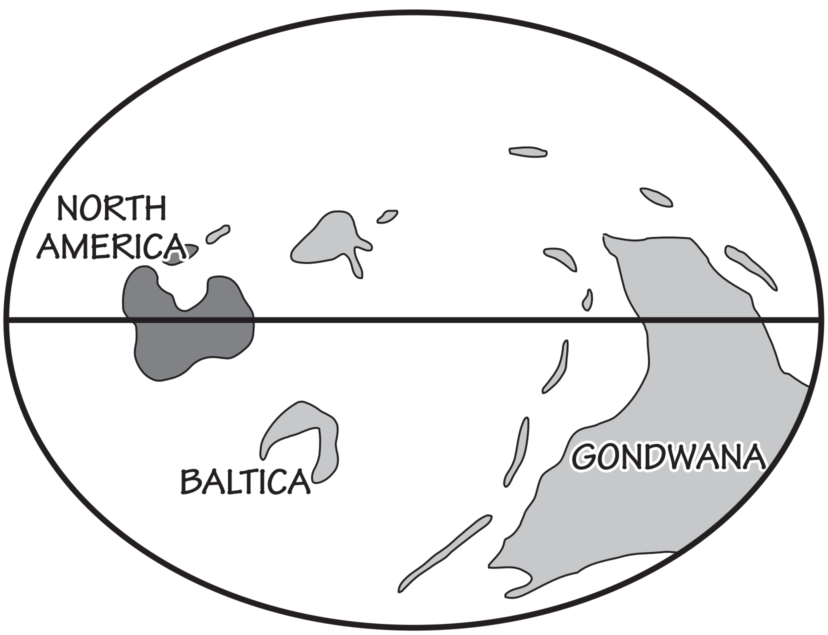


Figure 1.6: Ordovician: 458 million years ago. Shaded areas represent land that was above water.

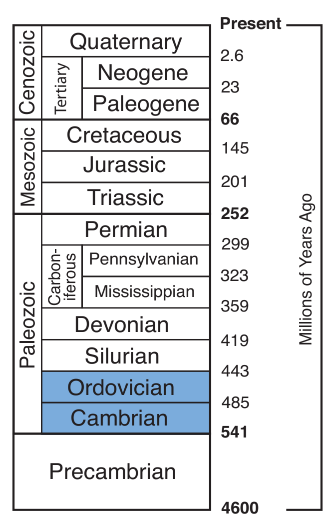
This folding propagated far to the west, forming waves parallel to the Taconic Mountains themselves that ran roughly southwest to northeast. Nearest the mountains, the **crust** warped downwards from central New York to central North Carolina, creating the **Appalachian Basin**. From western Ohio to Alabama, it was warped up into the **Cincinnati Arch**, and, most distally, down again,

igneous • *derived from the cooling of magma underground or molten lava on the Earth's surface.*

transgression • *a relative rise in sea level in a particular area, through global sea level rise or subsidence of land.*

regression • *a drop in sea level.*

Iapetus Ocean • *the proto-Atlantic Ocean, located against the eastern coast of North America's ancestral landmass before Pangaea formed.*



Mtn Building 2

Michigan Basin • *an inland basin centered on Michigan's Lower Peninsula, which formed when Baltica approached North America in the Ordovician.*

Illinois Basin • *an inland basin centered in the state of Illinois, which formed when Baltica approached North America in the Ordovician.*

inland basin • *a depression located inland from the mountains, and formed by the buckling (downwarping) of the Earth's crust.*

creating the **Michigan** and **Illinois basins**. These formations are prominent features of Midwestern geology. The **inland basins** were flooded by the ocean for nearly all of their existence.

The mountain building ceased around the beginning of the **Silurian**, but the Taconic Mountains still played a major role in the formation of the Midwest. As sediment was eroded from the western side of the Taconic Mountains, deposits spread away, through the Northeast and Midwest, as far west as Wisconsin (*Figure 1.7*). Thousands of feet of this sediment built up on the floors of the seas that filled the Midwestern basins, and this sediment, along with the millions of generations of marine organisms that lived there, formed the Silurian and **Devonian** bedrock of much of the area.

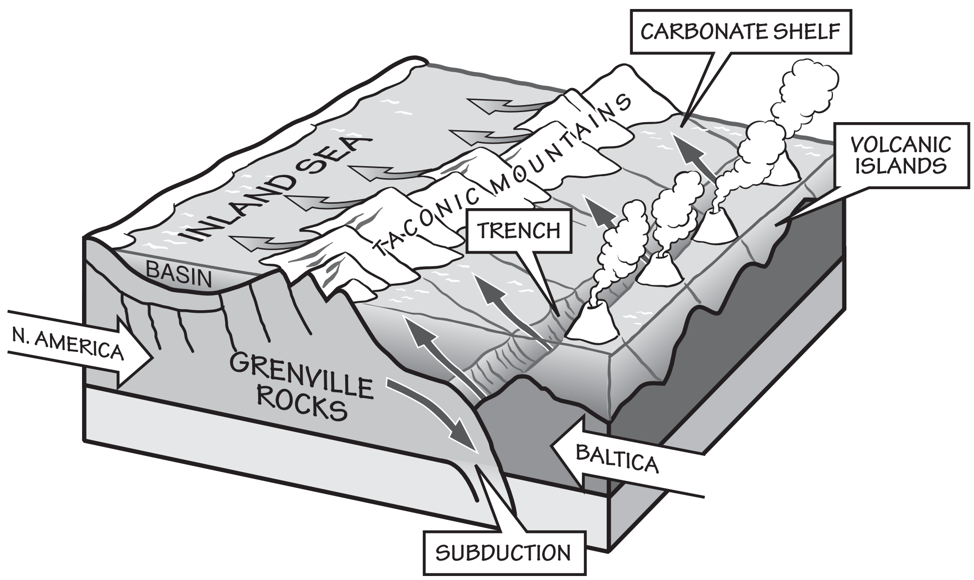
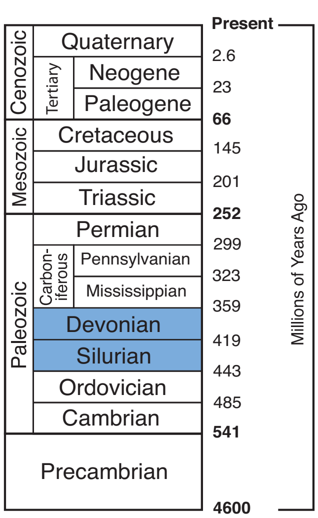


Figure 1.7: Volcanic islands formed where the plates were forced together as the Iapetus Ocean closed. The compression crumpled the crust, forming the Taconic Mountains and shallow inland seas.



For millions of years during the Paleozoic, an inland extension of the Iapetus Ocean covered the eastern half of North America, filling the basins formed by the mountain-building events. The inland ocean was separated from the main Iapetus Ocean by the Taconic and Acadian Mountains.

Sea level rose and fell in this inland sea during the Paleozoic, in part because the convergence of the plates carrying North America and Baltica continued to buckle the inland basin, deepening the ocean. Sediment eroded from the mountains, however, was also filling the inland ocean.

For about 60 million years, the eastern margin of North America was relatively quiet. The **subduction** of the oceanic Iapetus plate caused volcanic eruptions that occasionally spread ash over the Midwest, but for the most part, the Taconics were slowly eroding. Finally, Baltica collided with North America near the end of the Devonian period, around 380 million years ago, and mountain-building began again, creating the Acadian Mountains. The Acadian Mountains effectively replaced the Taconics, creating a massive range that was similar in location and extent (*Figure 1.8*). Just as in the Taconic mountain-building period, **compression** from the Acadian continental collision warped the crust downward, reinforcing the inland seas. Sediments eroding from the mountains formed the Catskill Delta, creating a new wedge of sediments stretching into a shallow inland sea; the Devonian and **Mississippian** rocks of Ohio are evidence of this event.

subduction • *the process by which one plate moves under another, sinking into the mantle.*

compression • *forces acting on an object from all or most directions, resulting in compression (flattening or squeezing).*

At the time of the Acadian mountain building and subsequent erosion during the Devonian, the Midwest was located at the Equator and experienced a tropical climate (*Figure 1.9*). Baltica and North America were united as one larger landmass. Africa, South America, India, Australia, Antarctica, and Florida formed a second continent—**Gondwana**—in the southern hemisphere.

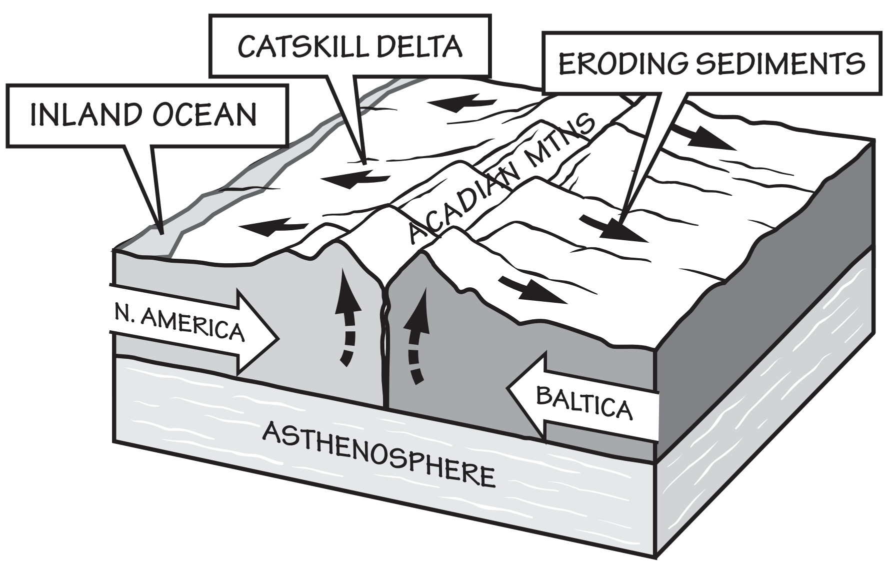
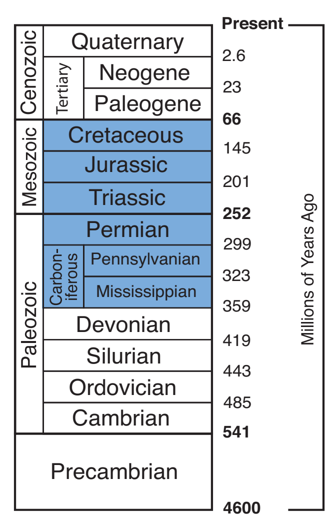


Figure 1.8: The collision of Baltica and North America, which led to the deposition of sediments in the shallow seas of the Midwest.

During the **Carboniferous**, the collision of North America with Gondwana (*Figure 1.10*) was the genesis of Pangaea. This event also resulted in the formation of both the Appalachian Mountains and, in the South Central region, the Interior Highlands. The interior seaways ultimately regressed from the Midwest.

In the Midwest, Mesozoic-aged rocks are preserved primarily in Minnesota, Iowa, and, to a lesser extent, in Illinois. For the remainder of the Midwest, the Mesozoic was a time of erosion and very little deposition. The rocks that do exist were deposited mainly during the **Cretaceous**. At that time,



Mtn Building 2

Phanerozoic • *a generalized term used to describe the entirety of geological history after the Precambrian, from 541 million years ago to the present.*

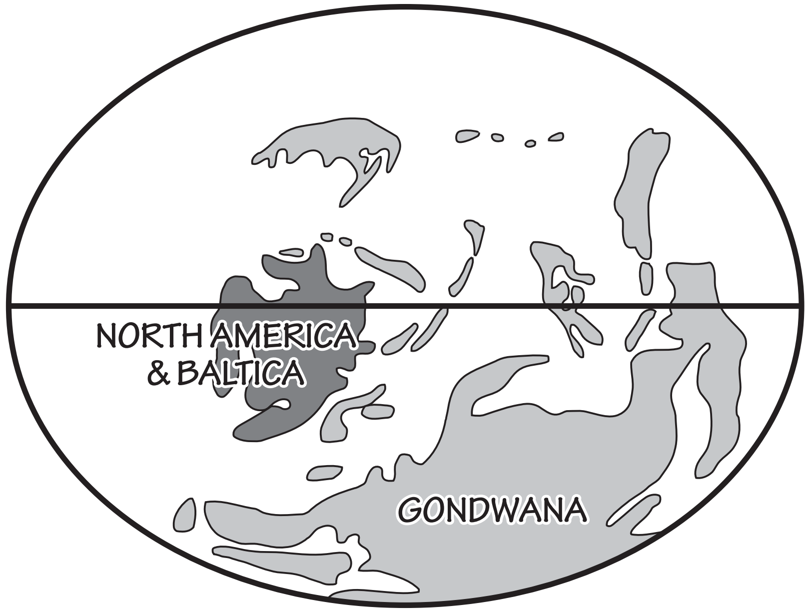


Figure 1.9: The Devonian period globe.

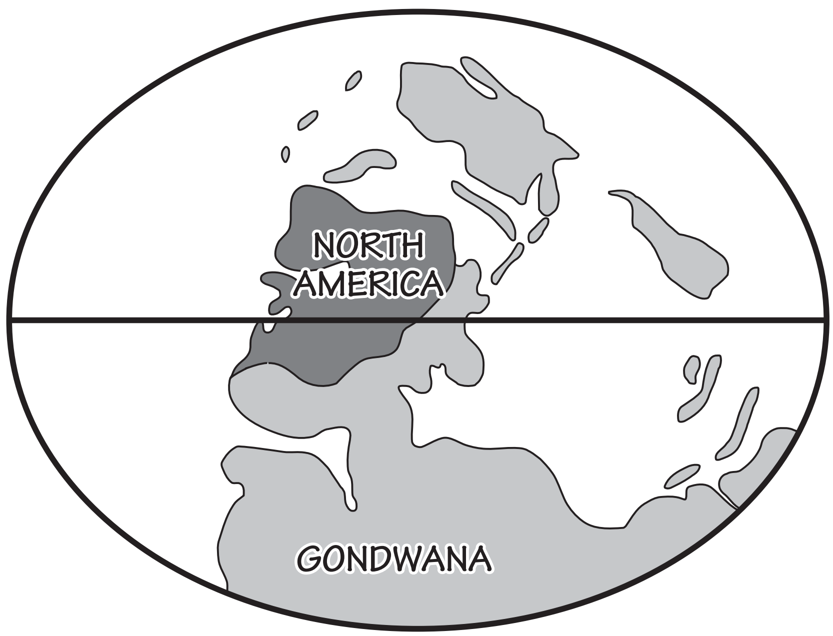


Figure 1.10: Late Carboniferous.

Era		Period	Millions of Years Ago
			Present
Cenozoic		Quaternary	2.6
Cenozoic	Tertiary	Neogene	23
Cenozoic	Tertiary	Paleogene	**66**
Mesozoic		Cretaceous	145
Mesozoic		Jurassic	201
Mesozoic		Triassic	**252**
Paleozoic		Permian	299
Paleozoic	Carbon-iferous	Pennsylvanian	323
Paleozoic	Carbon-iferous	Mississippian	359
Paleozoic		Devonian	419
Paleozoic		Silurian	443
Paleozoic		Ordovician	485
Paleozoic		Cambrian	**541**
		Precambrian	**4600**

North America was roughly divided into thirds: a western portion, an eastern portion, and a vast seaway inundating the center. This seaway stretched from Utah to the western edge of the Midwest and connected the Gulf of Mexico to the Arctic Ocean (*Figure 1.12*). Deposits in western Minnesota and Iowa contain a variety of Cretaceous creatures that lived near the shores of the Western Interior Seaway. The early Cretaceous was the first time during the **Phanerozoic** that the Midwest was north of the tropics, approaching its current position.

Evidence for Pangaea

How do we know that Pangaea (*Figure 1.11*) existed 250 million years ago? Fossil evidence and mountain belts provide some of the clues. For example, the Permian-age fossil plant *Glossopteris* had seeds too heavy to be blown across an ocean. Yet *Glossopteris* fossils are found in South America, Africa, Australia, India, and Antarctica! The mountain belts along the margins of North America, Africa, and Europe line up as well and have similar rock types, an indication that the continents at one time were joined as Pangaea. Despite the discovery of Glossopteris and other geologic evidence, the theory of continental drift was not accepted for decades, until the mechanisms of continental movement were discovered and reformulated under the modern theory of plate tectonics. The supercontinent Pangaea existed for approximately 100 million years, reaching its largest size during the Triassic period. During the Jurassic, the landmass began to fragment into the modern continents, slowly moving toward their present-day positions over the following 150 million years.

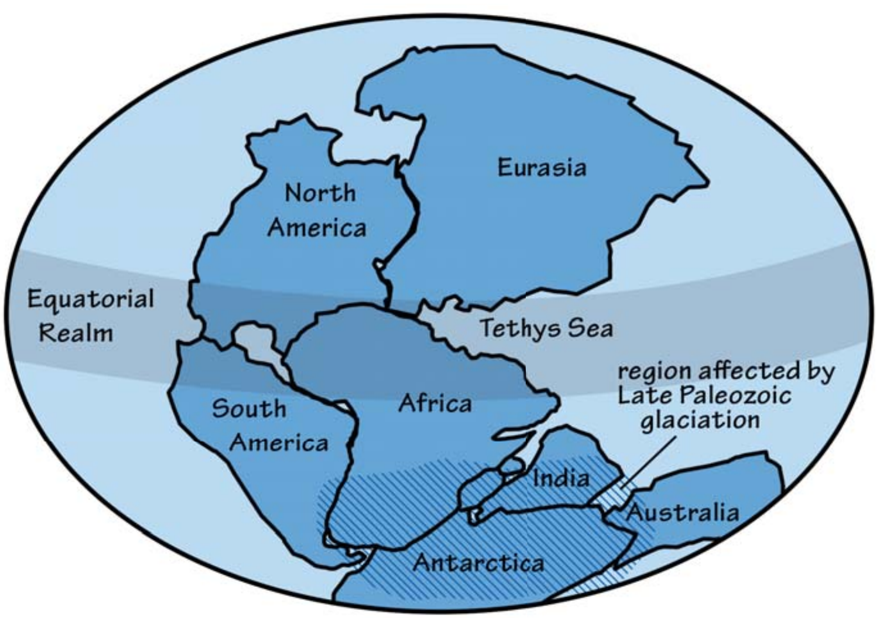
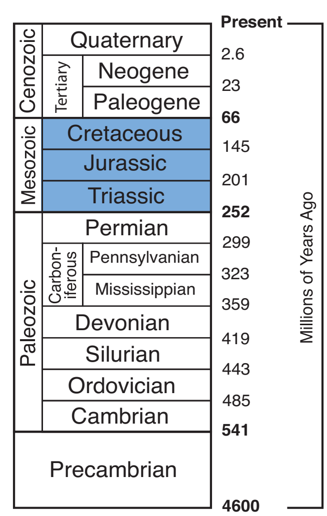


Figure 1.11: Pangaea during the late Paleozoic Era.



Ice Age

glacier • *a body of dense ice on land that does not melt away annually and has sufficient mass to move under its own weight.*

interglacial • *a period of geologic time between two successive glacial stages.*

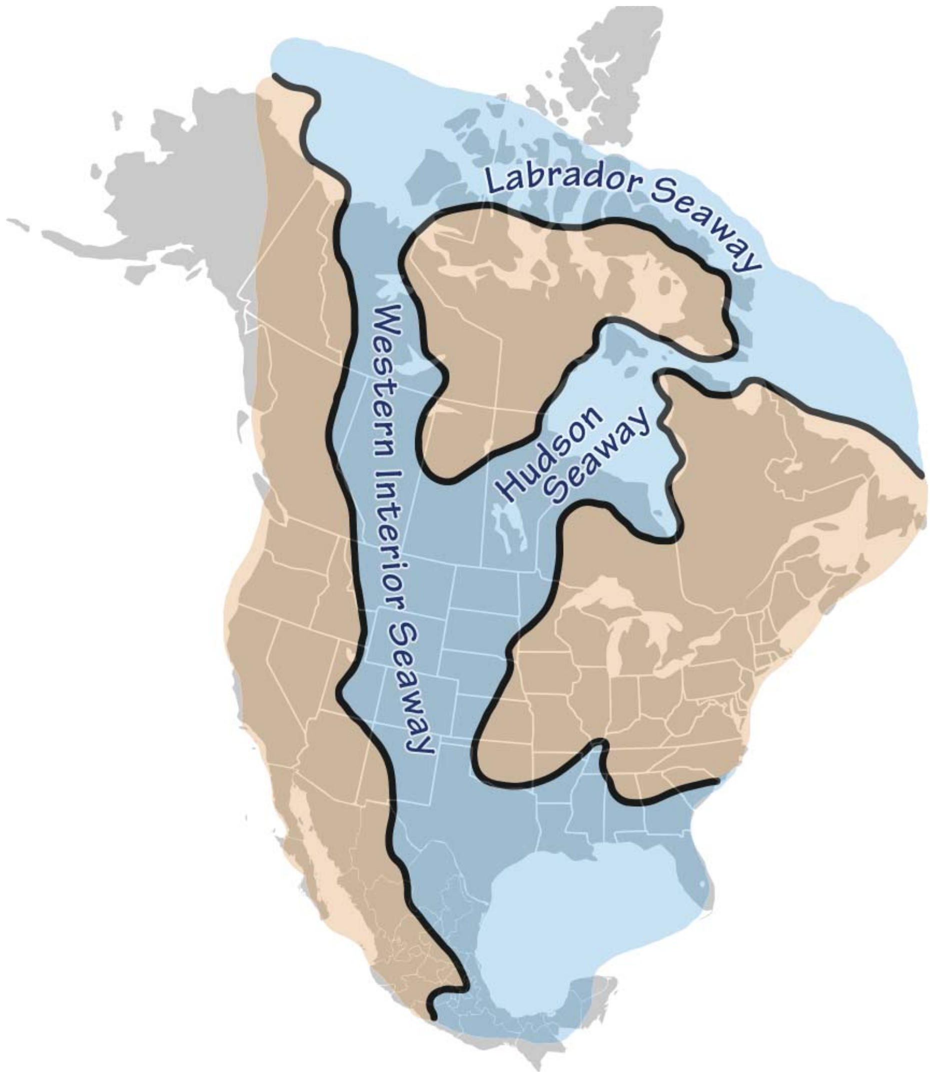
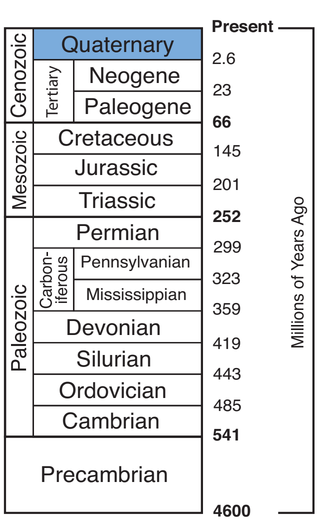


Figure 1.12: Cretaceous continental seas over North America.



The Ice Age: Mountains of Ice

At the start of the **Quaternary** period, about 2.5 million years ago, continental ice sheets began to form in northernmost Canada. Throughout this period, the northern half of North America has been periodically covered by continental **glaciers** (*Figures 1.13, 1.14*). The Quaternary period is divided into two epochs: the **Pleistocene** and **Holocene**. During the Pleistocene, the ice sheets advanced south and retreated north several dozen times. The Holocene Epoch is the most recent (and current) period of retreat, called an **interglacial** interval. The most recent glacial advance in North America reached its maximum extent 21,000–18,000 years ago, while the beginning of the Holocene is considered to be 11,700 years ago, or about 9,700 BCE.

Ice Age

Figure 1.13: Continental glaciers originating in Canada spread across North America, including nearly all of the Midwest, during the Quaternary period.

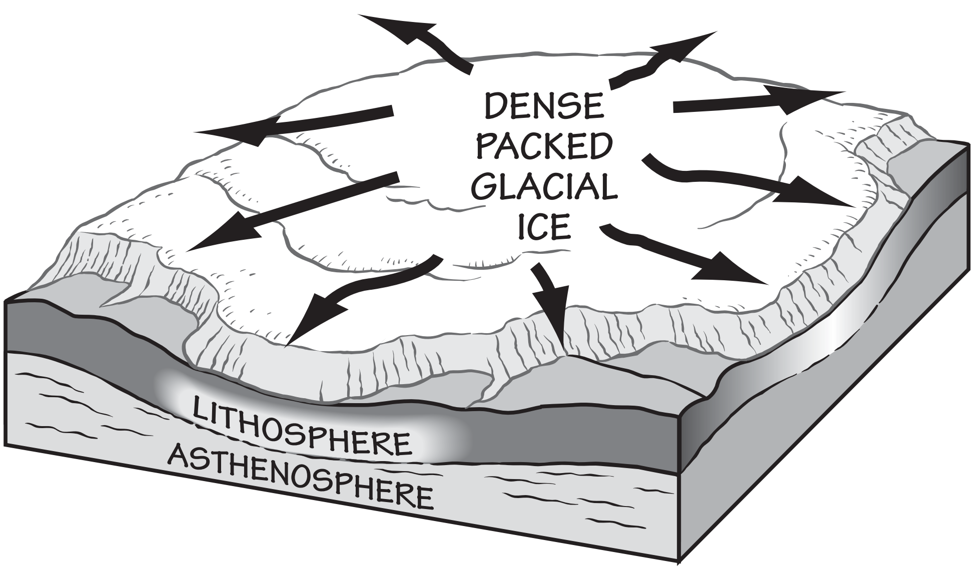
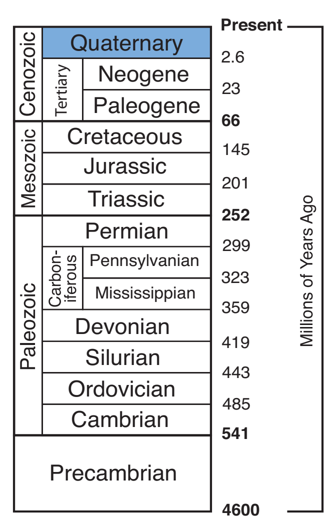


Figure 1.14: As dense glacial ice piles up, a glacier is formed. The ice begins to move under its own weight and pressure.



Geologic History

Ice Age

esker *• a sinuous, elongated ridge of sand and gravel.*

drumlin *• a teardrop-shaped hill of till that was trapped beneath a glacier and streamlined in the direction of the flow of the ice moving over it.*

braided stream *• a stream consisting of multiple, small, shallow channels that divide and recombine numerous times, forming a pattern resembling strands of braided hair.*

kettle *• a lake formed where a large, isolated block of ice became separated from the retreating ice sheet.*

moraine *• an accumulation of unconsolidated glacial debris (soil and rock) that can occur in currently glaciated and formerly glaciated regions, such as those areas acted upon by a past ice age.*

The landscape of the Midwest has been heavily influenced and shaped by the advance and retreat of these glaciers, with the surface of every state shaped by the forces of the moving ice that scraped loose rock, gouged the bedrock beneath, and deposited sediment and water as the ice advanced and retreated (*Figure 1.15*).

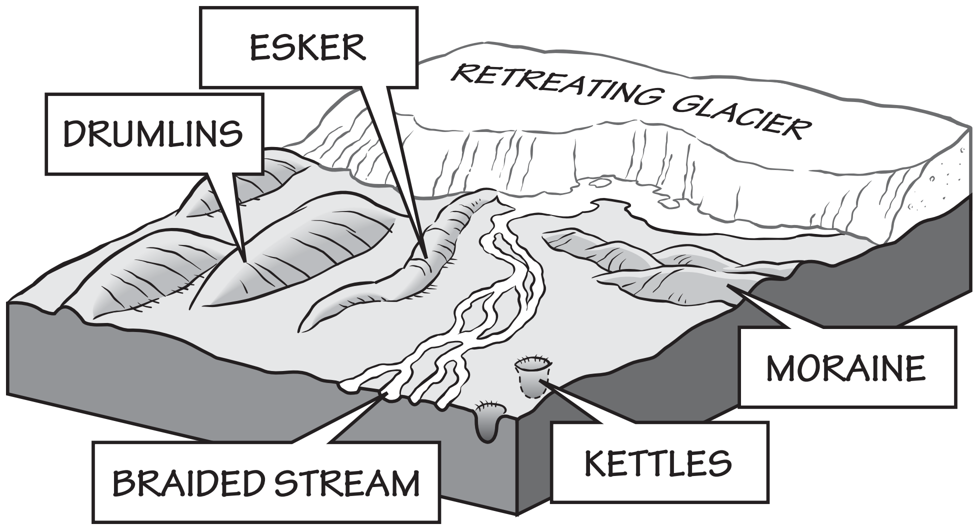


Figure 1.15: Glacial features.

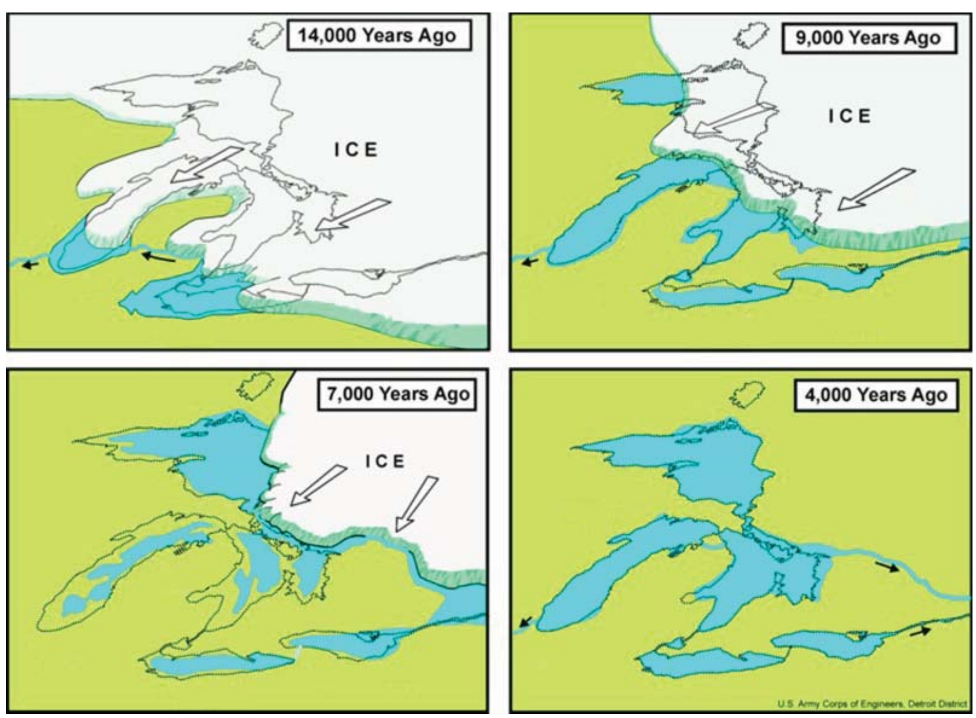


Figure 1.16: The formation of the Great Lakes.

Ice Age

The **Great Lakes** of the Midwest and Northeast were formed during the last great glacial advance some 18,000 years ago. The broad, deep basins of the Great Lakes were flooded as the glaciers receded (*Figure 1.16*). Glacial meltwater poured into these basins, and the ice blocked the drainage that would eventually flow to the northeast via the St. Lawrence River. Once this path was available, the lakes gradually dropped to their current levels.

The ice age continues today, but the Earth is in an interglacial stage, since the ice sheets have retreated for now. The glacial-interglacial cycling of ice ages predicts that the world will return to a glacial stage in the future, but the impacts of human-induced climate change might radically shift the direction of these natural cycles.

With the onset of the Industrial Revolution, significant amounts of greenhouse gases have been released into the atmosphere that contribute to *global warming*.

See Chapter 9: Climate for more details.

Great Lakes • *the largest group of freshwater lakes on Earth (by total surface area and volume), located on the US-Canadian border.*

global warming • *the current increase in the average temperature worldwide, caused by the buildup of greenhouse gases in the atmosphere.*

Resources

Books

Bjornerud, M., 2005, *Reading the rocks: the autobiography of the Earth*. Westview Press: Cambridge, MA.
Fortey, R. A., 2004, *The Earth, an intimate history*. HarperCollins: London.
Hazen, R. M., 2012, *The story of Earth: the first 4.5 billion years, from stardust to living planet*. Viking: New York.
Kious, J. and Tilling, R.I., 1996, *The Dynamic Earth: The Story of Plate Tectonics*. USGS: Washington, DC.
Online at http://pubs.usgs.gov/gip/dynamic/dynamic.html.
Macdougall, J. D., 1996, *A short history of planet Earth: mountains, mammals, fire, and ice*. Wiley: New York.
Morton, J. L., & Morton, J. L., 2004, *Strata: the remarkable life story of William Smith, the father of English geology* (new ed.). Brocken Spectre: Horsham, UK.
Powell, J., 2001, *Mysteries of terra firma: The age and evolution of the Earth*. Free Press: New York.
Winchester, S., & Vannithone, S., 2001, *The map that changed the world: William Smith and the birth of modern geology*. HarperCollins: New York, NY.

Maps

AAPG, 1979, *Great Lakes Geological Highway Map* (Illinois, Indiana, Michigan, Ohio, and Wisconsin). AAPG: Tulsa, OK.
AAPG, 1984, *Northern Great Plains Geological Highway Map* (North Dakota, South Dakota, Iowa, Nebraska, and Minnesota). AAPG: Tulsa, OK.

Websites

The Paleomap Project, Scotese, C.R., http://www.scotese.com.
Paleogeography, Blakey, R. (The older, but free, version of the site.) https://www2.nau.edu/rcb7/RCB.html.
Reconstructing the Ancient Earth, Colorado Plateau Geosystems, Blakey, R. (Blakey's updated site.) http://cpgeosystems.com/index.html.

Chapter 2: Rocks of the Midwestern US

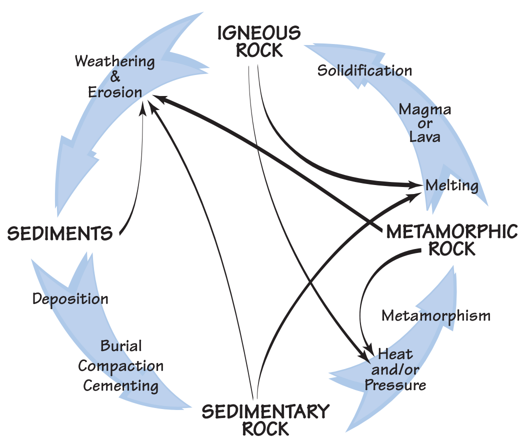
There is an amazing diversity of rocks in the Midwest, but in many places they are hidden by a thick layer of **soil**. They record more than a three-billion-year history of failed **rifts**, **inland seas**, deposition, **erosion**, **uplift**, igneous **intrusions** and **extrusions**, and glacial activity. The different rock types of the Midwest influence its **topography** and tell us where to look for certain **fossils** and natural resources. Each type of rock forms in a particular environment under particular conditions (*Figure 2.1*).

Igneous Rocks of the Midwest

rhyolite	granite
anorthsite	syenite
andesite	diorite
basalt	gabbro
serpentine	

Sediments of the Midwest (not consolidated into rocks)

gravel
sand
silt
clay



Metamorphic Rocks of the Midwest

slate
phyllite
schist
gneiss
marble
quartzite
amphibolite
serpentine

Sedimentary Rocks of the Midwest

iron formation	chert
rock salt	gypsum
limestone	dolomite
argillite	shale
siltstone	sandstone
greywacke	conglomerate

Figure 2.1: The rock cycle.

soil • *the collection of natural materials that collect on Earth's surface, above the bedrock.*

uplift • *upward movement of the crust due to compression, subduction, or mountain building.*

intrusion • *a plutonic igneous rock formed when magma from within the Earth's crust escapes into spaces in the overlying strata.*

extrusion • *an igneous rock formed by the cooling of lava after magma escapes onto the surface of the Earth through volcanic craters and cracks in the Earth's crust.*

topography • *the landscape of an area, including the presence or absence of hills and the slopes between high and low areas.*

CHAPTER AUTHORS

Richard A. Kissel
Alex F. Wall

2 Rocks

A rock is a naturally occurring solid substance composed of one or more **minerals**. Broadly speaking, there are three types of rock: sedimentary, igneous, and metamorphic. The rock cycle describes the many processes that produce rocks, while also illustrating the differences between rock types. One type of rock may be transformed into either of the other types, often with the help of other parts of the Earth **system**, including **plate tectonics**, the water cycle, and biological processes, to name a few.

Sedimentary rock is formed by the **lithification** of sediments (e.g., unconsolidated mineral and organic particles created through the **weathering** of other materials, like rock and organic matter). Typically, sediments are created in an environment where erosion is a dominant force, and they are transported by wind, water, or ice to a depositional environment. For example, a rushing river can wear away the rock it is flowing over, and it also has enough energy to transport the resulting sediment to a lake. The water slows down, losing energy, and deposits the sediment on the bottom of the lake.

Sedimentary Rock Classification

Sedimentary rocks are classified by their sediment size or their mineral content, and each one reveals the story of the depositional environment where its sediments accumulated and were eventually lithified.

Sediment size (decreasing size)	Sedimentary rock	Environment of deposition
gravel	conglomerate	river beds, mountains
sand	sandstone	beaches, river sand bars, sand dunes
sand, silt, clay	graywacke	continental shelf
silt	siltstone	quiet water
clay	shale	very quiet water, lakes, swamps, shallow oceans

Lithification of sediments occurs in several ways. As sediments build up and lower layers are buried more deeply, they may become permeated by water. Minerals dissolved in the water are precipitated, filling the spaces between particles and cementing them together. This cementation helps to form many common sedimentary rocks, such as **shale**, **sandstone**, and most **conglomerates**. The evaporation of water may also form sedimentary rocks by leaving behind **evaporites** (previously-dissolved minerals) like **salt**. Deposits of calcium carbonate, usually created through the accumulation of calcium carbonate skeletal material (such as clams and corals), form the sedimentary rocks **limestone** and **dolostone**.

Review

mineral • *a naturally occurring solid with a specific chemical composition and crystalline structure.*

plate tectonics • *the way by which the plates of the Earth's crust move and interact with one another at their boundaries.*

lithification • *the process of creating sedimentary rock through the compaction or sementation of soft sediment.*

weathering • *the breakdown of rocks by physical or chemical means.*

shale • *a dark, fine-grained, laminated sedimentary rock formed by the compression of successive layers of silt- and clay-rich sediment.*

sandstone • *sedimentary rock formed by cementing together grains of sand.*

conglomerate • *a sedimentary rock composed of multiple large and rounded fragments that have been cemented together in a fine-grained matrix.*

Rocks 2

Igneous rocks form from the cooling of **magma** (molten rock underground) or **lava** (molten rock at the Earth's surface). When magma cools slowly underground, it has time to produce large crystals that are visible to the naked eye. Rocks that form in this manner, such as **granite**, are called **plutonic**. Molten rock that breaks through the **crust** to the surface (usually through a volcano) cools quickly as its heat escapes to the **atmosphere**. This produces **volcanic** or **glassy** rocks with very tiny crystals or no crystals at all.

Igneous Rock Classification

Igneous rocks differ not only in their cooling rates and subsequent crystal sizes, but also in their chemical compositions. Rocks found in continental crust, such as granite, have high silica content and low iron and magnesium content. They are light in color and are called *felsic*. Rocks found in oceanic crust, like basalt, are low in silica and high in iron and magnesium. They are dark in color and are called *mafic*.

Crystal size	Felsic	Intermediate	Mafic	Ultramafic
large (plutonic)	granite	diorite	gabbro	peridotite
small (volcanic)	rhyolite	andesite	basalt	--
none (glassy)	obsidian, tuff, pumice	obsidian	obsidian	--

Metamorphic rocks form from pre-existing sedimentary, igneous, and metamorphic rocks that are exposed to increased temperature and pressure as a result of plate movements, very deep burial, or contact with molten rock or superheated water. The minerals within the rock recrystallize and realign, forming a much harder rock. This process destroys features in the rock that would have revealed its previous history, transforming it into an entirely new form.

See Chapter 1: Geologic History for a description of the mountain building episodes that created much of the metamorphic rock, and read about the rift valley that created many of the igneous rocks as a result of magma intrusions and volcanic events.

Review

salt • *a mineral composed primarily of sodium chloride (NaCl).*

limestone • *a sedimentary rock composed of calcium carbonate ($CaCO_3$).*

dolostone • *a rock (also known as dolomitic limestone and once called magnesian limestone) primarily composed of dolomite, a carbonate mineral.*

plutonic rock • *a large body of intrusive igneous rock that formed under the Earth's surface through the slow crystallization of magma.*

crust • *the uppermost, rigid outer layer of the Earth, composed of tectonic plates.*

atmosphere • *a layer of gases surrounding a planet.*

glassy rock • *a volcanic rock that cooled almost instantaneously, resulting in a rock with tiny crystals or no crystals at all.*

2

Rocks

Review

sand • *rock material in the form of loose, rounded, or angular grains, and formed as a result of the weathering and decomposition of rocks*

iron • *a metallic chemical element (Fe).*

ore • *a type of rock that contains minerals with valuable elements, including metals, that are economically viable to extract.*

coal • *a combustible, compact black or dark-brown carbonaceous rock formed by the compaction of layers of partially decomposed vegetation.*

gypsum • *a soft sulfate mineral that is widely mined for its use as fertilizer and as a constituent of plaster.*

aquifer • *a water-bearing formation of gravel, permeable rock, or sand that is capable of providing water, in usable quantities, to springs or wells.*

Metamorphic Rock Classification

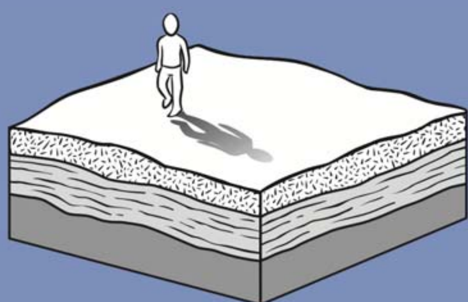
Metamorphic rocks are classified differently depending on the protolith (parent rock) they are made from. The following chart shows common rocks and the metamorphic rocks that they can become.

Parent rock	Metamorphic rocks
shale	slate, phyllite, schist, gneiss (in order of increasing heat and pressure)
granite	gneiss
sandstone	quartzite
limestone	marble
peridotite	serpentinite

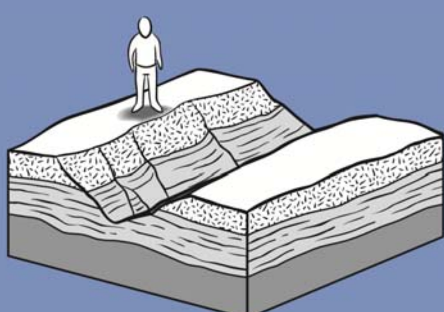
As you read through this chapter, keep in mind that once you understand the geologic events that have affected a given region, you should be able to predict the type of rocks found in that area. The Midwest has seen many dramatic changes, which are reflected in the diversity of the rocks found throughout the area. The oldest rocks of the Midwest formed more than three billion years ago from **sand** deposits, but being buried and "baked" for hundreds of millions of years metamorphosed them. Many of these rocks are largely composed of **iron**-rich minerals and are therefore, not surprisingly, mined for **ore**. Metamorphic rocks make up the majority of the bedrock of the Superior Upland. Sedimentary rocks, often fossiliferous, are found in every state. They represent the overwhelming majority of bedrock in the Midwest and include some important natural resources such as **coal**, salt, **gypsum**, and limestone, and some of their layers serve as **aquifers**. Igneous rocks, while not as abundant, are also widespread.

Why do we see different kinds of rocks at the surface?

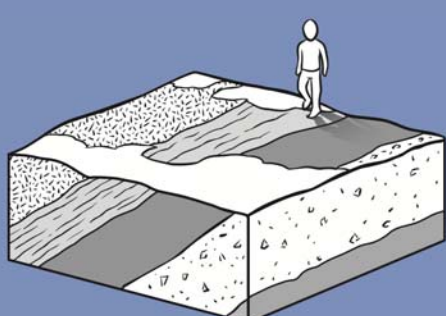
As you walk across the surface of the Earth, you will observe an amazing variety of rock types. If all rocks were flat-lying layers and there was no erosion, then we would only see one type of rock exposed on the surface. Often, however, rocks have been worn away (eroded), and the underlying layers are now exposed at the surface. Layers of rock may also be tilted, folded, or faulted to reveal the underlying rocks at the surface.



When rocks are flat-lying layers and there is no erosion, folding, or faulting, the person walking across the surface sees only one rock type.



When rocks are worn away (often by streams), the person walking across the surface sees the underlying layers of rock exposed.



When rocks are folded or tilted, the person walking across the surface sees several layers of rock exposed.

2 Rocks

Region 1

Rocks of the Superior Upland

Region 1

The Superior Upland is the midwestern portion of the **Canadian Shield**, which extends from Minnesota to Nunavut and Greenland to New York. The shield as a whole represents the first portion of the North American continent to have emerged above sea level.

The Canadian Shield is the exposed portion of a larger **craton**. Its extremely old, hard rock was resistant to the weathering of repeated glacial advances, compared to the softer sedimentary strata to the south in the Central Lowland region, and this resulted in a higher, more rugged geographic upland.

The oldest rock in the region, and indeed the United States, is the **Morton Gneiss**. It was initially formed 3.6 billion years ago, during the **Archean** Eon. For hundreds of millions of years, magma welled up from the **mantle**, creating the foundation of granite below the surface, a rock composed mainly of **quartz**, **mica**, and **feldspar**. These minerals have densities that are lower than both those of oceanic crust and the average density of the mantle, allowing this lighter rock to essentially float on the upper portion of the **lithosphere**. The lithosphere, in turn, is pushed around on the **asthenosphere**, which effectively acts as a conveyor belt (*Figure 2.2*).

A *craton* can be thought of as the heart of a continent—it is typically the oldest, thickest, and most stable part of the bedrock. It is also usually far from the margins of tectonic plates, where new rock is formed and old destroyed. This very mature rock has usually been metamorphosed at some point during its history, making it very hard.

Over its exceedingly long history, this rock was metamorphosed, resulting in alternating bands that are distinctive of **gneiss**. Upwelling continued for hundreds of millions of years, injecting more and more magma into the region, which helped to metamorphose existing granite into gneiss. This magma would then cool to form yet more granite. This cycle continued until at least 2.7 billion years ago, though subsequent erosion could have erased rocks that are younger still. The result is a sequence of metamorphic and igneous rocks spanning nearly a billion years, remnants of which are found in northeastern Minnesota, northern Wisconsin, and parts of Michigan's Upper Peninsula.

Unless rock layers are overturned, older rocks are found at the bottom and younger rocks are found at the top of a sedimentary sequence. This is known as the *Law of Superposition*.

One of the chief causes of the metamorphosis of the ancient granites of the Superior

Canadian Shield • *the stable core of the North American continental landmass, containing some of the oldest rocks on Earth.*

Archean • *a geologic time period that extends from 4 billion to 2.5 billion years ago.*

quartz • *the second most abundant mineral in the Earth's continental crust (after feldspar), made up of silicon and oxygen (SiO_2).*

mantle • *the layer of the Earth between the crust and core.*

mica • *a large group of sheetlike silicate minerals.*

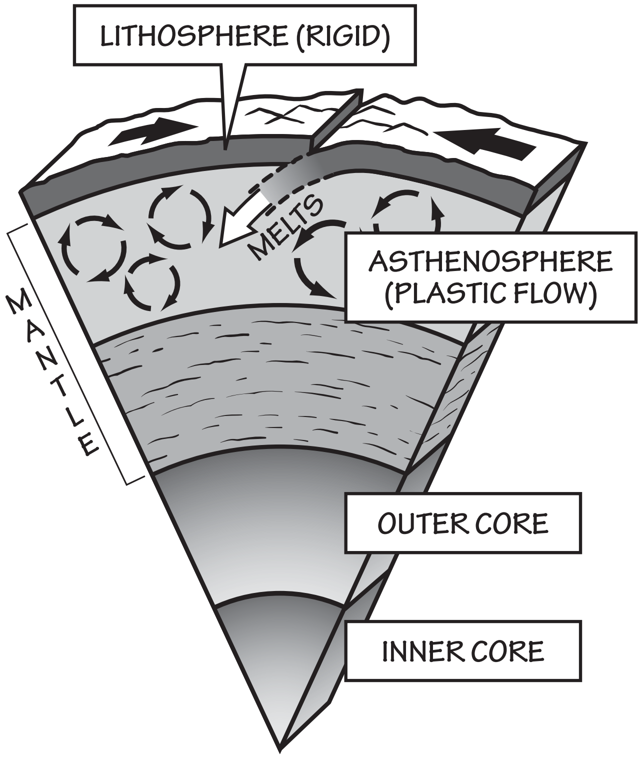


Figure 2.2: The layers of the Earth include the rigid crust of the lithosphere, which is constantly moving over the plastically flowing asthenosphere.

Upland was the collision of the Superior Province with the Minnesota River Valley **terrane** around 2.7 billion years ago. This triggered a period of intense mountain building, called an **orogeny**, as the two small continents pressed on each other, causing their rock to buckle, which forced some of the rock up as mountains and some down to be subjected to even greater pressure and heat (*Figure 2.3*).

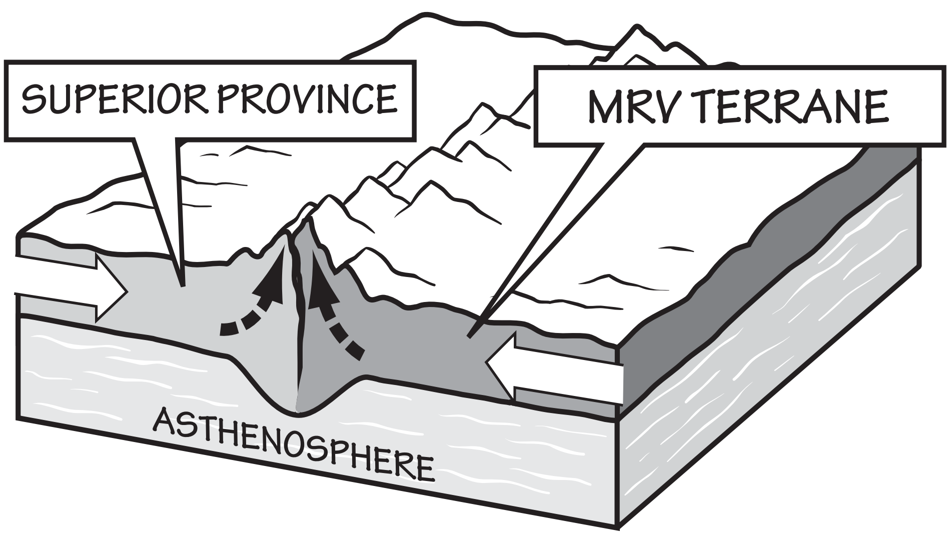


Figure 2.3: The Superior Province collides with the Minnesota River Valley (MRV) terrane, crumpling the margins of both continents.

Region 1

feldspar • *an extremely common, rock-forming mineral found in igneous, metamorphic and sedimentary rocks.*

lithosphere • *the outermost layer of the Earth, comprising a rigid crust and upper mantle broken up into many plates.*

asthenosphere • *a thin semifluid layer of the Earth, below the outer rigid lithosphere, forming the upper part of the mantle.*

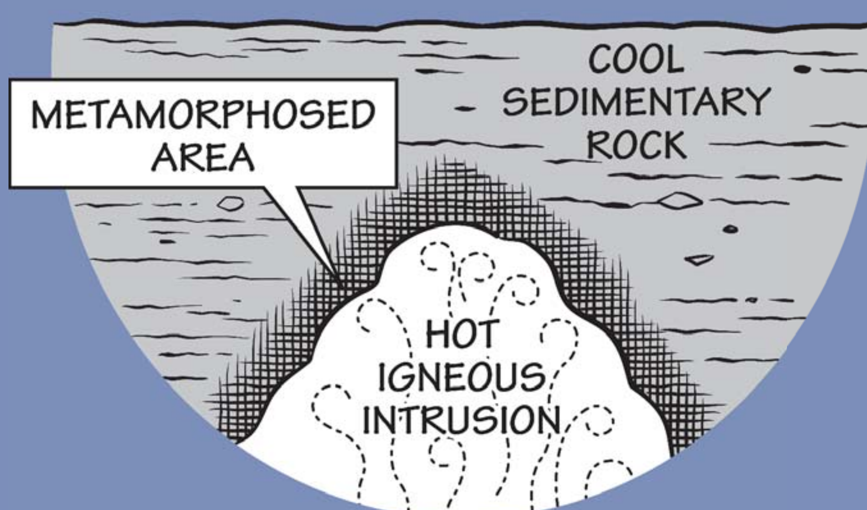
gneiss • *a metamorphic rock that may form from granite or layered sedimentary rock such as sandstone or siltstone.*

terrane • *a piece of crustal material that has broken off from its parent continent and become attached to another plate.*

What happens to a rock when it is metamorphosed?

When rocks are subjected to high enough temperatures or pressures, their characteristics begin to change. The weight of overlying rock can cause minerals to realign perpendicularly to the direction of pressure, layering them in a pattern called foliation, as exemplified in gneiss and schist. Recrystallization, as seen in marble and quartzite, results as rock is heated to high temperatures, and individual grains reform as interlocking crystals, making the resulting metamorphic rock much harder than its parent rock.

Contact metamorphism describes a metamorphic rock that has been altered by direct contact with magma. Changes that occur due to contact metamorphism are greatest at the point of contact. The further away the rock is from the point of contact, the less pronounced the change.



Regional or dynamic metamorphism describes a metamorphic rock that has been altered due to deep burial and great pressure. This type of metamorphic rock tends to occur in long belts. Different types of metamorphic rock are created depending on the gradients of heat and pressure applied.

Region 1

After a 200-million-year gap, the rock record picks up in the **Proterozoic** with 2.4-billion-year-old quartz sandstones and dolostones, which were deposited in a shallow marine environment. In some cases, these sedimentary rocks preserve **ripple marks** and **stromatolites**. Ancient glacial sediments are also found in the Superior Upland, evidence of the Huronian glaciation, which is thought to be the first-ever **ice age** on Earth. Following a gap of about 100 million years from 2.2 to 2.1 billion years ago, the sandstones reappeared and extended to 1.9 billion years ago.

Stromatolites

Stromatolites are regularly banded accumulations of sediment created by the trapping and cementation of sediment grains in bacterial mats (especially photosynthetic cyanobacteria). Cyanobacteria emit a sticky substance that binds settling clay grains and creates a chemical environment leading to the precipitation of calcium carbonate. The calcium carbonate then hardens the underlying layers of bacterial mats, while the living bacteria move upward so that they are not buried. Over time, this cycle of growth combined with sediment capture creates a rounded structure filled with banded layers.

Stromatolites peaked in abundance around 1.25 billion years ago, and likely declined due to predation by grazing organisms. Today, stromatolites exist in only a few locations worldwide, such as Shark Bay, Australia. Modern stromatolites form thick layers only in stressful environments, such as very salty water, that exclude animal grazers. Even though there are still modern stromatolites, the term is often used to refer specifically to fossils. For more information, see Chapter 3: Fossils.

Proterozoic • *a geologic time interval that extends from 2.5 billion to 541 million years ago.*

ripple marks • *surface features created when sediment deposits are agitated, typically by water currents or wind.*

ice age • *a period of global cooling of the Earth's surface and atmosphere, resulting in the presence or expansion of ice sheets and glaciers.*

2 Rocks

Region 1

Beginning about 2 billion years ago, thick and increasingly widespread **banded iron formations** also appear in the Superior Upland. As with much of the Canadian Shield, most of this rock has been metamorphosed to some degree: sandstones have become **quartzite**, **dolomites** have become **marble**, and banded iron formations have been deformed and folded. The Penokean Orogeny, from 1.9 to 1.8 billion years ago, transformed the area into a primarily erosional environment, so few rocks are preserved from this time. The tectonic activity did, however, force some magma up near the surface where it cooled into the granite found in northeastern Wisconsin and the Upper Peninsula.

See Chapter 1: Geologic History for more information on the Penokean Orogeny and Midcontinental Rift.

About 1.1 billion years ago, a major event in the history of the Superior Upland took place when the North American continent began to split apart along the Midcontinental Rift. It is thought that a **hot spot** in the mantle caused a great upwelling of magma, centered near where Lake Superior is today. Over the course of 20 million years, the pressure from below caused the crust to spread in all directions, eventually thinning the Canadian Shield considerably.

The rift eventually failed, but it left its mark on the region. Huge volumes of lava burst through to the surface, forming deposits of **basalt**. Magma of the same composition cooled underground to form gabbro. The tectonic activity also broke up many of these new rocks, producing large amounts of sediment that were preserved as sandstones and conglomerates. An age of 1.1 billion years is old even for a rock, yet this is currently the youngest exposed bedrock in the Superior Upland. On the southern and western shores of Lake Superior, one can see volcanic sequences, sandstones, and the Copper Harbor Conglomerate, evidence of the processes occurring during rifting (*Figure 2.4*). While the rocks produced by the Midcontinental Rift are only found at the surface around Lake Superior, now-buried legs of the failed rift extend north into Canada, southeast nearly to Lake Erie, and southwest all the way to Kansas (*Figure 2.5*).

In some areas, water and carbon dioxide that had been trapped in the magma formed bubbles. After the lava cooled, these bubbles were slowly filled by mineral-rich water flowing through them, depositing layers of fine quartz crystals and enough iron to color the resulting rocks red. Lake Superior agate, the Minnesota state gemstone, was formed in this manner.

banded iron formation • *rocks with regular, alternating thin layers of iron oxides and either shale or silicate minerals.*

quartzite • *a hard metamorphic rock that was originally sandstone.*

dolomite • *a carbonate mineral, consisting of calcium magnesium carbonate ($CaMg(CO_3)_2$).*

marble • *a metamorphic rock composed of recrystallized carbonate minerals, most commonly calcite or dolomite.*

hot spot • *a volcanic region thought to be fed by underlying mantle that is anomalously hot compared with the mantle elsewhere.*

Region 1

basalt • *an extrusive igneous rock, and the most common rock type on the surface of the Earth.*

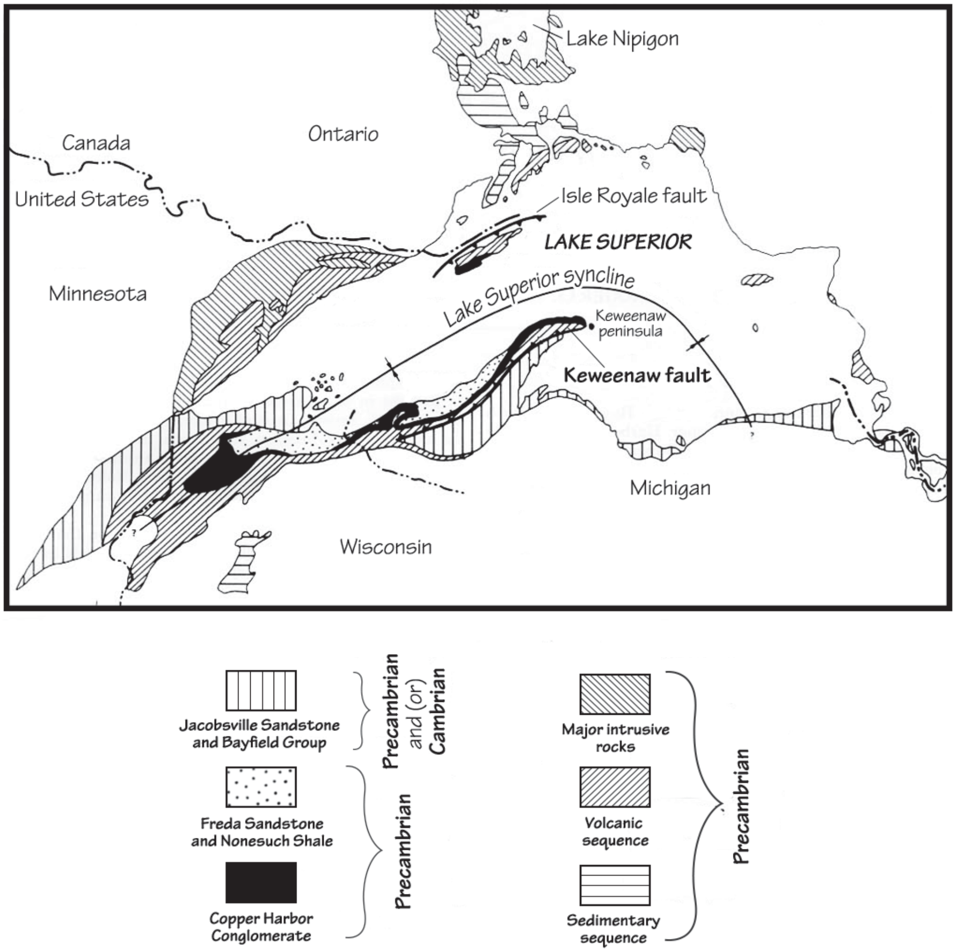


Figure 2.4: The geology around Lake Superior is perhaps the most complex in the Midwest. A variety of sedimentary, igneous, and metamorphic rocks representing more than a billion years of history are found within a few kilometers of each other.

2 Rocks

Regions 1–2

Paleozoic • *a geologic time period that extends from 541 to 252 million years ago.*

Mesozoic • *a geologic time period that spans from 252 to 66 million years ago.*

rhyolite • *a felsic volcanic rock high in abundance of quartz and feldspar.*

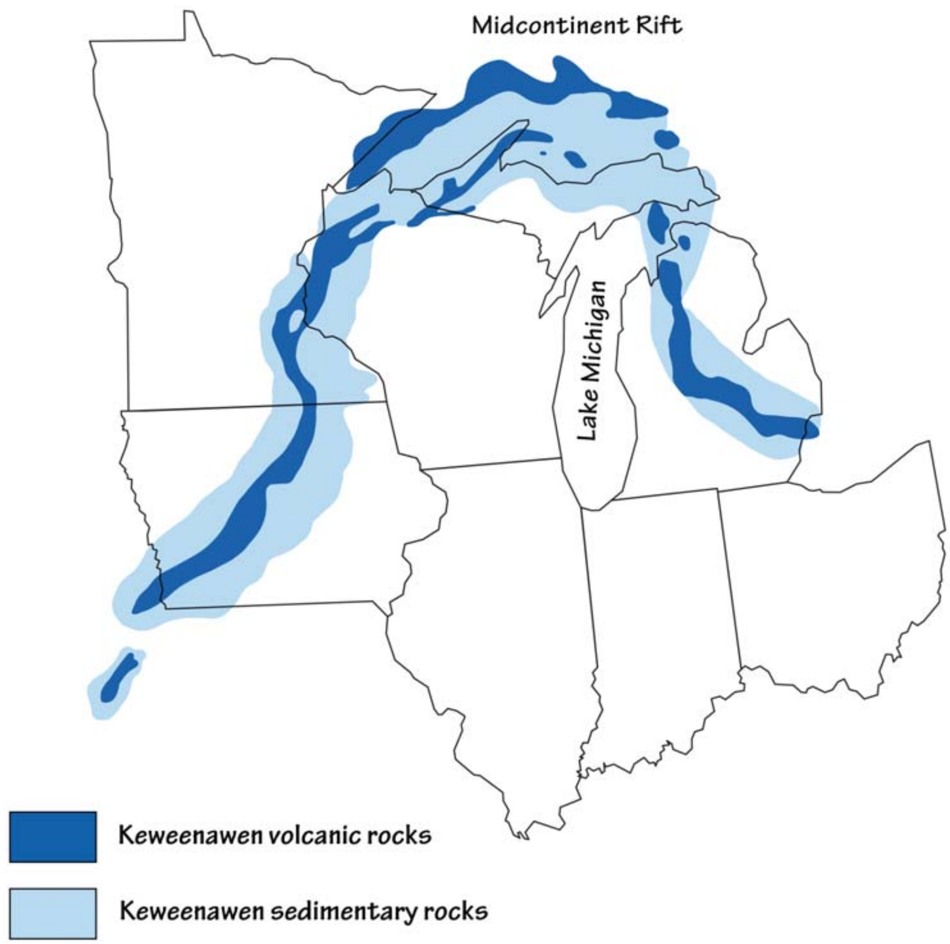


Figure 2.5: The scars of the Midcontinental Rift span nearly the entire Midwest, but are buried deep below the surface in most of the region. The inset box represents the outcrops of Midcontinental Rift rocks found at the surface.

Rocks of the Central Lowland
Region 2

While most of the Central Lowland's bedrock is **Paleozoic** in age, and some is **Mesozoic**, there is a single exposure that is as much as 1.6 billion years old. Both **rhyolite** and the pink to purple quartzite (an extremely hard metamorphic rock) (*Figure 2.6*) found at Baraboo, Wisconsin stand out above the flatter and much younger landscape around it. At just 40 kilometers (25 miles) long and 16 kilometers (10 miles) wide, it is not an extensive range, yet, as it is more than a billion years older than any other rock in the region, it is extremely significant. Based on the ripple marks that persist in many of the quartzite layers, it has been determined that this rock was deposited during the Proterozoic eons on the shores of an ancient sea.

Region 2

Cambrian • *a geologic time period lasting from 541 to 485 million years ago.*

Driftless Area • *a region that did not experience glaciation, located in parts of southwestern Wisconsin, eastern Minnesota, and northeastern Illinois and Iowa.*

Ordovician • *a geologic time period spanning from 485 to 443 million years ago.*

bentonite • *a clay, formed from decomposed volcanic ash, with a high content of the mineral montmorillonite.*

Figure 2.6: The Baraboo Quartzite is the remains of a 1.6-billion-year-old shoreline that, in its incredibly long history, has been tilted nearly vertical.

The vast majority of bedrock in the Central Lowland is sedimentary and was formed during the Paleozoic. These rocks were primarily formed in shallow seas that covered great portions of North America at different times during its history.

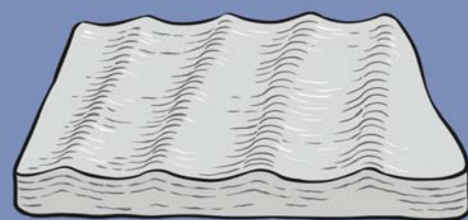
See Chapter 6: Glaciers for more on the Driftless Area.

Cambrian age sandstones and shales are exposed around the Mississippi River Valley through the **Driftless Area**, or Paleozoic Plateau, near where the borders of Iowa, Illinois, Minnesota, and Wisconsin converge, and they extend in a band northeast across central Wisconsin to Michigan's Upper Peninsula. These rocks are often fossiliferous, but they are covered by glacial material in many areas. Since the sea level was quite high at this time, and most of the Midwest was underwater, much of the rock formed is fine-grained.

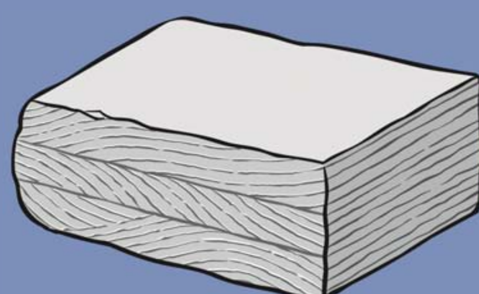
By the **Ordovician**, reef ecosystems had become more extensive, forming expanses of limestone, dolostone, and limey (i.e., calcium carbonate-rich) shales. Occasional **bentonite** deposits may be found in Minnesota and Iowa, the result of volcanic ash blown from other parts of the continent. In the western part of the region, the Ordovician deposits overlie, and may be found generally southward of, the Cambrian deposits mentioned above. Ordovician rocks are also found around the southern part of Indiana and Ohio's shared border. While the rocks here are similar in composition, the sediment came primarily from the Taconic Mountains to the northeast.

Sedimentary Structures

Sedimentary rocks often reveal the type of environment in which they formed by the presence of structures within the rock. Sedimentary structures include ripple marks, cross-beds, mud cracks, and even raindrop impressions. Consider the type of environments in which you see these sedimentary structures today in the world around you.



Ripple marks suggest the presence of moving water (though wind can also create ripples and even dunes). Mud cracks indicate that the sediment was wet but exposed to the air so that it dried and cracked.



Cross-beds form as flowing water or wind pushes sediment downcurrent, creating thin beds that slope gently in the direction of the flow as migrating ripples. The downstream slope of the ripple may be preserved as a thin layer dipping in the direction of the current, across the natural flat-lying repose of the beds. Another migrating ripple will form an additional layer on top of the previous one.

Why are there different sedimentary rocks in different environments?

Most sedimentary rock deposited in underwater settings originated from material eroded on land and washed down streams or rivers before settling to the bottom of a body of water. Intuitively, the faster the water is moving, the larger the sediments it may carry. As the water slows down, the size of sediments it can carry decreases. Furthermore, the farther the grains of sediment are carried, the more rounded they become as they are tumbled against each other. In this way, rivers emptying into a sea are effectively able to sort sediment. Near the mouth of the river, the water is still relatively high-energy, dropping only the largest pieces; farther from the shore, the dropped particles get smaller. Therefore, conglomerates and sandstones are interpreted to have been deposited on or near the shore, siltstone farther from the shore, and shale in deep water quite far from shore where currents are slow enough that even very tiny particles may settle.

Increased distance from shore and water depth can also reduce the presence of oxygen in the water, causing organic material to decompose less completely. This causes more carbon-rich, darker rocks, including some that contain exploitable fossil fuels, to form in these areas. Limestone is made primarily of calcium carbonate, the components of which are dissolved in the water. Living creatures, like coral and foraminifera, take those components out of the water to make calcium carbonate shells, which, after the creatures die, accumulate to become limestone. This process happens over much of the seafloor, yet if more than 50% of the sediment being deposited is from another source, the rock that forms is, by definition, not limestone. Furthermore, these shelled creatures tend to fare better in clear water, so limestone tends to form far from other sources of sediment.

Region 2

Silurian *• a geologic time period spanning from 443 to 419 million years ago.*

capstone *• a harder, more resistant rock type that overlies a softer, less resistant rock.*

Great Lakes *• the largest group of freshwater lakes on Earth (by total surface area and volume), located on the US-Canadian border.*

Devonian *• a geologic time period spanning from 419 to 359 million years ago.*

Mississippian *• a subperiod of the Carboniferous, spanning from 359 to 323 million years ago.*

Similar processes continued through the **Silurian** and helped form many of the dominant ridges around the northwest of Lake Michigan, an arc through Lake Huron, and, most famously, the foundation of Niagara Falls in the east. The top of the escarpment is a hard dolostone, which protects the softer shales beneath it from erosion. This resistant **capstone** helps define the shapes of the basins of the **Great Lakes**, but these rock formations are also found beneath the surface in parts of Illinois, Michigan, and Ohio (*Figure 2.7*).

Figure 2.7: The Niagara Escarpment, shown in blue, creates such a distinct topographic and geologic boundary that the Great Lakes Michigan, Huron, and Ontario owe large portions of their shorelines to its influence.

In the east, Ohio and Indiana were sediment-starved as tens of millions of years of weathering made the Taconic Mountains low and mature, allowing reefs to cover the area and produce thick beds of limestone. West of Indiana, limestones were also deposited extensively, and often subsequently converted to dolostone. Relatively deep basins in the Upper Peninsula were surrounded by reefs that reduced circulation. This resulted in increased salinity in the basin, leading to the deposition of salt and gypsum on the basin floor. Evaporation in shallow basins in Michigan and northern Ohio caused a similar process to occur, evidenced by the salt and gypsum deposits also present there.

The **Devonian** saw the formation of the Acadian Mountains in the east, which provided a new source of sediment to Ohio, Indiana, and Michigan. Because of this, rocks found in these states that date from this time are mostly shales and mudstones. Limestone and dolostone dominate the swath of Devonian rock in eastern Iowa, spilling over into Minnesota, Illinois, and Wisconsin.

Changes in sea level during the **Mississippian** and **Pennsylvanian** periods turned much of the Midwest into dry land at various times. Sequences of familiar marine rocks began to give way to sediments deposited near shore, in extensive deltas, and in freshwater settings. Sandstones and mudstones dominate the bedrock from these periods, as well as coal formed from vast volumes of vegetation from the swampy forests covering the region.

For most of the Central Lowland, the rock record stops here—if much rock formed afterward, it was subsequently eroded away. In western Minnesota and Iowa, following a 240-million-year gap, rocks of the **Cretaceous** period are found. The oldest of these are sandstones deposited by rivers running towards the Western Interior Seaway. As time went on, the shores of the seaway moved eastward, laying down muddier sediment and finally limey shales, which sometimes contain marine fossils. Two isolated outcrops in Illinois contain sandstone and mudstone deposited by rivers flowing into an arm of the ancient Gulf of Mexico, called the Mississippi Embayment. One of these outcrops is in the Central Lowland, near Quincy, Illinois, while the other is at the southern tip of the state and is part of the **Inland Basin**.

Pennsylvanian • *a subperiod of the Carboniferous, spanning from 323 to 299 million years ago.*

Cretaceous • *a geologic time period spanning from 144 to 66 million years ago.*

Rocks of the Inland Basin

Region 3

Mississippian Rocks

The Inland Basin is a large geophysical province, and only a small portion of it exists in the Midwest in eastern Ohio, southern Indiana, and Illinois. Here, only a relatively narrow slice of time is represented in the rocks. During the Mississippian and Pennsylvanian periods, the limestones, sandstones, and shales of this region formed. Except for a small band of Cretaceous sedimentary rock in extreme southern Illinois, rock from no other period is found here.

Inland sea **may sound like a contradiction in terms, but there is a very simple, yet important, distinction that differentiates it from other seas: an inland sea is located on continental crust, while other seas are located on an oceanic crust. An inland sea may or may not be connected to the ocean. For example, Hudson Bay is on the North American plate and connects to the Atlantic and Arctic Oceans, while the Caspian Sea is on the European plate but does not drain into any ocean at all.**

During the Mississippian and Pennsylvanian periods, the Inland Basin region was an inland sea environment, with sediment being shed into the basin from the Acadian highlands to the east (*Figure 2.8*). Gradually, the amount of sediment settling into the basin declined, as the mountains were weathered down. The shoreline of the inland sea moved back and forth across the basin as the sea level rose and fell during this period. The

climate • a description of the average temperature, range of temperature, humidity, precipitation, and other atmospheric/hydrospheric conditions a region experiences over a period of many years (usually more than 30).

peat • an accumulation of partially decayed plant matter.

fluctuating water levels created alternating sequences of marine and non-marine sedimentary rocks, known as **cyclothems**, that are characterized by their light and dark colors (*Figure 2.9*). Limestones were also forming in the inland sea in areas receiving very little sediment. The Midwest was still located near the equator at this time, and the warm **climate** created lush vegetation. Large swamp forests covered the shorelines, and plant remains accumulated as thick piles of **peat**. Buried by sediment and more vegetation, the peat was compressed. Over time and through continued burial, the peat was transformed into layers of coal. The Pennsylvanian and Mississippian rocks of the Inland Basin region are the result of shorelines advancing and retreating, creating alternating bands of marine sandstone or mudstone and terrestrial coal deposits, respectively.

See Chapter 1: Geologic History for more information on the position of the Midwest during the Paleozoic.

Figure 2.8: Much of the Midwest region was covered by an inland sea during the Mississippian and Pennsylvanian periods, with sediment being brought in from the erosion of the Acadian highlands to the east.

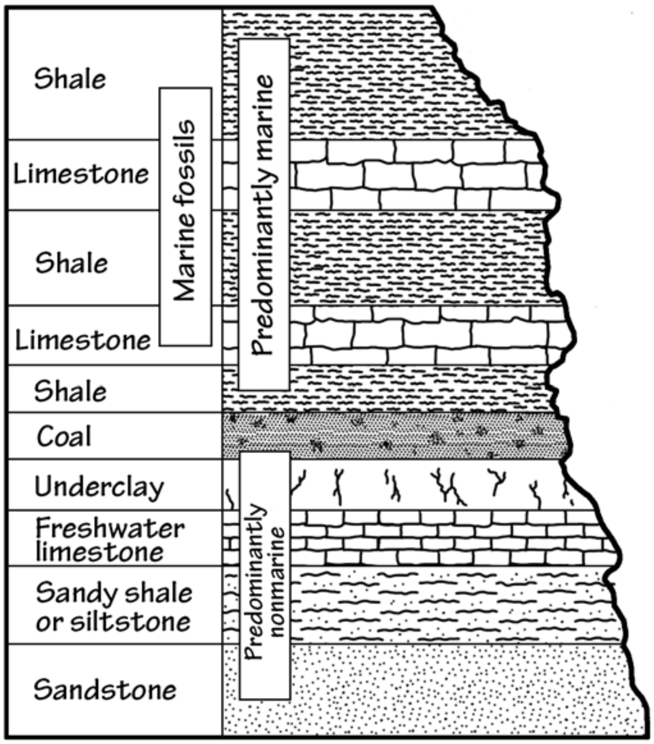


Figure 2.9: An example of a cyclothem.

As mentioned above, a portion of the Inland Basin in the southern tip of Illinois is made up of the second isolated outcrop of sandstone and mudstone from the Mississippi Embayment.

State Rocks, Minerals, and Gems

Illinois

State mineral: **fluorite**

Southeastern Illinois once produced the majority of fluorite in the US, and it is the site of the most recently active fluorite mine in the country.

Indiana

State rock: Salem limestone

Salem limestone is a high-quality building material that may be seen in the facades of buildings from the Empire State Building to the Pentagon to Yankee Stadium. It has also been used in the construction of scores of university and government buildings throughout the country.

Iowa

State rock: **geode**

The town of Keokuk in southeastern Iowa is one of the most productive sites of geodes in the world. The formation of these geodes is not completely understood, but it is thought that when the bedrock initially formed, spherical **concretions** of calcium carbonate were accumulated among the layers of mudstone. Subsequently, water richer in silicon dissolved these concretions, leaving an open space in the rock where silicon, as quartz, could precipitate. In this way, the quartz crystals grew slowly from the outside inward, frequently leaving a hollow space in the center. Because quartz geodes are much harder than mudstone, the hollow orbs may often be found loose on the ground after the bedrock has been eroded away.

Michigan

State rock: Petoskey stone

Petoskey stone is fossilized *Hexogonaria* coral from the Devonian period.

State gem: **chlorastrolite**

Also called Michigan Greenstone, chlorastrolite is a variety of **pumpellyite** with a distinctive "turtleback" pattern created by its interlocking green crystals. It formed in void spaces in basalt during the Midcontinental Rift event, and, because it is substantially harder than the surrounding igneous rock, it is often found as loose, bean-sized pebbles. It is especially abundant on Michigan's Isle Royale.

State Rocks

fluorite • *the mineral form of calcium fluoride (CaF_2).*

geode • *a hollow, roughly spherical node of crystal that forms when minerals precipitate within hardened vesicles (gas bubbles) in volcanic rocks, or within dissolved nodules that leave openings within sedimentary rock.*

concretion • *a hard, compact mass, usually of spherical or oval shape, found in sedimentary rock or soil.*

pumpellyite • *a group of metamorphic silicate minerals that produce translucent green crystals with a fibrous texture.*

glacier • *a body of dense ice on land that does not melt away annually and has sufficient mass to move under its own weight.*

State Rocks

Minnesota

State gem: Lake Superior agate

Characteristically red, Lake Superior agate originates near its namesake lake, but **glaciers** have redistributed enough of the stone that it may be found throughout much of the state.

Ohio

State gem: Ohio **flint**

Ohio flint is a high-quality **chert** found throughout eastern and central portions of the state. Native Americans used Ohio flint to make tools as early as 12,000 years ago. It is a variety of microcrystalline quartz and a favorite of lapidarists.

Wisconsin

State mineral: **galena**

Galena played an important role in the founding of the state of Wisconsin because early settlers mined it as a **lead** ore.

State rock: red granite

Red granite is mined extensively in Wisconsin and, depending on its quality, is used to make products from countertops to gravel. It was formed around 1.85 billion years ago when an island arc crashed into the Superior Upland.

flint • *a hard, high-quality form of chert that occurs mainly as nodules and masses in sedimentary rock.*

chert • *a common sedimentary rock composed of microcrystaline quartz.*

galena • *an abundant sulfide mineral with cubic crystals.*

lead • *a metallic chemical element (Pb).*

Resources

Rock and Mineral Field Guides

Dixon, Dougal, 1992, *The Practical Geologist: The Introductory Guide to the Basics of Geology and to Collecting and Identifying Rocks*. Simon and Schuster: New York.

Johnsen, O., 2002, *Minerals of the world*. Princeton University Press: Princeton, NJ.

National Audubon Society, 1979, *Field Guide to North American Rocks and Minerals*. National Audubon Society Field Guides: New York.

Mitchell, J., 2008, *The rockhound's handbook*. Gem Guides Book Co.: Baldwin Park, CA.

Pellant, C., 2002, *Smithsonian Handbooks: Rocks & Minerals* (Smithsonian Handbooks). DK Publishing, Inc.: New York.

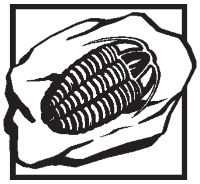
Prinz, M., Harlow, G., and Peters, J. (eds.), 1978, *Simon & Schuster's Guide to Rocks & Minerals*. Simon and Schuster: New York.

Books

Vernon, R. H., 2000, *Beneath our feet: The rocks of planet Earth*. Cambridge University Press: Cambridge, UK.

Websites

Atlas of Igneous and Metamorphic Rocks, Minerals and Textures, Univ. North Carolina Geology Department (Older but still useful resource.) http://leggeo.unc.edu/Petunia/IgMetAtlas/mainmenu.html.



Chapter 3: Fossils of the Midwestern US

Fossils (from the Latin word *fossilis*, meaning "dug up") are the remains or traces of organisms that lived in the geologic past (older than the last 10,000 years), now preserved in the Earth's **crust**. Most organisms never become fossils, but instead decompose after death, and any hard parts are broken into tiny fragments. In order to become fossilized, an organism must be buried quickly before it is destroyed by **erosion** or eaten by other organisms. This is why fossils are found almost exclusively in sediment and **sedimentary rocks**. **Igneous rocks**, which form from cooling **magma** or **lava**, and **metamorphic rocks**, which have been altered by **heat** and pressure, are unlikely to contain fossils.

Since rapid burial in sediment is important for the formation of fossils, most fossils form in marine environments, where sediments are more likely to accumulate. Fossils come in many types. Those that consist of an actual part of an organism, such as a bone, shell, or leaf, are known as **body fossils**; those that record the actions of organisms, such as footprints and burrows, are called **trace fossils**. Body fossils may be preserved in a number of ways. These include preservation of the original **mineral** skeleton of an organism, mineral **replacement** (chemical replacement of the material making up a shell by a more stable mineral), **recrystallization** (replacement by a different **crystal form** of the same chemical compound), **permineralization** (filling of empty spaces in a bone or shell by minerals), and molds and casts (see *Figure 3.10A*), which show impressions of the exterior or interior of a shell. **Chemical fossils** are chemicals produced by an organism that leave behind an identifiable record in the geologic record. Chemical fossils provide some of the oldest evidence for life on Earth.

The "soft" tissues of an organism, such as skin, muscles, and internal organs are typically not preserved as fossils. Exceptions to this rule occur when conditions favor rapid burial and mineralization or very slow decay. The absence of oxygen and limited disruption of the sediment by burrowing are both important for limiting decay in those deposits where soft tissues are preserved. Examples of such exceptional preservation include fossils in concretions, such as those in the Mazon Creek deposit in Illinois.

crust • *the uppermost, rigid outer layer of the Earth, composed of tectonic plates.*

erosion • *the transport of weathered materials.*

sedimentary rock • *formed through the accumulation and consolidation of grains of broken rock, crystals, skeletal fragments, and organic matter.*

magma • *molten rock located below the surface of the Earth.*

lava • *molten rock located on the Earth's surface.*

mineral • *a naturally occurring solid with a specific chemical composition and crystalline structure.*

crystal form • *a physical property of minerals, describing the shape of the mineral's crystal structure.*

CHAPTER AUTHORS

Alex F. Wall
Warren D. Allmon

3 Fossils

Review

extinction • *the end of species or other taxonomic groups, marked by death of the last living individual.*

stratigraphy • *the branch of geology specifically concerned with the arrangement and age of rock units.*

Cambrian • *a geologic time period lasting from 541 to 485 million years ago.*

biodiversity • *the number of kinds of organisms at any given time and place.*

Paleontologists use fossils as a record of the history of life. Fossils are also extremely useful for understanding the ancient environment that existed in an area when they were alive. The study of the relationships of fossil organisms to one another and their environment is called **paleoecology**.

Fossils are also the most important tool for dating the rocks in which they are preserved. Because species only exist for a certain amount of time before going **extinct**, their fossils only occur in rocks of a certain age. The relative age of such fossils is determined by their order in the stacks of layered rocks that make up the **stratigraphic** record (older rocks are on the bottom and younger rocks on the top—a principle called **superposition**). Such fossils are known as **index fossils.** The most useful index fossils are abundant, widely distributed, easy to recognize, and occur only during a narrow time span. The use of fossils to determine relative age in geology is called **biostratigraphy**.

***Index fossils* are used to determine the age of many deposits that cannot be dated radiometrically. An ideal index fossil lived during a short period of time, was geographically and environmentally widespread, and is easy to identify. Some of the most useful index fossils are hard-shelled organisms that were once part of the marine plankton.**

Ancient Biodiversity

Since life began on Earth more than 3.7 billion years ago, it has continuously become more abundant and more complex. It wasn't until the beginning of the **Cambrian** period, around 543 million years ago, that *complex life*—living things with cells that are differentiated for different tasks—became predominant. The diversity of life has, in general, increased explosively through time since then. Measurements of the number of different kinds of organisms—for example, estimating the number of species alive at a given time—attempt to describe Earth's **biodiversity**. With a few significant exceptions, the rate at which new species evolve is significantly greater than the rate of extinction.

Most species have a lifespan of several million years; rarely do species exist longer than 10 million years. The extinction of a species is a normal event in the history of life. There are, however, intervals of time during which extinction rates are unusually high, in some cases at a rate of 10 or 100 times the normal rate. These intervals are known as **mass extinctions** (*Figure 3.1*). There were five particularly devastating mass extinctions in geologic history, and these specific mass extinction events have helped to shape life through time. Unfortunately, this is not just a phenomenon of the past—it is estimated that the extinction rate on Earth right now may be as much as 1000 times higher than normal, and that we are currently experiencing a mass extinction event.

Fossils

3

Review

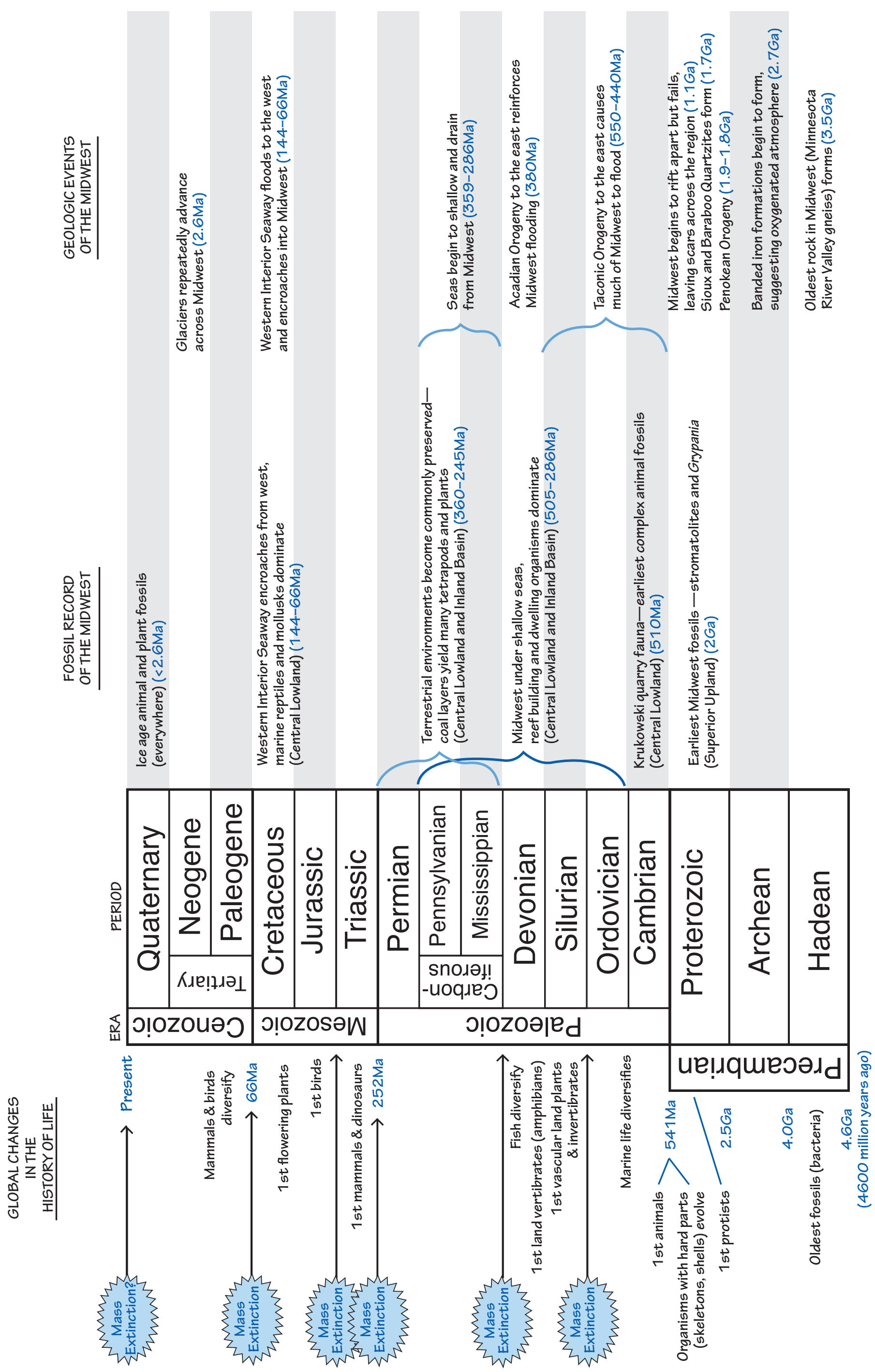


Figure 3.1. The history of life in relation to global and regional geological events and the fossil record of the Midwest (time scale is not to scale).

3 Fossils

Different fossils are found in different regions because of the presence of rocks deposited at different times and in a variety of environments. The availability of fossils from a given time period depends both on the deposition of sedimentary rocks and the preservation of these rocks through time.

Discovering Ancient Environments

The kinds of animals and plants living in a particular place depend on the local environment. The fossil record preserves not only fossil organisms, but also evidence of what the environment in which these organisms lived was like. By studying the geological and biological information recorded in a rock that contains a fossil, scientists can determine some aspects of its environment.

Grain size and composition of the rock **can tell us what type of sediment surface the animal lived on, what the water flow was like, or whether it was transported in a current. Grain size also tells us about the clarity of the water. Fine-grained rocks such as shales are made of tiny particles of** ***silt*** **or** ***clay*** **that easily remain suspended in water. Thus a fossil found in shale might have lived in muddy or very quiet water. Filter-feeding organisms, such as clams or corals, are not usually found in muddy water because the suspended sediment can clog their filters!**

Sedimentary structures**, such as asymmetrical ripples and** ***cross-beds*****, can indicate that the organism lived in moving water. Mud cracks or symmetrical ripples are characteristic of shoreline or intertidal environments.**

Broken shells or concentrated layers of shells **may indicate transportation and accumulation by waves or currents.**

Color of the rock **may indicate the amount of oxygen in the water. If there is not enough oxygen in the water, organic material (carbon) in sediments will not decompose, and the rock formed will be dark gray or black in color.**

Review

silt • *fine granular sediment most commonly composed of quartz and feldspar crystals.*

clay • *the common name for a number of very fine-grained, earthy materials that become plastic (flow or change shape) when wet.*

cross-bedding • *layering within a bed in a series of rock strata that does not run parallel to the plane of stratification.*

Paleozoic • *a geologic time period that extends from 541 to 252 million years ago.*

reef • *a feature lying beneath the surface of the water, which is a buildup of sediment or other material built by organisms, and which has positive relief from the sea floor.*

Pennsylvanian • *a subperiod of the Carboniferous, spanning from 323 to 299 million years ago.*

inland sea • *a shallow sea covering the central area of a continent during periods of high sea level.*

Fossils 3

The rocks of the Midwest preserve an excellent fossil record of the history of life, especially from the **Paleozoic** Era. Most periods of the Paleozoic are very well represented in the Midwest, with fossils of increasingly diverse **reef** communities found in parts of every state. When the sea level dropped after the **Pennsylvanian** period, the **inland sea** drained from the region. Since the region was exposed to the air during most of the **Mesozoic**, far less of this era's fossil record was preserved. **Cenozoic** fossils in the region include abundant **Pleistocene** land mammals.

Fossils of the Superior Upland

Region 1

The Superior Upland region of the Midwest contains the largest surface exposure of North America's ancient core, the **Canadian Shield**. The shield is composed almost entirely of metamorphic rock that is 1.6 to 2.6 billion years old. Its composition would normally preclude it from containing fossils, as the heat and pressure associated with metamorphism would typically destroy any original fossil remains, but this region contains significant evidence of ancient life! The Earth's first photosynthesizers have been implicated in aiding the creation of the **banded iron formations** throughout the region. **Stromatolites** provide some of the earliest direct fossil evidence for life on Earth, and they can be found in northern Minnesota and Michigan's Upper Peninsula (*Figure 3.2*).

Stromatolites are formed by mats of single-celled **cyanobacteria**—as the bacteria reproduce, new generations form new layers on top of the older mats, also trapping sediment. After many generations, the layers form a dome above the surface of the seafloor. The sediment stuck in these structures makes them fairly robust and easily preserved, some of them surviving despite the fact that even the *youngest* rocks in this region are 1.6 billion years old.

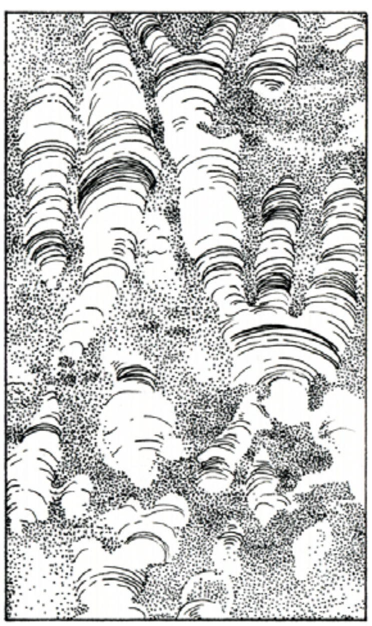


Figure 3.2. Precambrian stromatolites, about 1–2 billion years old, from northern Minnesota. About 4.5 cm (1.75 inches) wide.

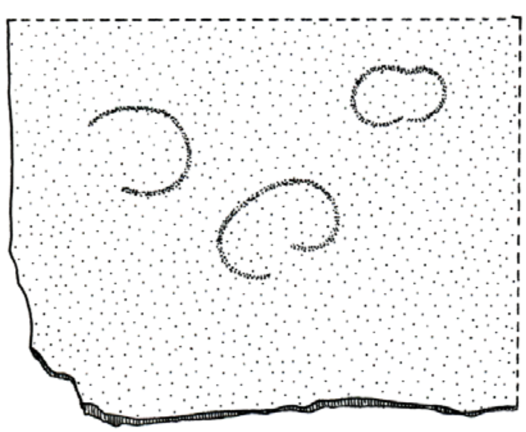


Figure 3.3. Grypania. *Possibly one of the oldest known multicellular fossils. About 2.1 billion years old from Marquette County, Michigan. Each fossil is about 1.5 cm (0.6 inches) across.*

Region 1

Mesozoic • *a geologic time period that spans from 252 to 66 million years ago.*

Cenozoic • *the geologic time period spanning from 66 million years ago to the present.*

Pleistocene • *a subset of the Quaternary, lasting from 2.5 million to about 11,700 years ago.*

banded iron formation • *rocks with regular, alternating thin layers of iron oxides and either shale or silicate minerals.*

cyanobacteria • *a group of bacteria, also called "blue-green algae," that obtain their energy through photosynthesis.*

3 Fossils

Regions 1–2

The Upper Peninsula of Michigan is home to fossils of *Grypania spiralis* (*Figure 3.3*), which many experts think may be filaments of algae appearing as spirals on rock that is about 2.1 billion years old. These fossils are very important because if they are the oldest examples of multicellular organisms, then they are also the first **eukaryotes**. Before eukaryotes, all life consisted of single-celled, **prokaryotic** organisms, which were similar to bacteria in that their cells were small and had no organelles. This means that if *Grypania* is indeed the first eukaryote, it is a very early relative of all plants, fungi, animals, and **protists**.

Banded iron formations consist of repeated, thin layers (a few millimeters to a few centimeters in thickness) of silver to black **iron** oxides, either **magnetite** (Fe_3O_4) or **hematite** (Fe_2O_3), alternating with bands of iron-poor **shales** and **cherts**, often red in color, of similar thickness, and containing thin layers of iron oxides. They are not fossils in the strictest sense, yet they are important evidence for the **Precambrian** life of the region located around the northern edge of Lake Superior.

See Chapter 1: Geologic History for more about banded iron formations.

Although the details of their formation are still not completely understood, it is thought that banded iron formations formed when the oceans on the early Earth were anoxic and contained significant quantities of dissolved iron. With the evolution of photosynthesis, increasing amounts of oxygen were released as waste products. This oxygen combined with dissolved iron to form insoluble iron oxides, which precipitated out of solution to form layers. Eventually, all the readily available iron was used up, and oxygen levels became too high for the cyanobacteria to survive, so their population plummeted. In their absence, iron was allowed to build up in the water again, creating a band of iron-poor rock to be deposited. With a renewed buffer against oxygen, the photosynthesizers could rebound, and the cycle repeated itself, creating the regular bands that give the rock its name. Today, banded iron formations are a crucial source of iron ore.

No younger rock is preserved in the Superior Upland portion of the Canadian Shield, but **ice age** fossils found in this region are discussed near the end of this chapter.

protists • *a diverse group of single-celled eukaryotes.*

shale • *a dark, fine-grained, laminated sedimentary rock formed by the compression of successive layers of silt- and clay-rich sediment.*

chert • *a sedimentary rock composed of microcrystaline quartz.*

Precambrian • *a geologic time period that spans from the formation of Earth (4.6 billion years ago) to the beginning of the Cambrian (541 million years ago).*

ice age • *a period of global cooling of the Earth's surface and atmosphere, resulting in the presence or expansion of ice sheets and glaciers.*

Fossils of the Central Lowland

Region 2

The Paleozoic is well represented in the Central Lowland region of the Midwest, from the Cambrian through the Pennsylvanian periods. Together, fossils from across the region record some of the most important chapters in life's story. The Central Lowland's fossils take us on a journey from when complex organisms first became abundant, through the development of reefs and other recognizable components of marine ecosystems, to the invasion of land. To the west, a few **Cretaceous** fossils of giant marine reptiles and **sharks** may be found. Terrestrial fossils from the most recent ice age, beginning just two million years ago, have also been discovered in every state in the Midwest, preserved in sediment left by the **glaciers**.

Cambrian

The Cambrian period is represented in the Central Lowland by an irregular strip that cuts east and west through Wisconsin, crossing into neighboring parts of Minnesota and Michigan. The beginning of this period is marked by the relatively sudden appearance of an unprecedented diversity of creatures. Within a span of roughly 30 million years, all of the major animal groups that we know today, such as mollusks, **arthropods**, **echinoderms**, and vertebrates, appeared within the Earth's oceans. This time of rapid diversification and evolution is known as the "Cambrian Explosion." These new kinds of animals interacted with each other and their environments radically in new ways. It was during this time that animals quickly evolved a suite of innovations, including mobility, vision, and hard mineralized parts.

While the Cambrian period was the beginning of complex life, its cast of characters is very unlike the animals of today. Cambrian-aged rocks in Wisconsin and Minnesota preserve the hard parts of **trilobites** (*Figure 3.4*), **brachiopods**, trace fossils of worms, algae, and jellyfish, and the mysterious **hyoliths** (*Figure 3.5*). Hyoliths are animals with cone-shaped shells that existed throughout the Paleozoic Era. Their affinities to other animals are uncertain, with some scientists classifying them as mollusks and others placing them in their own phylum. The Krukowski Quarry in central Wisconsin reveals an extraordinary fossil assemblage of Cambrian marine invertebrate trackways and jellyfish in cream-colored **sandstone** that looks like it formed on a beach.

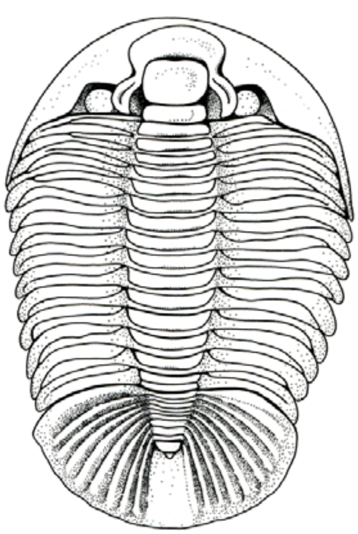


Figure 3.4. Trilobite. Dikelocephalus*. Length about 2 cm (1 inch).*

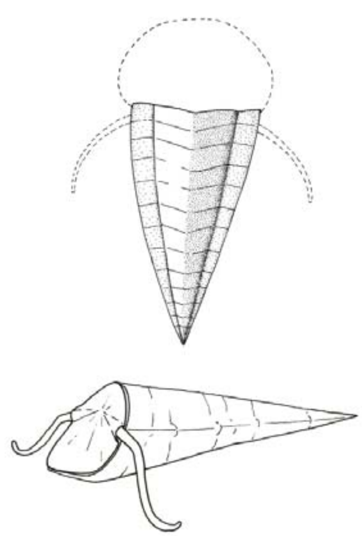


Figure 3.5. Hyolithid. About 1–2 cm (less than an inch) long.

Cretaceous • *a geologic time period spanning from 144 to 66 million years ago.*

glacier • *a body of dense ice on land that does not melt away annually and has sufficient mass to move under its own weight.*

echinoderm • *members of the Phylum Echinodermata, which includes starfish, sea urchins, and crinoids.*

trilobite • *an extinct marine invertebrate animal characterized by a three-part body and a chitinous exoskeleton divided longitudinally into three lobes.*

brachiopod • *a marine invertebrate animal characterized by upper and lower calcareous shell valves joined by a hinge, and a crown of tentacles (lophophore) used for feeding and respiration.*

Fossils

Region 2

Ordovician • *a geologic time period spanning from 485 to 443 million years ago.*

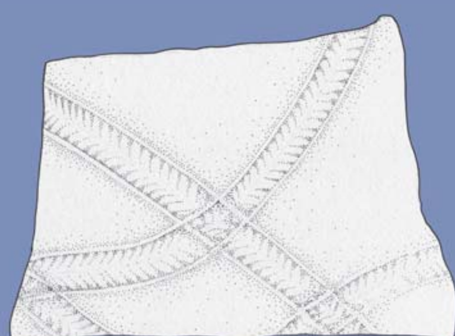
Devonian • *a geologic time period spanning from 419 to 359 million years ago.*

ice sheet • *a mass of glacial ice that covers part of a continent and has an area greater than 50,000 square kilometers (19,000 square miles).*

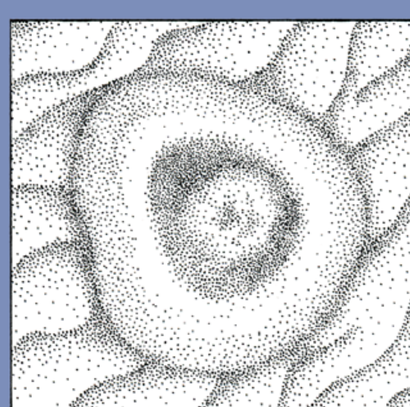
bryozoan • *a marine or freshwater colonial invertebrate animal characterized by an encrusting or branching calcareous skeleton from which multiple individuals (zooids) extend from small pores to filter-feed using crowns of tentacles (lophophores).*

The Krukowski Quarry

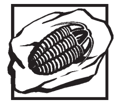
The Krukowski Quarry, near Mosinee, Wisconsin, is a locality famous for its unique preservation of trace fossils from a 510-million-year-old beach. Fossilized trackways found there give paleontologists clues about the organisms and the way they moved around under the shallow water. Amazingly, the quarry also contains fossilized traces of scyphozoan jellyfish. Preservation of such soft creatures is rare enough, but these are both the oldest and, at a diameter of up to 50 centimeters, several times larger than any other fossil jellyfish! At a time when few animals had hard parts, these jellyfish were likely top predators. Their extraordinary preservation seems to indicate that these unfortunate individuals had become stranded on the beach, long before any life (except perhaps bacteria) had colonized land.



Climactichnites. ***The maker of this trackway is unknown, but may have been a mollusk. Each trackway is about 10 cm (4 inches) wide. The trackways can extend for many meters.***



Jellyfish impression from the Cambrian of Wisconsin. Impression is about 30 cm (1 foot) in diameter.



Ordovician to Pennsylvanian

Trilobites and brachiopods, which had dominated the Cambrian period, expanded somewhat in diversity and abundance in the post-Cambrian. As the Paleozoic Era progressed, they were joined by many other new or expanding groups of animals. Many of these were **filter feeders**. Trilobites (which probably fed on seafloor mud) developed defenses against threats from new kinds of predators and competitors: spines, acute vision, and the ability to swim or burrow.

***Filter feeding* describes a method of consumption characterized by passing water through a filtering structure that traps food. The water may then be expelled and the food digested. This strategy is employed by a wide range of animals today, from clams and krill to flamingos and whales.**

Ice ages occurred at the ends of both the **Ordovician** and **Devonian** periods, dramatically affecting life in the then-tropical Central Lowland by sequestering water in polar **ice sheets**. This caused dramatic changes in sea level, which resulted in devastating mass extinctions, allowing new successions of organisms to come to the fore.

Ordovician fossils are found in all seven Midwestern states. Life in the tropical sea that covered much of the central United States at the time experienced a burst of diversity, which increased fourfold compared with that of the Cambrian. Beginning in the Ordovician and expanding through the rest of the Paleozoic, great reefs were formed by organisms like **bryozoans**, corals, algae, and sponges, which are found in rocks in the Central Lowland region. These reefs played a major role in forming the ecosystems that were also home to straight-shelled **cephalopods** (*Figure 3.6*)**,** trilobites (*Figure 3.7*), **bivalves, gastropods, crinoids**, **graptolites** (*Figure 3.8*), brachiopods (*Figures 3.9–3.11*), and fish (*Figure 3.12*). By the Devonian, fish had become increasingly prominent and diverse. Meanwhile, plants and arthropods had begun to populate the hitherto barren land.

***cephalopod* • a marine invertebrate animal characterized by a prominent head, arms and tentacles with suckers, and jet propulsion.**

***bivalve* • a marine or freshwater invertebrate animal characterized by right and left calcareous shells (valves) joined by a hinge.**

***gastropod* • a marine, freshwater, or terrestrial invertebrate animal characterized by a single, coiled, calcareous shell, a muscular foot for gliding, and internal asymmetry caused by torsion.**

***crinoid* • a marine invertebrate animal characterized by a head (calyx) with a mouth surrounded by feeding arms.**

***graptolite* • an extinct colonial invertebrate animal characterized by individuals housed within a tubular or cup-like structure.**

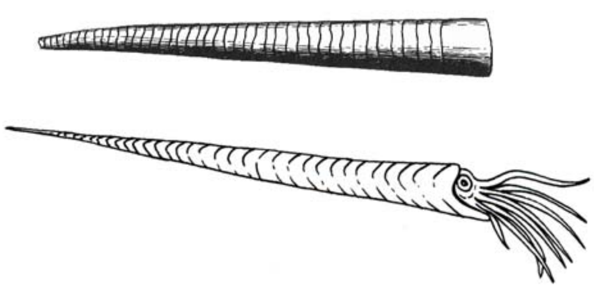


Figure 3.6: Straight (orthocone) nautiloid, shell and animal reconstruction. These animals reached lengths of more than 4 meters (12 feet), making them among the largest invertebrate animals that ever lived. Specimens 30–90 cm (1–3 feet) long are frequently found.

Fossils

Region 2

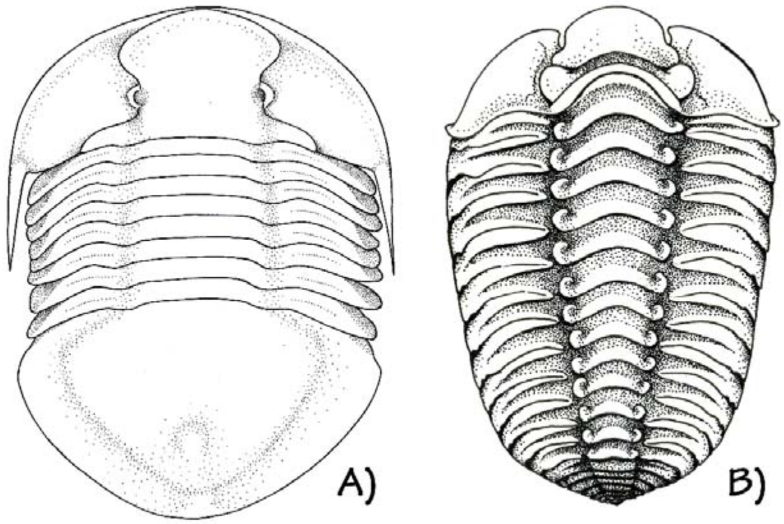


Figure 3.7: Ordovician trilobites. A) Isotelus maximus*, state fossil of Ohio. This species reached more than 30 cm (1 foot) long. B)* Calymene celebra*, state fossil of Wisconsin. About 2 cm (1 inch) long.*

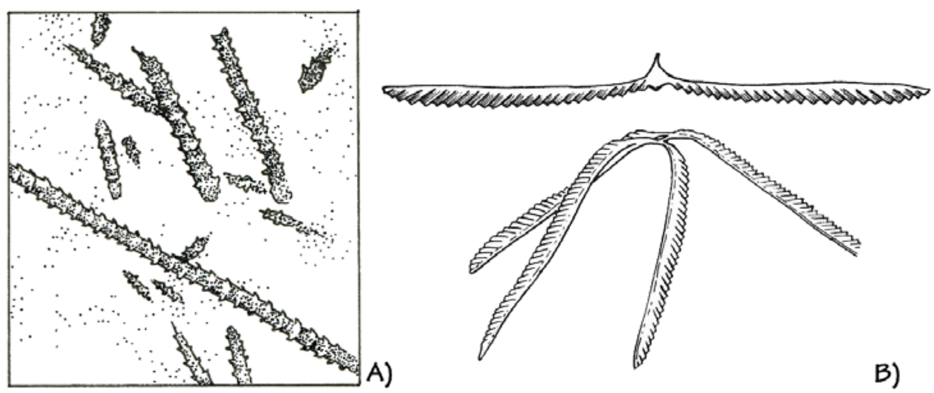


Figure 3.8: Graptolites. A) Specimen with many fragments of colonies of Climacograptus*. B) Restorations of what graptolite colonies may have looked like when they were alive, floating in the water. Graptolite specimens are 2–5 cm (1–2 inches) long*

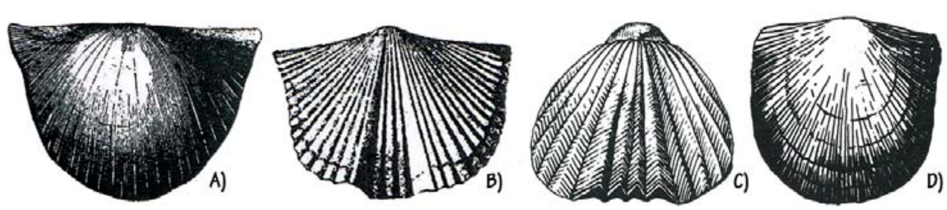


Figure 3.9: Ordovician brachiopods from Ohio and Minnesota. A) Strophomena incurvata*. B)* Platystrophia biforata*. C)* Rhynchotrema capax*. D)* Rafinesquina alternata*. Each about 4 cm (1.5 inches) wide.*

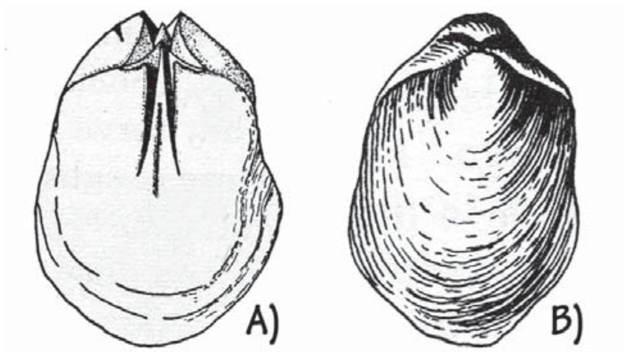


Figure 3.10: The Silurian brachiopod Pentamerus *is often preserved as an internal mold. A) The "slots" show the location of supports for internal organs that extended into the interior of the shell. These strange-looking fossils are sometimes called "pig's feet." B) The exterior of the shell. Specimens are about 2 cm (1 inch) long.*

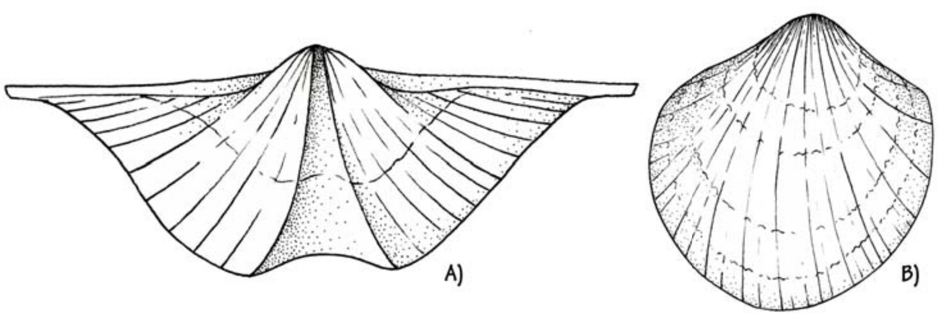


Figure 3.11. Devonian brachiopods from Iowa. A) Platyrachella *sp. [about 8 cm (3 inches) wide]. B)* Atrypa devoniana *[about 3.5 cm (1.5 inches) wide].*

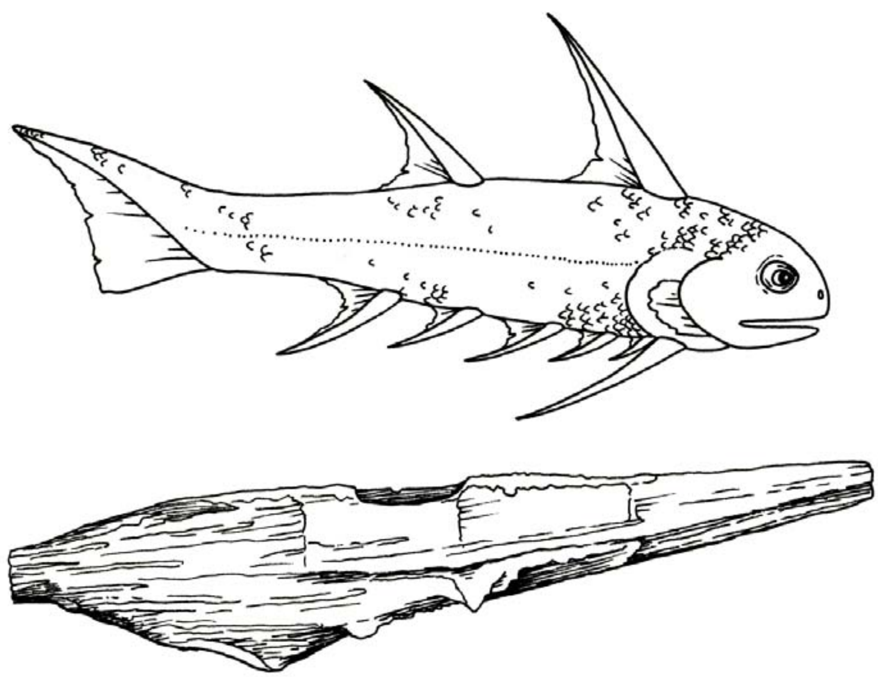


Figure 3.12: Silurian acanthodian fish reconstruction and spine. These fish reached lengths of up to 30 cm (1 foot). Spines are 5–10 cm (2–4 inches).

3 Fossils

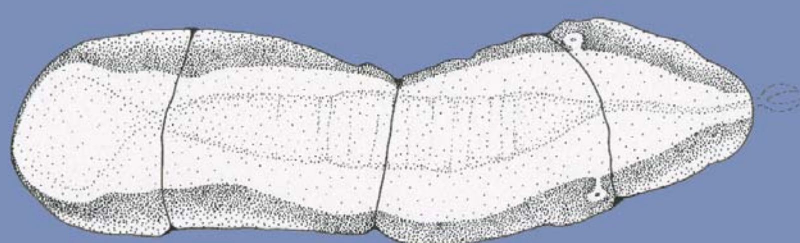
Region 2

lagerstätte *• fossil deposit containing animals or plants that are preserved unusually well, sometimes even including the soft organic tissues.*

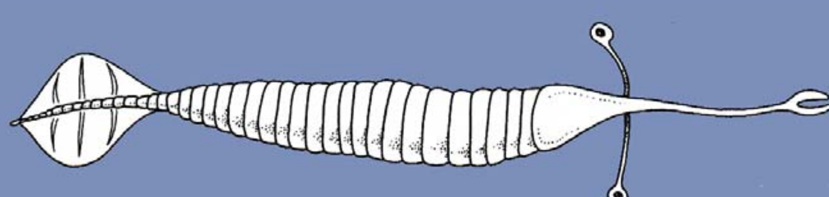
concretion *• a hard, compact mass, usually of spherical or oval shape, found in sedimentary rock or soil.*

Mazon Creek

The Mazon Creek *lagerstätte* is a fossil deposit of Pennsylvanian age exposed in coal mines in northeastern Illinois. It's hematite concretions (or nodules) preserve hundreds of fossil plant and animal species in beautiful detail,(both terrestrial and marine), with many found nowhere else in the world. Among the amazing fossils of Mazon Creek is Illinois' state fossil, the Tully Monster or *Tullimonstrum*, an unusual invertebrate that is thought to have swum using its three-finned tail and hunted using its eight-toothed proboscis to bring prey to the mouth. Its place on the tree of life is uncertain, though some scientists suspect it is a mollusk. Without the exceptionally preserved specimens at Mazon Creek, this soft-bodied predator would be unknown to science. Tully Monsters reached lengths of up to 30 cm (1 foot), but most specimens are less than half that length.



A fossil specimen of Tullimonstrum gregarium***, the state fossil of Illinois.***



A reconstruction of the Tully Monster in life.

During the **Mississippian** and Pennsylvanian, the expansion and contraction of glaciers far to the south caused sea levels to fluctuate. In the Central Lowland, these periods produced **cyclothems**, which are cycles of alternating marine and terrestrial rocks, often including **coal**. By that time, the first vertebrates had crawled onto the land, joining numerous arthropods that already lived in expansive, swampy forests. In the ocean, brachiopods, trilobites, and reef-builders were decimated by the mass extinction at the end of the Devonian.

Reef Builders

Through the **Silurian** and Devonian periods, reefs expanded across the shallow sea that covered the Midwest. While these reefs performed ecological functions similar to those of modern coral reefs, many of the animals that constructed them were very different. Now-extinct tabulate corals, like *Halysites* (*Figure 3.13*) found in Ohio, formed elaborate honeycomb-like colonies. Bryozoans (*Figure 3.14*) are an entire phylum of colonial marine animals, and during the Paleozoic, their erect, branching skeletons formed vast thickets that are fossilized in the Ordovician rock around Cincinnati. Michigan's state rock, the Petoskey Stone, is actually a colonial rugose coral of the genus *Hexagonaria (Figure 3.15*), a reef-builder that is also the namesake of Coralville, Iowa. Other rugose corals were solitary—composed of only one coral polyp (*Figure 3.16*). All tabulate corals were colonial.

Colonial **corals live in colonies of hundreds or even thousands of individuals that are attached to one another.**

Solitary **corals live independently, as single isolated polyps.**

The Cedar Valley Group in Iowa yields abundant remains of Devonian reefs composed of layered sponges called **stromatoporoids** (*Figure 3.17*). The mass extinction event at the end of the Devonian left bryozoans as the major reef-building group until the Mesozoic.

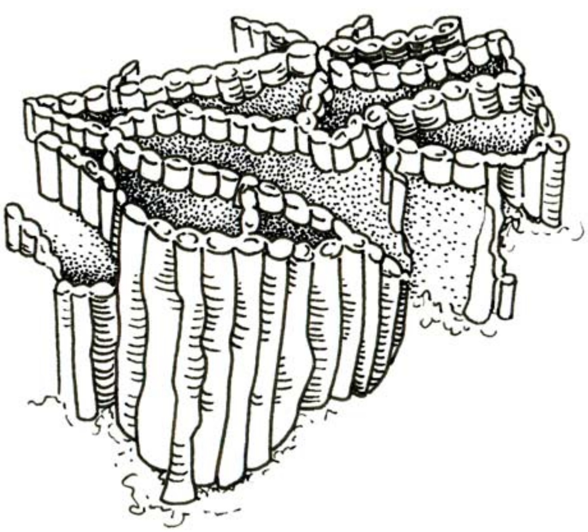


Figure 3.13: Tabulate coral, Halysites *sp. About 10 cm (4 inches) across.*

Mississippian • *a subperiod of the Carboniferous, spanning from 359 to 323 million years ago.*

cyclothem • *alternating sequences of marine and non-marine sedimentary rocks, usually including coal, characterized by their light and dark colors.*

coal • *a combustible, compact black or dark-brown carbonaceous rock formed by the compaction of layers of partially decomposed vegetation.*

Silurian • *a geologic time period spanning from 443 to 419 million years ago.*

stromatoporoid • *a type of calcareous sponge that acted as an important reef-builder throughout the Paleozoic and the late Mesozoic.*

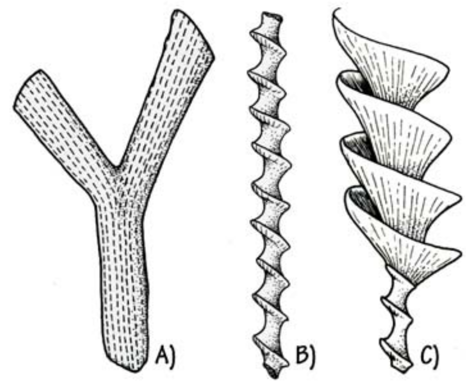


Figure 3.14: Bryozoans. A) Rhombopora *sp., Ordovician. About 5–10 cm (2–4 inches) long. B)* Archimedes *sp., Carboniferous.* Archimedes *colonies consisted of a screw-shaped axis, with a spiral fan connected to the "threads" of the screw. The tiny bryozoan animals lived in chambers on the fan. In some localities, thousands of these "fossil screws" cover the ground. They are usually less than an inch long. C)* Archimedes *life reconstruction.*

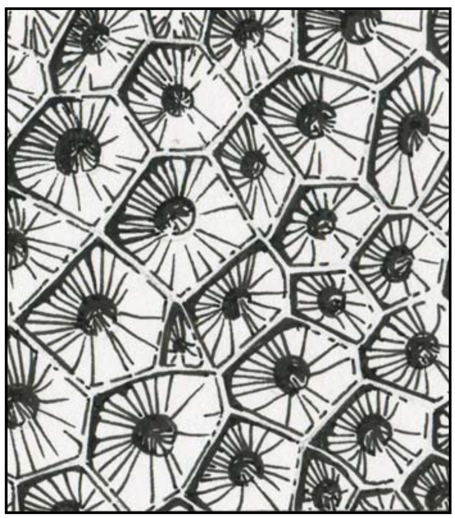


Figure 3.15: Surface of the colonial rugose coral Hexagonaria*, Devonian. When polished, this fossil is called the Petoskey Stone, the state rock of Michigan.* Hexagonaria *colonies were sometimes bowling ball-sized; most Petoskey stones are the size of ping pong balls. Individual corallites are about 12 mm (0.4 inches) in diameter.*

Figure 3.16: A solitary rugose, or "horn" coral. Some horn corals reached lengths of 20 cm (8 inches), but most were less than 2 cm (about 1 inch) long.

Figure 3.17: Stromatoporoid sponge. About 30 cm (1 foot) across.

Fishes and Filter-Feeders

Sharks trace their lineage to the Ordovician, more than 420 million years ago, and they became increasingly diverse throughout the remainder of the Paleozoic Era. Ohio's Cleveland Shale preserves specimens of the well-studied primitive shark *Cladoselache* (*Figure 3.18*). This shark was relatively common during the late Devonian and possessed an interesting blend of primitive and derived characteristics. Superficially, its body looked like that of a modern shark—but the 1.2-meter-long (4-foot-long) *Cladoselache* had a terminal mouth (rather than a mouth somewhat under the "nose" as in modern sharks), almost no scales, and no **claspers**—leaving scientists to wonder how they reproduced.

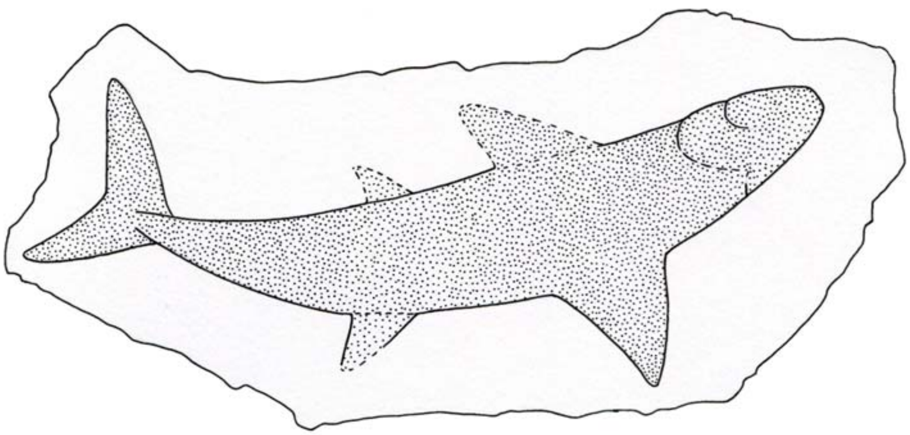


Figure 3.18: Cladoselache*, a shark about 1.2-meter-long (4-foot-long).*

The Devonian saw fishes explode in diversity, from tiny scavengers to huge hunters. The 9-meter-long (30-foot-long) *Dunkleosteus* (*Figure 3.19*) did not have a bony internal skeleton, but its head was covered in bony armor. While remains of its soft parts, including its unarmored rear two-thirds, have yet to be discovered, the plates of numerous specimens have been found in the Cleveland Shale of Ohio, and the Cleveland Museum of Natural History houses the largest known specimens. The plates that formed the jaw functioned as huge blades, rubbing against each other to stay sharp as the fish chomped its prey: sharks, other fish, and large invertebrates. Along with *T. rex*, it is estimated to have had one of the most powerful bites in the history of life, and it was the apex predator of the late Devonian seas. Despite its apparent advantages, it and all of its its **placoderm** kin became extinct at the end of the Devonian.

The Mississippian is sometimes known as the "Age of Crinoids" because of the increase in the abundance and diversity of crinoids (*Figure 3.20*), as well as starfish, **edrioasteroids** (*Figure 3.21*), urchins, and other echinoderms (*Figure 3.22*) during this time. Sites near Crawfordsville, Indiana are world-famous for containing abundant specimens of more than 60 well-preserved crinoid species. While it is common to find stem pieces of crinoids throughout the Midwest, discoveries of the head, or **calyx**, are much rarer. Crawfordsville provides a wealth of unbroken lengths of stem and calyxes from these filter-feeding animals.

Region 2

clasper • *an anatomical structure used by sharks for mating.*

placoderms • *an extinct class of heavily armored fishes.*

edrioasteroids • *an extinct class of echinoderms that had a simple, cushion-shaped body and five arms.*

calyx • *the head of a crinoid.*

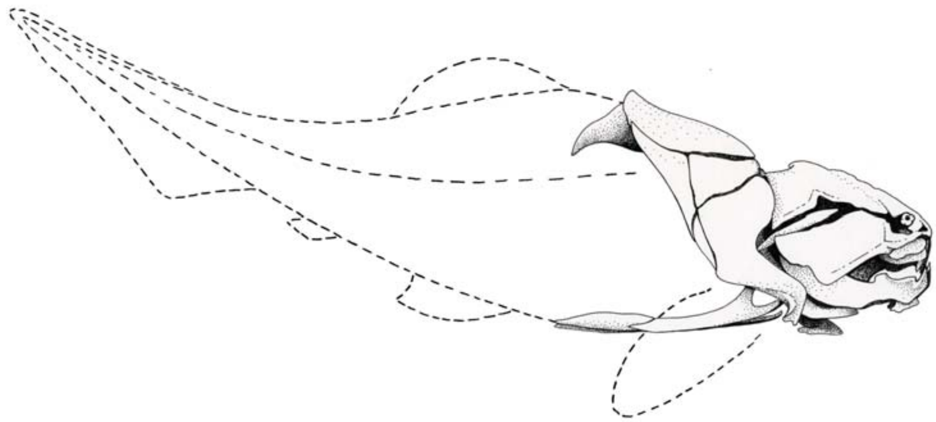


Figure 3.19: Dunkleosteus. The dotted lines show inferred shape of the unpreserved part of the body. Total length was probably about 9 meters (30 feet).

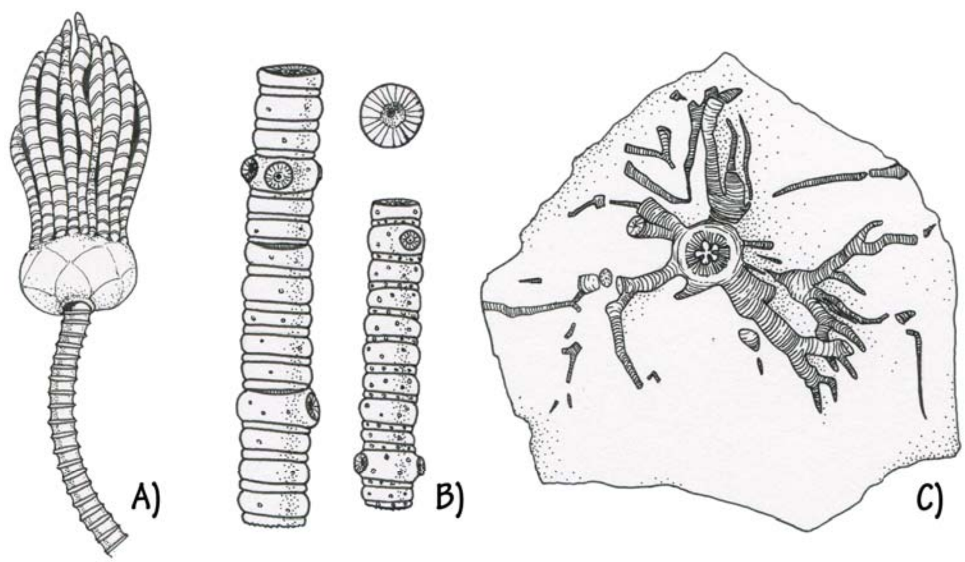


Figure 3.20: Crinoids from the Mississippian of Indiana. A) Crown and stem; about 15 cm (6 inches) long. B) Stem fragments. C) Holdfast; about 8 cm (3 inches) across.

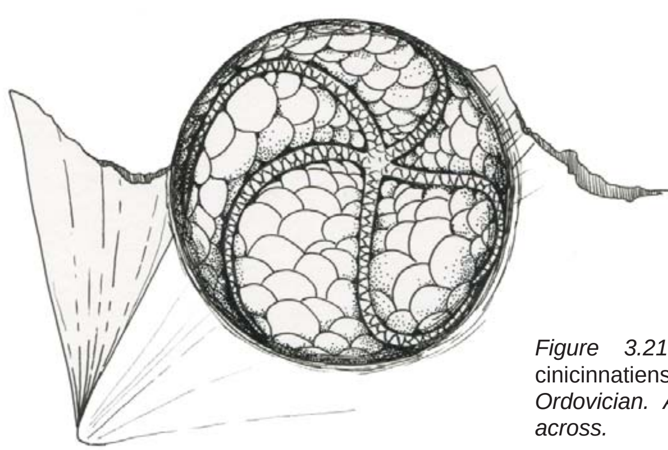


Figure 3.21: Edrioasteroid, Isorophus cinicinnatiensis*, attached to a bivalve shell. Ordovician. About 2 cm (about 1 inch) across.*

Region 2

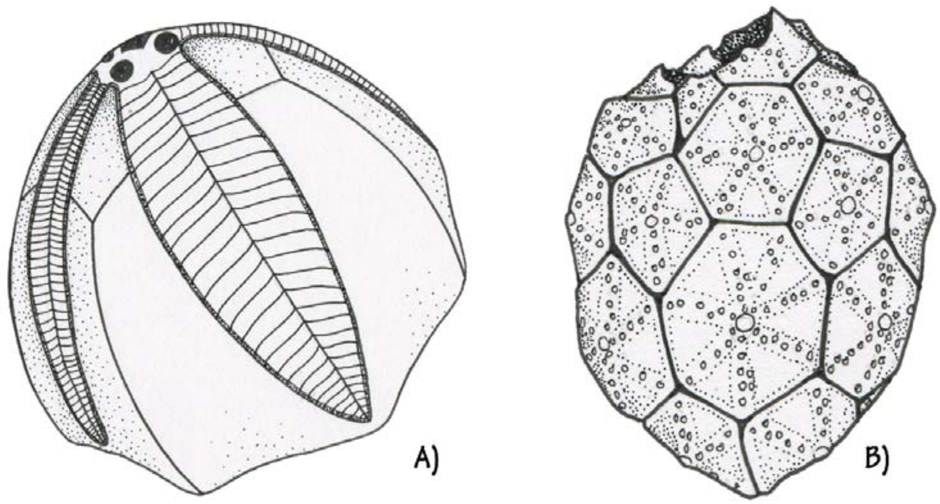


Figure 3.22: A) Blastoid. Pentremites *sp. 1–2 cm (about .75 inches) long. B) Cystoid.* Caryocrinites *sp. 1–2 cm (about .75 inches) long.*

Land Ho!

After the appearance of land plants in the Ordovician and the presence of established forests by the beginning of the Mississippian, much of the Midwest's land through the remainder of the Paleozoic consisted of swampy deltas. Wetland forests were home to a tangle of **lycopod** and **sphenopsid trees**, early **conifers**, the now-extinct **seed ferns** (*Figure 3.23*), and other plants. By the Pennsylvanian, huge lycopods like *Lepidodendron* (*Figure 3.24*) and other plants grew thickly on the Midwestern landscape. (Lycopods survive today but only as very small plants on the forest floor, sometimes called "ground pines.") These ancient ecosystems are sometimes called "coal swamps" because the stagnant, wet environments in which they thrived protected huge volumes of vegetation from decomposing. As the decaying plant matter accumulated for tens of millions of years, it formed thick, extensive deposits of coal underlying much of the Central Lowland as well as the parts of the Inland Basin.

A *tree* is any woody perennial plant with a central trunk. Not all trees are closely related; different kinds of plants have evolved the tree form through geological time. The trees of the Paleozoic were more closely related to club mosses or ferns than they were to today's trees.

Cretaceous

While an expansive record of Paleozoic life is present in the Midwest, the Mesozoic Era is relatively poorly represented. Still, Cretaceous-aged rocks in Minnesota, Iowa, and southern Illinois provide some glimpses into life during this time period.

To learn more about how the Midwest's coal is exploited for fuel today, see Chapter 7: Energy.

lycopod • *an extinct, terrestrial tree characterized by a tall, thick trunk covered with a pattern of diamond-shaped leaf scars, and a crown of branches with simple leaves.*

sphenopsid • *a terrestrial plant characterized by hollow, jointed stems with reduced, unbranched leaves at the nodes.*

conifer • *a woody plant bearing cones that contain its seeds.*

seed fern • *an extinct terrestrial plant characterized by a fern-like appearance, but bearing seeds instead of spores.*

dinosaurs • *a group of terrestrial reptiles with a common ancestor and thus certain anatomical similarities, including long ankle bones and erect limbs.*

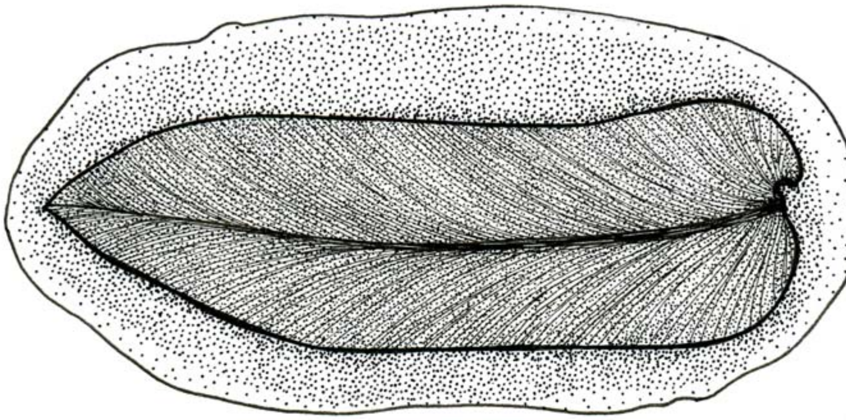


Figure 3.23: Neuropteris*, a seed fern in a Mazon Creek nodule. Length about 9 cm (4 inches).*

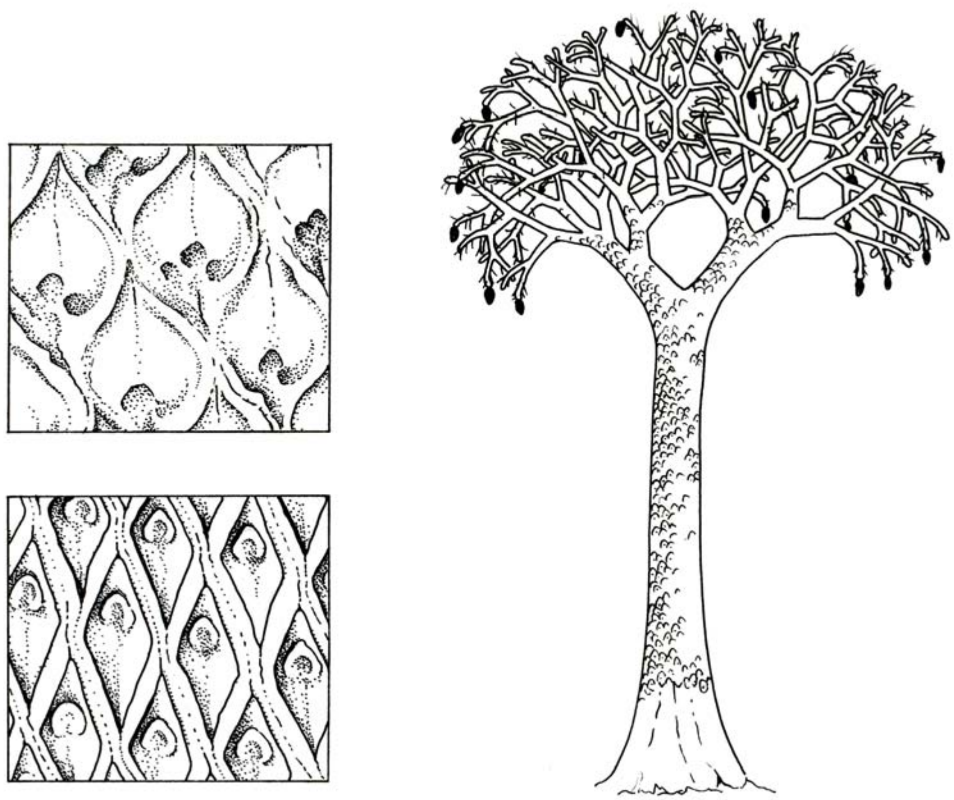


Figure 3.24: Lepidodendron*. Left: close-ups of leaf scars on the trunk. Right: reconstruction of the entire tree, which reached 30 meters (100 feet) in height.*

A few **dinosaur** fossils have been found in riverine deposits in the lower parts of the Dakota Formation of Minnesota and Iowa (and also in nearby Kansas and Nebraska). Later layers were deposited under marine conditions, as the huge Western Interior Seaway invaded farther into the upper Midwest. In Iowa, these marine strata (including the Graneros, Greenhorn, Carlile, and Niobrara formations) have yielded a few bones of large sea reptiles called **plesiosaurs**

Early Vertebrates

A Mississippian-aged site near Delta, Iowa has yielded some of the best-preserved examples of early land-dwelling vertebrates. For example, *Whatcheeria deltae*, described in 1985, is considered a "reptile-like amphibian," having some anatomical features more like those of amphibians and some more like those of *amniotes*. This animal measured about 1 meter (3 feet) long, and dates to around 340 million years ago.

(*Figure 3.25*). In southern and western Minnesota, similar layers have produced shark teeth (*Figure 3.26*), sea turtles, and scattered marine invertebrates, including ammonites (*Figure 3.27*), bivalves, and microfossils (**foraminifera**). Abundant fossil leaves of flowering broadleaf plants have been found in south-central Minnesota (*Figure 3.28*).

These Midwestern fossils provide a snapshot of the dramatic changes in marine fauna once the Paleozoic ended. The once-dominant trilobites were now extinct, brachiopods and bryozoans had become very scarce, and tabulate and rugose corals, once abundant, were gone. Reefs remained a crucial ecosystem for marine life, but they were now formed almost exclusively by **scleractinian corals** and bizarre rudist clams. Other mollusks like ammonoid cephalopods, snails, and clams were also much more diverse and abundant than they had

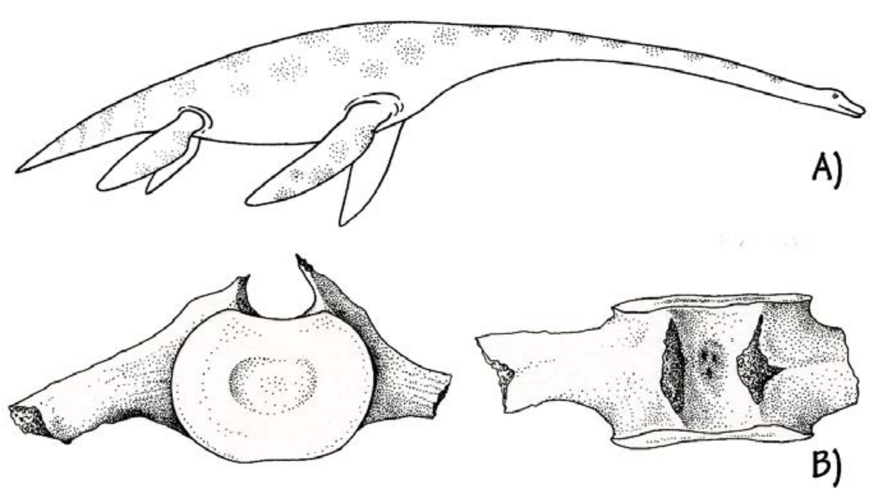


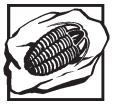
Figure 3.25: A) Reconstruction of a plesiosaur in life. Some plesiosaurs reached 15 meters (50 feet) long. B) Plesiosaur vertebrae. About 20 cm (8 inches) across.

amniotes • *the group of tetrapods distinguished from amphibians by the development of an egg capable of maturing entirely out of water.*

plesiosaur • *a group of extinct long-necked Mesozoic marine reptiles.*

foraminifera • *a class of aquatic protists that possess a calcareous or siliceous exoskeleton.*

scleractinian coral • *a colonial or solitary marine invertebrate animal characterized by an encrusting calcareous skeleton enclosing polyps that capture prey with small tentacles equipped with stinging cells (nematocysts).*



Fossils

Region 2

mosasaurs *• extinct, carnivorous, marine vertebrate reptiles characterized by a streamlined body for swimming, a powerful fluked tail, and reduced, paddle-like limbs.*

ichthyosaurs *• extinct Mesozoic marine reptiles that were probably similar in size and habitat to the toothed whales, dolphins, and large sharks of today.*

pterosaurs *• extinct flying reptiles with wingspans of 30 cm to 15 meters.*

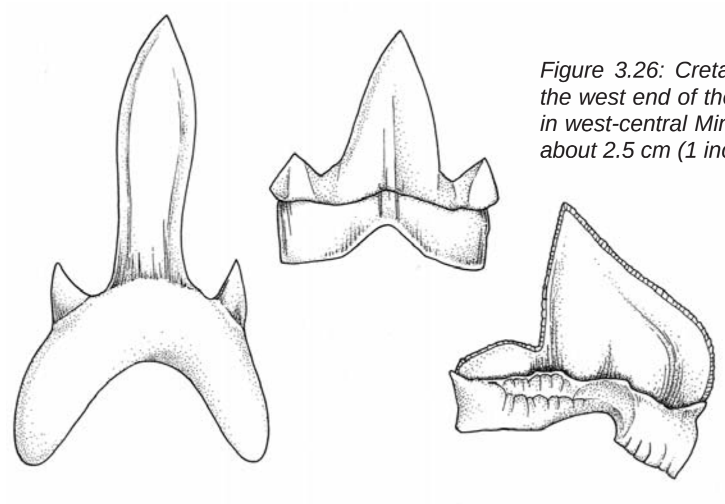


Figure 3.26: Cretaceous shark teeth from the west end of the Minnesota River valley in west-central Minnesota. Tooth on far left about 2.5 cm (1 inch) long.

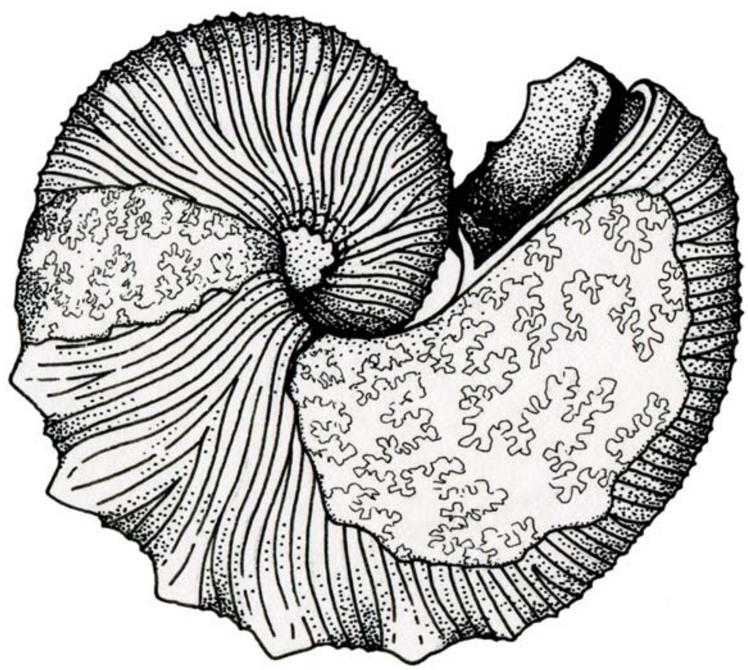


Figure 3.27: Jeletzkytes*, a scaphitid ammonite cephalopod. Fossils of these animals have been found in Cretaceous rocks in southern Minnesota. Specimen is about 10 cm (4 inches) across.*

been during the Paleozoic. Life on land also changed dramatically: by the mid-Cretaceous, flowering plants and insects had suddenly become ubiquitous. In addition to dinosaurs, which dominated the land, various other kinds of reptiles, including **mosasaurs, ichthyosaurs,** and plesiosaurs, dominated the sea, and **pterosaurs** as well as the first birds filled the air. The oceans teemed with newly abundant and diverse bony fish, sharks, and rays.

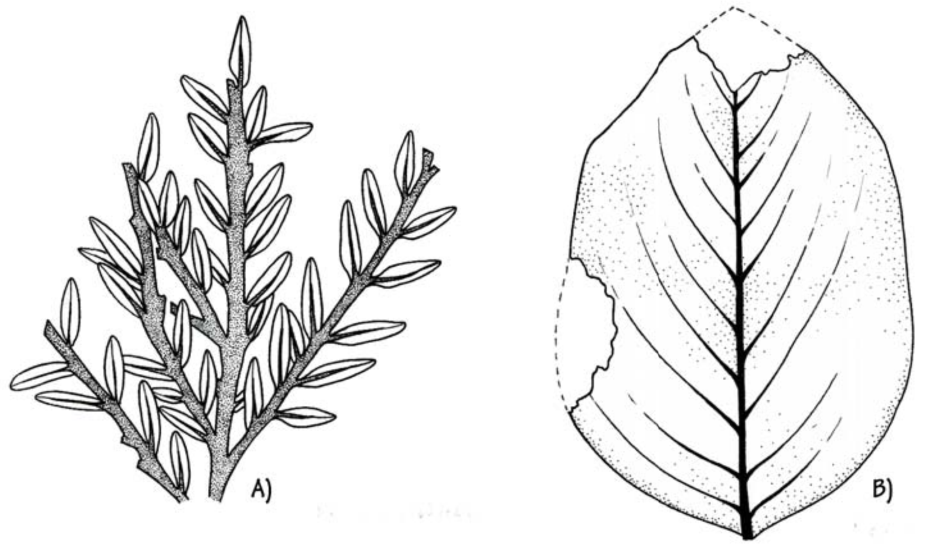


Figure 3.28: Cretaceous fossil leaves from Minnesota. A) Metasequoia *sp. Leaves about 0.25 cm (0.1 inch) long. B)* Magnolia *sp. Leaf about 12 cm (5 inches) long.*

Ice Age Fossils in Pleistocene Deposits

About 2.6 million years ago, permanent ice sheets formed in the Northern hemisphere, marking the beginning of the **Quaternary** period (which extends to the present). During this time, glaciers repeatedly scraped their way southward across the Midwest and melted back northward. Some gaps in the fossil record are due to glaciers eroding bedrock away. Fossils from the Quaternary are found either in pond and stream sediment dating from the receding of glaciers, or they exist as isolated tooth or bone fragments found in glacial **till**. Some important animal fossils are preserved in Pleistocene caves. The glaciers began to retreat from the Midwest about 15,000 years ago, leaving behind the landscape we see today as well as the sediment in which we find fossils and sometimes human artifacts.

As the glaciers melted away from the Midwest, some of the geographic features they created filled with water and formed many of the lakes and ponds present in those states today. Even the **Great Lakes** were formed by ice sheets, though their geologic underpinnings go back much farther. Many smaller bodies of water left by the glaciers have since been filled with sediment and are virtually invisible at the surface. When flooding or construction exposes these pond sediments, the organisms preserved in them are suddenly revealed. Nearly all glacial-age ponds contain a rich fossil record of small freshwater mollusks, pieces of wood, pollen, and seeds, many of which increased over time as plant communities recolonized land freed from the ice. Since the shape of pollen indicates the kind of plant it came from, the pollen record can give a detailed account of how vegetation moved into an area as the **climate** changed. As plants returned, so did large animals: large vertebrate remains include those of **mammoths** (*Figure 3.29*), **mastodons** (*Figure 3.30*), giant beavers, peccaries, tapirs, foxes, bears, seals, deer, caribou, bison, and horses. Numerous mastodon skeletons have been found throughout the Midwest, especially in Michigan, Illinois, Ohio, and Indiana.

Quaternary *• a geologic time period that extends from 2.6 million years ago to the present.*

till *• unconsolidated sediment that is eroded from the bedrock, then carried and eventually depositied by glaciers as they recede.*

Great Lakes *• the largest group of freshwater lakes on Earth (by total surface area and volume), located on the US-Canadian border.*

climate *• a description of the average temperature, range of temperature, humidity, precipitation, and other atmospheric/hydrospheric conditions a region experiences over a period of many years (usually more than 30).*

3 Fossils

Region 2

The remains of a mastodon that is two-thirds complete was discovered near Boaz, Wisconsin. The bones were found with a stone spearhead, suggesting the huge animals were hunted by humans. The point and reconstructed skeleton are housed at the University of Wisconsin in Madison.

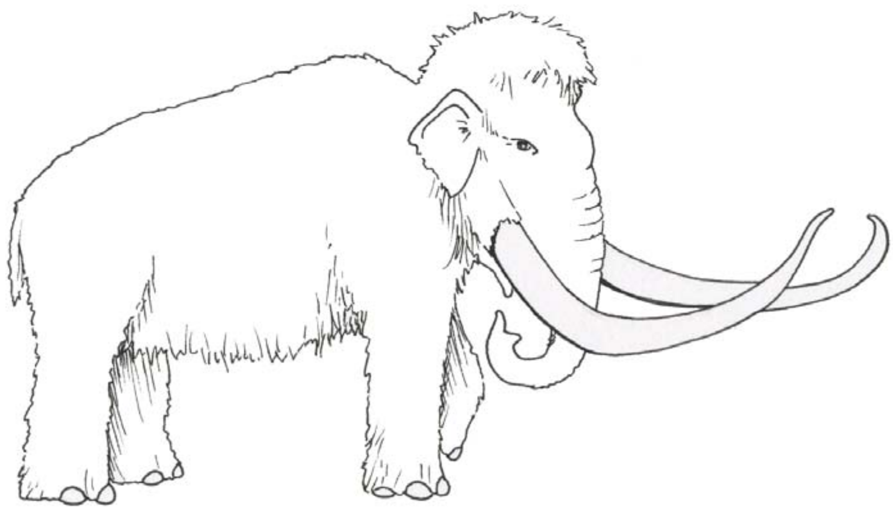


Figure 3.29: A Pleistocene woolly mammoth, Mammuthus primigenius*.*

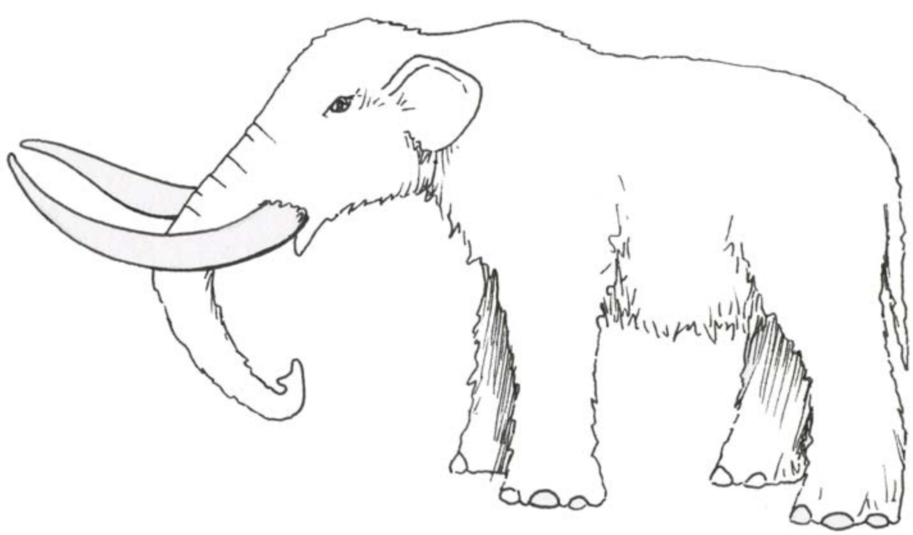
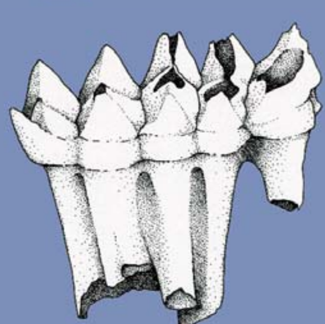


Figure 3.30: A Pleistocene mastodon, Mammut americanum*.*

Mastodons & Mammoths

Among the most common Pleistocene vertebrate fossils in the Midwest are those of mastodons and mammoths. People frequently confuse these two kinds of ancient elephants (or, more technically, proboscideans). Both were common during the Pleistocene, but they had different ecological preferences and are usually found separately. Mammoths are from the same line of proboscideans that gave rise to African and Asian elephants; mastodons are from a separate line of proboscideans that branched off from the modern elephant line in the Miocene. Mastodons have a shorter, stockier build and longer body; mammoths are taller and thinner, with a rather high "domed" skull. In skeletal details, the quickest way to tell the difference is with the teeth: mastodons have teeth with conical ridges, a bit like the bottom of an egg carton; mammoths, in contrast, have teeth with numerous parallel rows of ridges. The teeth are indicative of the two species' ecological differences. Mastodons preferred to bite off twigs of brush and trees, while mammoths preferred tough siliceous grasses. Thus, mastodon teeth are more suitable for cutting, while mammoth teeth are more suitable for grinding.

A mammoth tooth, suitable for grinding grass and softer vegetation. About 25 cm (almost a foot) long.



A mastodon tooth, suitable for chewing twigs and tree leaves. About 20 cm (8–9 inches) long.

Region 3

Fossils of the Inland Basin

Permian • *the geologic time period lasting from 299 to 252 million years ago.*

Carboniferous • *a geologic time period that extends from 359 to 299 million years ago.*

Fossils of the Inland Basin
Region 3

Much of the Inland Basin is located in the Northeastern United States, but the parts extending into the Midwest span nearly 100 million years of the Paleozoic Era. A band of rocks running from extreme northeastern to central southern Ohio are from the Devonian period, while most of the Inland Basin, including eastern Ohio, and the southern portions of Indiana and Illinois, is composed of younger Mississippian and Pennsylvanian rocks. The youngest bedrock of the region, from the **Permian** period, is located in the southeasternmost part of Ohio.

When the rocks of this region were formed, much of central North America was covered by a relatively shallow, tropical, inland sea. The late Devonian- and early **Carboniferous**-aged rocks of the Inland Basin contain the fossils of a diverse marine ecosystem. Younger Carboniferous rocks show the environment transitioning from the shallow sea to an environment of extensive deltas and swamps. These rocks contain the fossils of organisms from freshwater and forest ecosystems.

Marine Environments in the Devonian

During the Devonian period, communities of corals, crinoids, bryozoans, brachiopods, and mollusks thrived in the warm sea that covered most of the Inland Basin. Fish and sharks were also common, but their fossils are much rarer. At the time, what is now the Midwest was just south of the equator. Sediment was washed from the rising Acadian mountain range far to the east, carried down rivers, and deposited into the sea where it settled to the bottom and occasionally buried the organisms living there. Driftwood from the world's first terrestrial forests, made up mostly of lycopod trees, sometimes found its way to the seafloor to be preserved alongside the shells of the animals living there.

The Carboniferous and a Transition to Terrestrial Environments

At the end of the Devonian, fluctuations in sea level caused the water to retreat from portions of the Inland Basin. By the beginning of the Carboniferous, the landscape was dominated by deltas and swampy forests, similar to what occurred in the Central Lowland region at this time. In addition to plants, the fossils of freshwater fish, sharks, early amphibians, and arthropods can be found in coal beds from the late Carboniferous. At the beginning of the Permian, Ohio was a terrestrial environment where lake and river deposits preserved horsetail and fern fossils. These are the youngest fossils found in the Inland Basin's bedrock.

State Fossils

Illinois
Tullimonstrum gregarium (Pennsylvanian “Tully Monster”) (page 68)

Indiana
Indiana has no state fossil.

Iowa
Iowa has no state fossil.

Michigan
Mammut americanum (American Mastodon) (*Figure 3.30*)

Minnesota
Minnesota has no state fossil.

Ohio
Isotelus maximus (Ordovician trilobite) (*Figure 3.7A*)

Wisconsin
Calymene celebra (Ordovician trilobite) (*Figure 3.7B*)

Resources

General Books on the Fossil Record and Evolution

Allmon, W., 2009, *Evolution & creationism: A very short guide*. Paleontological Research Institution: Ithaca, NY.

Benton, M. J., 2008, *The history of life: A very short introduction*. Oxford University Press: Oxford, UK.

Fenton, C. L., & Fenton, M. A., 1958, *The fossil book: a record of prehistoric life* (1st ed.). Doubleday: Garden City, NY. (a well-illustrated classic)

Fortey, R. A., 1998, *Life: a natural history of the first four billion years of life on Earth*. Alfred A. Knopf: New York.

Knoll, A. H., 2003, *Life on a young planet: the first three billion years of evolution on Earth*. Princeton University Press: Princeton, NJ.

Switek, B.,2010, *Written in stone: evolution, the fossil record, and our place in nature*. Bellevue Literary Press: New York.

Thomson, K. S., 2005, *Fossils: a very short introduction*. Oxford University Press: Oxford, UK.

Fossils of Specific Areas

Anderson, W.I., 1998, *Iowa's geological past: Three billion years of change*. University of Iowa Press, Iowa City, 440 p.

Feldmann, R.M., ed., 1995, *Fossils of Ohio*. Ohio Geological Survey Bulletin 70, 577 p.

Hagadorn, J.W., R.H. Dott, and D. Damrow, 2002, Stranded on an Upper Cambrian shoreline: Medusae from central Wisconsin. *Geology*, 30: 147-150.

Han, T. M., and Runnegar, B., 1992, Megascopic eukaryotic algae from the 2.1-billion-year-old Negaunee iron-formation, Michigan. *Science*, 257: 232–235.

Holland , S., 2013, The Stratigraphy and Fossils of the Upper Ordovician near Cincinnati, Ohio. In: *University of Georgia Stratigraphy Lab*. http://strata.uga.edu/cincy/index.html.

Holman, J.A., 2001, *In quest of Great Lakes Ice Age vertebrates*. Michigan State University Press, East Lansing, 230 p.

Kesling, R.V. and Chilman, R.B., 1975, *Strata and megafossils of the Middle Devonian Silica Formation*. University of Michigan Museum of Paleontology Papers on Paleontology No. 8, 408 p.

Kchodl, J.J. and Chase, R., 2006, *The complete guide to Michigan fossils*. University of Michigan Press, Ann Arbor, and Petoskey Publishing Co., Traverse City, 109 p.

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

Mueller, B., and Wilde, W. H.,2004, *The complete guide to Petoskey stones*. University of Michigan Press, Ann Arbor.

Nehm, R.H., Bemis, B.E., 2002, *Common Paleozoic Fossils of Wisconsin*. Wisconsin Geological and Natural History Survey , Educational Series 45, 25 p.

Phillips, T.L., Avcin, M.J., Berggren, D., 1976, *Fossil peat of the Illinois Basin: A guide to the study of coal balls of Pennsylvanian age*. Illinois State Geological Survey, 39 p.

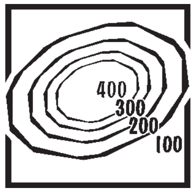
Rose, J.N., 1967, *Fossils and rocks of eastern Iowa. A half-billion years of Iowa history*. Iowa Geological Survey, Educational Series 1, 147 p.

Shabica, C.W., and Hay, A.A. (eds.), 1997, *Richardson's guide to the fossil fauna of Mazon Creek*. Northeastern Illinois University Press: Chicago, 308 p.

Sloan, R., 2005, *Minnesota fossils and fossiliferous rocks*. Published by the author, Winona, MN, 218 p.
Wittry, J., 2012, *The Mazon Creek fossil fauna.* Earth Science Club of Northern Illinois, in association with Northeastern Illinois University, Chicago, 202 p.
Wolf, R., 1983, *Fossils of Iowa: Field guide to Paleozoic deposits*. Iowa State University Press: Ames, 212 p.

Guides to Collecting and Identifying Fossils

Arduini, P., Teruzzi, G., & Horenstein, S. S., 1986, *Simon & Schuster's guide to fossils*. Simon and Schuster: New York.
Garcia, F. A., & Miller, D. S., 1998, *Discovering fossils how to find and identify remains of the prehistoric past*. Stackpole Books: Mechanicsburg, PA.
Lichter, G., 1993, *Fossil collector's handbook: finding, identifying, preparing, displaying*. Sterling Publishing Co.: New York.
Macdonald, J. R., 1983, *The fossil collector's handbook: a paleontology field guide*. Prentice-Hall: Englewood Cliffs, NJ.
Murray, M., 1967, *Hunting for Fossils: A Guide to Finding and Collecting Fossils in All Fifty States*, The Macmillan Company: Toronto, Canada.
Parker, S., 1990, *The Practical Paleontologist. A Step-by-step guide to finding, studying, and interpreting fossils.* Simon and Schuster: New York.
Parker, S., 2007, *Fossil Hunting: An Expert Guide to Finding, and Identifying Fossils and Creating a Collection*. Southwater: London Lanham, MD.
Ransom, J. E., 1964, *Fossils in America: Their nature, origin, identification and classification and a range guide to collecting sites*, Harper and Row, Publishers: New York.
Thompson, I., 1982, *The Audubon Society field guide to North American fossils*. Knopf: New York.
Walker, C., Ward, D. & Keates, C., 2009, *Smithsonian Handbook of Fossils*. Dorling Kindersley Coven Garden Books: New York.



Chapter 4: Topography of the Midwestern US

Does your region have rolling hills? Mountainous areas? Flat land where you never have to bike up a hill? The term **topography** is used to describe the changes in elevation over a particular area and is, generally speaking, the result of two processes: deposition and **erosion**. These processes can happen on an enormous range of timescales. For example, a flash flood can erode away tons of rock in a matter of hours, yet which rock is broken down and which remains can depend on how it was formed hundreds of millions of years ago. In addition to these processes, the topography of the Midwest is intimately tied to **weathering** and erosional forces, along with the type and structure of the underlying bedrock.

Weathering includes both the mechanical and chemical processes that break down a rock. **Wind**, water, and ice are the media by which physical weathering and erosion occur. Streams are constantly trying to erode the bedrock down to sea level, creating valleys in the process. With sufficient time, streams can cut deeply and create wide flat **floodplains** on the valley floor.

Wave action on the shores of the **Great Lakes** contributes to the erosion of rocks and sediments. Ice plays a major role in the weathering and erosion of the Midwest landscape because of the frequent episodes of freezing and thawing in temperate latitudes. On a small scale, as water trapped in fractures within the rock freezes and thaws, the fractures widen farther and farther. This alone can induce significant breakdown of large rock bodies. On a larger scale, ice in the form of **glaciers** in mountain valleys and continental **ice sheets** can reshape the surface of a continent through physical weathering.

Working in conjunction with physical weathering, chemical weathering also helps to break down rocks. Some **minerals** contained in **igneous** and **metamorphic rocks** that are formed at high temperatures and pressures (far below the surface of the Earth) become unstable when they are exposed at the surface where the temperature and pressure are considerably lower, especially when placed in contact with water. Unstable minerals transition into more stable minerals, which results in the breakup of rock. Weak acids, such as carbonic acid found in rainwater, promote the disintegration of certain types of rocks. **Limestone** and **marble** may be rapidly broken down chemically as carbonic acid reacts with the **carbonate** mineral composition of these rocks, forming cavities and caverns in the rock. Other **sedimentary rocks** held together by carbonate cement are also particularly susceptible to chemical weathering.

See Chapter 2: Rocks to learn more about igneous, metamorphic, and sedimentary rocks.

Great Lakes • *the largest group of freshwater lakes on Earth (by total surface area and volume), located on the US-Canadian border.*

glacier • *a body of dense ice on land that does not melt away annually and has sufficient mass to move under its own weight.*

mineral • *a naturally occurring solid with a specific chemical composition and crystalline structure.*

metamorphic rocks • *rocks formed by the recrystallization and realignment of minerals in pre-existing sedimentary, igneous, and metamorphic rocks when exposed to high enough temperature and/or pressure.*

sedimentary rock • *formed through the accumulation and consolidation of grains of broken rock, crystals, skeletal fragments, and organic matter.*

CHAPTER AUTHOR

Alex F. Wall

4 Topography

Review

Devonian • *a geologic time period spanning from 419 to 359 million years ago.*

recrystallization • *the change in structure of mineral crystals that make up rocks, or the formation of new mineral crystals within the rock.*

schist • *a medium grade metamorphic rock with sheet-like crystals flattened in one plane.*

sandstone • *sedimentary rock formed by cementing together grains of sand.*

till • *unconsolidated sediment that is eroded from the bedrock, then carried and eventually depositied by glaciers as they recede.*

plates • *large, rigid pieces of the Earth's crust and upper mantle, which move and interact with one another at their boundaries.*

crust • *the uppermost, rigid outer layer of the Earth, composed of tectonic plates.*

The specific rock type at the surface has an important influence on the topography of a region. Certain rocks are able to resist weathering and erosion more easily than are others; resistant rocks that overlie weaker layers act as caps and form ridges. The inland ocean basins of the Ordovician Taconic and the **Devonian** Acadian mountain-building events collected and preserved sediments that eventually became sedimentary rocks. Sedimentary rocks weather and erode differently than do the crystalline, and generally harder, igneous and metamorphic rocks that are more common in the Superior Upland province. **Silica**-rich igneous rocks have a crystalline nature and mineral composition that resists weathering far better than do the cemented grains of a sedimentary rock. The metamorphic equivalents of sedimentary and igneous rocks are often more resistant due to **recrystallization**. There are exceptions, however, such as **schist**, which is much weaker than its pre-metamorphic limestone or **sandstone** state. Landscapes of unconsolidated sediments like **soil** or glacial **till** are the least resistant to erosion.

The underlying structure of the rock layers also plays an important role in the topography at the surface. Sedimentary rocks are originally deposited in flat-lying layers that rest on top of one another. Movement of tectonic **plates** creates stress and tension within the **crust**, especially at plate boundaries, which often deform the flat layers by folding, **faulting**, intruding, or overturning. These terms are collectively used to describe rock structure, and they can also be used to determine which forces have affected rocks in the past. The folding of horizontal rock beds followed by erosion and **uplift** exposes layers of rock to the surface. Faulting likewise exposes layers at the surface to erosion, due to the movement and tilting of blocks of crust along the fault plane. Tilted rocks expose underlying layers. Resistant layers erode relatively slowly and remain as ridges, while surrounding layers of less resistant rock erode away.

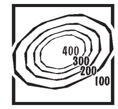
See Chapter 1: Geologic History for more information about the mountain-building events that helped to shape the Midwest.

Glacial ice sheets of the most recent **ice age** covered most of the Midwest and had a dramatic effect on the topography of the area. Glaciers carved away at the land's surface as they made their way generally southward, creating characteristic glacial depositional features such as **drumlins**, **eskers**, and **moraines**. Hills were worn and valleys widened.

See Chapter 6: Glaciers for more about glacial depositional features.

Just as we were able to make sense of the type of rocks in an area by knowing the geologic history of the Midwest, we are able to make sense of its topography (*Figure 4.1*) based on the rocks and structures resulting from past geologic events.

Topography



4

Topography of the Superior Upland

Region 1

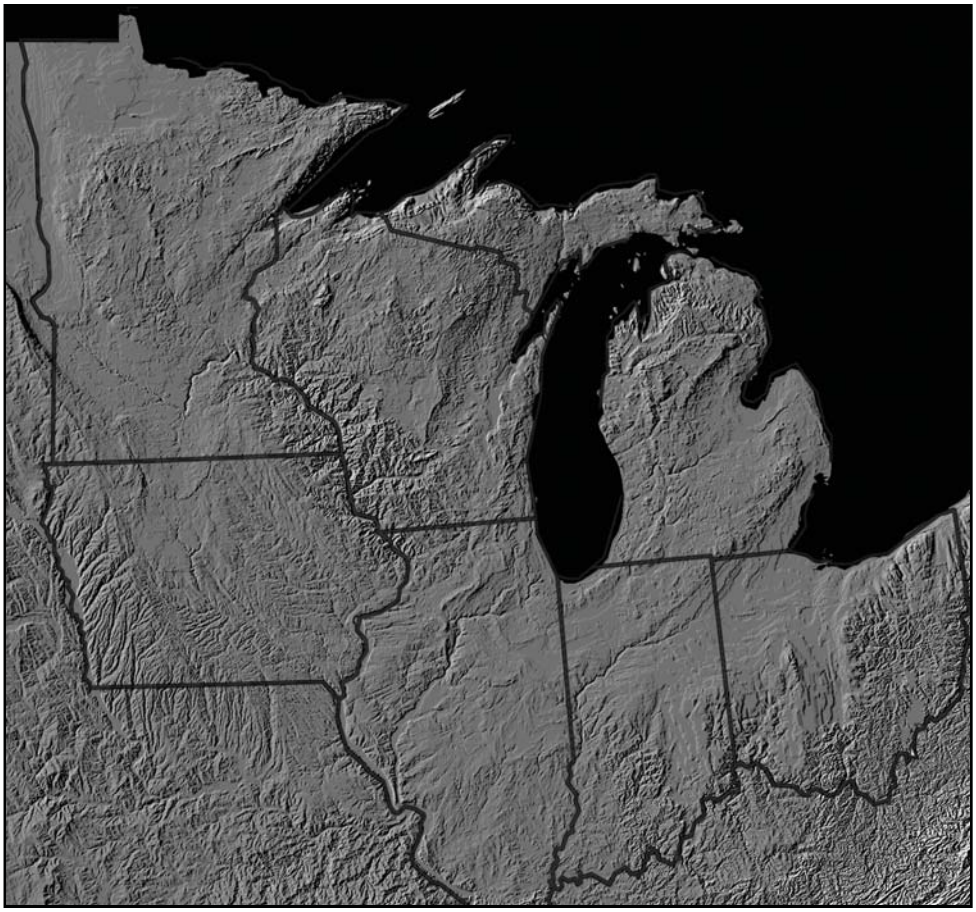


Figure 4.1: Digital shaded relief map of the Midwest.

While the Superior Upland is not mountainous, it has a more dramatic topography than does much of the Midwest. The highest points in each of the three states in the Superior Upland are found in that region, rather than in the southern portions of the states, which are part of the Central Lowland. The ice sheets of the last ice age heavily **scoured** much of the Midwest, but the hard metamorphic and igneous bedrock of this region was more resistant, retaining some of the relief of the mountain ranges that once existed here. Hills reach over 610 meters (2000 feet) above sea level, while the shores of Lake Superior are at about 180 meters (600 feet), and its bottom plunges to more than 210 meters (700 feet) below sea level.

The more easily eroded igneous and sedimentary rocks created during the Midcontinental Rift event 1.1 billion years ago are partially responsible for the depth of the Great Lakes. The **rifting** caused a basin to form that was

Region 1

fault • *a fracture in the Earth's crust in which the rock on one side of the fracture moves measurably in relation to the rock on the other side.*

ice age • *a period of global cooling of the Earth's surface and atmosphere, resulting in the presence or expansion of ice sheets and glaciers.*

drumlin • *a teardrop-shaped hill of till that was trapped beneath a glacier and streamlined in the direction of the flow of the ice moving over it.*

esker • *a sinuous, elongated ridge of sand and gravel.*

moraine • *an accumulation of unconsolidated glacial debris (soil and rock) that can occur in currently glaciated and formerly glaciated regions.*

> ***lava*** • *molten rock located on the Earth's surface.*

> ***Archean*** • *a geologic time period that extends from 4 billion to 2.5 billion years ago.*

repeatedly filled with **lava** flows and sediment. When glaciers scraped across the landscape, they gouged these rocks much more deeply than they did the surrounding **Archean** rocks (*Figure 4.2*).

See Chapter 1: Geologic History for more about this rifting event.

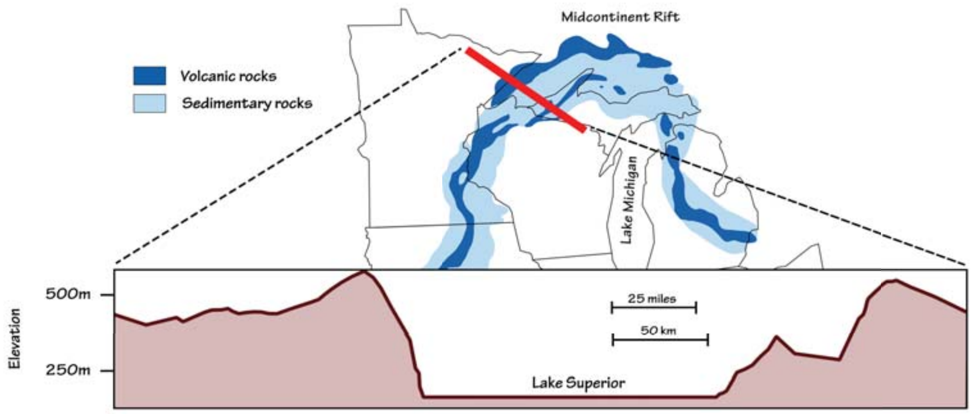


Figure 4.2: Cross-section showing topographic relief across rocks within the Midcontinental Rift.

In addition to wearing down the ancient rugged landscape, glaciers also left deposits on the Superior Upland. Much of the region has a thin layer of glacial till, but, for the most part, the topography is controlled by the underlying bedrock. The drumlin fields north of Duluth are an exception to this generality. These low hills are strongly elongated from the northeast to the southwest, indicating the direction the glaciers flowed while the sediment was deposited to a depth of 15 meters (50 feet).

Topography of the Central Lowland

Region 2

Nearly all of the bedrock in the Central Lowland is sedimentary and fairly easily eroded. During the last ice age, a series of huge ice sheets worked their way primarily southward and flattened most of whatever varied topography the region once had. Furthermore, as the glaciers retreated, they dumped sediment that formed the flatlands and the low, rolling hills that are characteristic of most of the region. There are several areas with present-day relief caused by glacial deposits, especially that created by hill-forming moraines and drumlins. While these formations stand out against the surrounding landscape, they do not usually rise more than 60 meters (200 feet) from base to peak.

Most of the topography of the Central Lowland is controlled by the rivers running through it. Since the ice last retreated from the region, rivers have had only

20,000 years, at the most, to shape the young terrain, so even the largest river valleys are not yet that deep.

Within the Central Lowland, the **Driftless Area** may be viewed as a window into the region's topographic past (*Figure 4.3*). The glaciers of the last several advances did not reach as far south as where the borders of Minnesota, Wisconsin, Iowa, and Illinois meet, leaving that area with bedrock similar to the surrounding landscape but with starkly different topography. Here, streams and rivers have had hundreds of thousands, and perhaps tens of millions, of years to carve steep relief into the same types of rocks that, just miles away, glaciers recently scraped flat. Both mechanical and chemical weathering here have created a **karst topography**, defined by bedrock that has been affected by dissolution in water to form features like sinkholes, caves, and cliffs. The highest points in Iowa and Illinois are both located in the Driftless Area. Given enough time, the rest of the Central Lowland might appear as the Driftless Area does today, after running water washes away the glacial sediment and cuts into the bedrock. West Blue Mound, with an elevation of 523 meters (1716 feet), is the highest point in the Driftless Area, while the Mississippi River is appreciably lower at 184 meters (603 feet). Ultimately, this does not result in huge changes in elevation, but the steep cliffs and valleys contrast dramatically with the nearby flatland.

See Chapter 6: Glaciers for more about the Driftless Area.

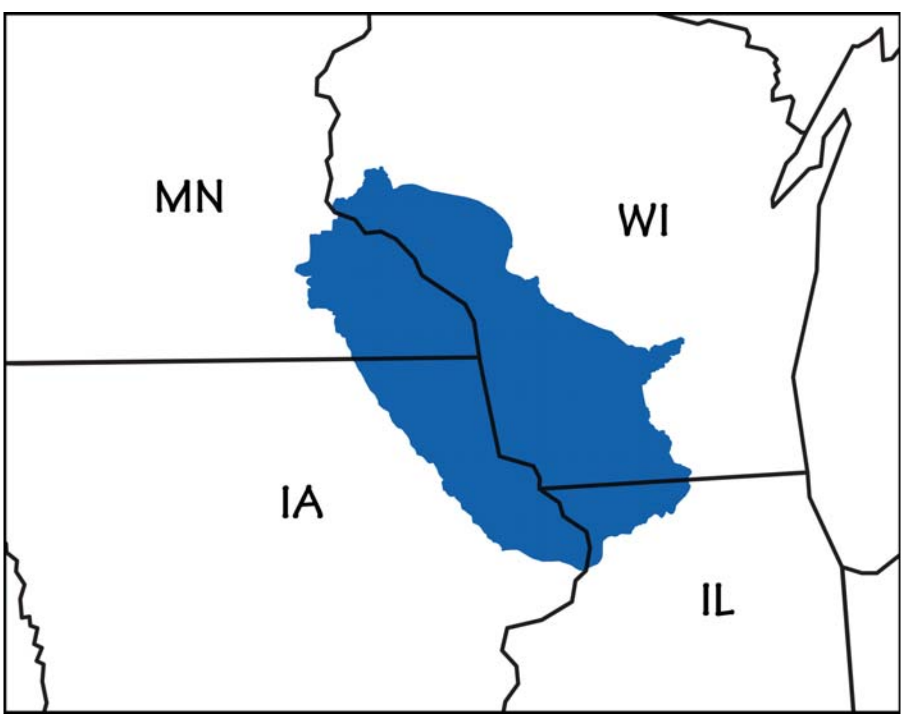


Figure 4.3: Map showing location of the "Driftless Area" of the Central Lowland.

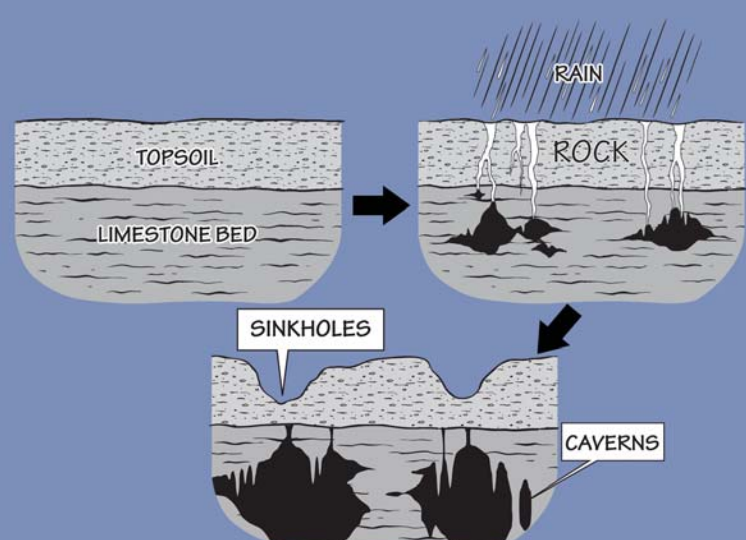
4 Topography

Region 2

atmosphere • a layer of gases surrounding a planet.

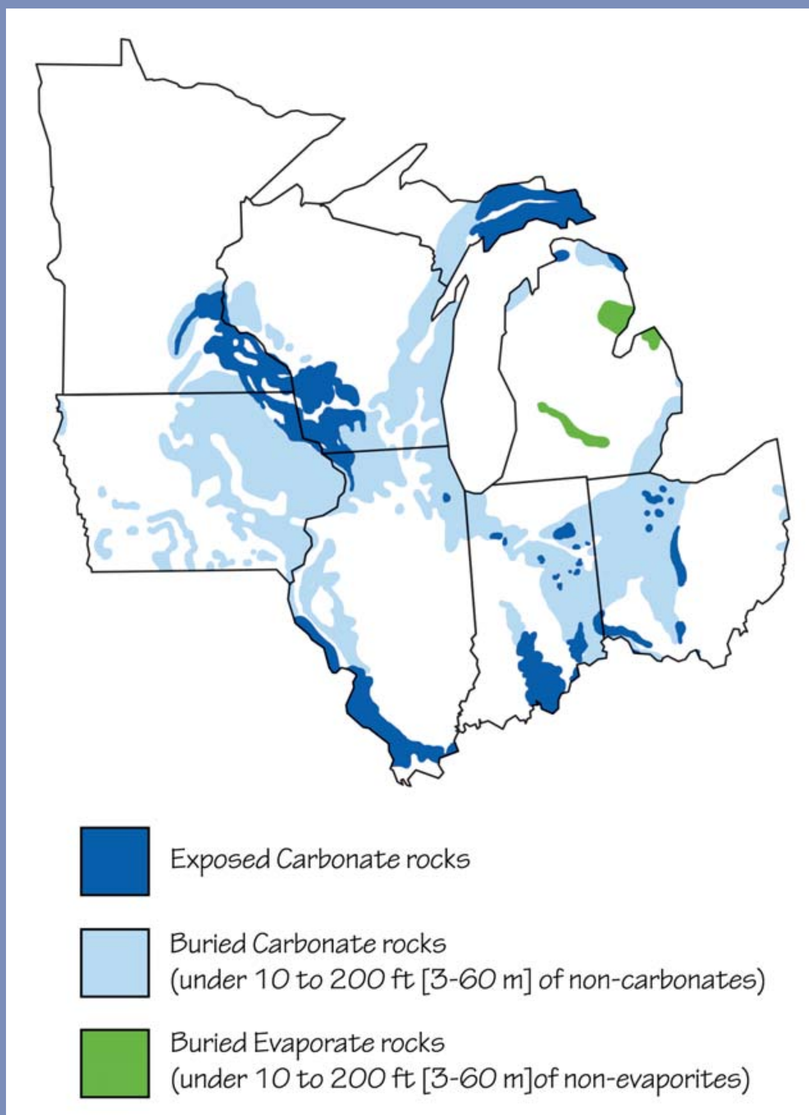
Karst Topography

Karst topography refers to a region where the landscape's features are largely the result of chemical weathering by water, resulting in caves, sinkholes, disappearing and reappearing streams, cliffs, and steep-sided hills called towers. These structures form when water picks up carbon dioxide from the *atmosphere* and ground to form carbonic acid. Even this fairly weak and dilute acid dissolves carbonate rocks (such as limestone) relatively easily, resulting in dramatic features while other rock is comparatively unaffected. Karst is found in every state except Hawaii, and it is the source of a significant amount of our drinking water, particularly in the Midwest. While common, karst is not always easily identifiable since it is often not expressed at the surface or its topography has been affected by other factors. Karst topography is a relatively mature type of landscape, taking many tens of thousands of years to develop, and it can indicate that a region has been free of other forms of erosion, or deposition, for an extended period. Karst topography in the Midwest is found in places that were not eroded by glaciers during the last ice age, including northern Michigan, Mitchell Plateau and Muscatatuck Plateau in Indiana, and the Driftless Area. (See discussion above in Topography of the Central Lowland and Chapter 6: Glaciers.)



inland sea • a shallow sea covering the central area of a continent during periods of high sea level.

Karst Topography (continued)



Topography of the Inland Basin
Region 3

The Inland Basin is a large region that extends from southern Illinois to northern Alabama to central New York. Its rock formed primarily in the basins of **inland seas** many millions of years ago, and while its origin affects the way it is eroded, its topography is quite varied. In the Midwest, the region includes only eastern Ohio, southern Indiana, and the southernmost portion of Illinois.

4 Topography

Region 3

Most of the eastern half of Ohio is part of the Allegheny Plateau, which extends from northeastern Kentucky well into central New York. This portion of Ohio is further divided into glaciated and unglaciated areas (*Figure 4.4*). The glaciated northwest portion is quite flat, with relief features of little more than 30 meters (100 feet) high. The southeast portion of the state was never flattened by glaciers or buried in till, so relief here is several times greater, occasionally reaching up to 120 meters (400 feet). Millions of years of running water carving into the bedrock has resulted in high hills, steep cliffs, and gorges.

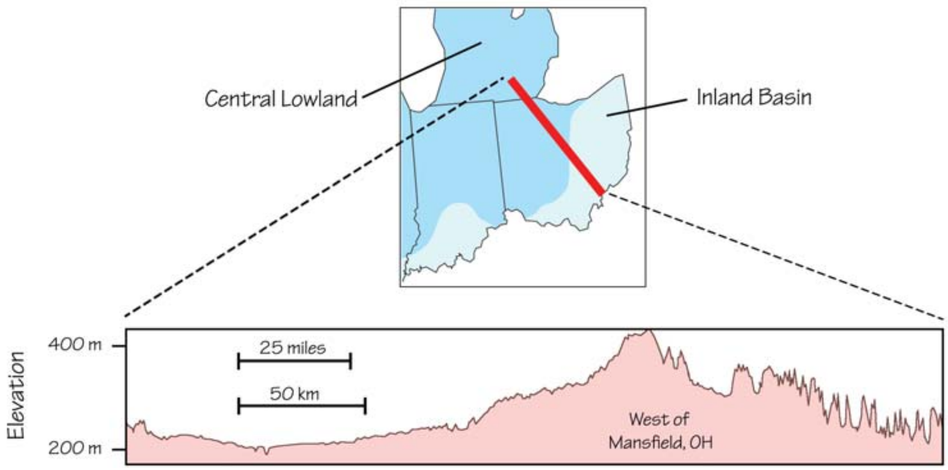


Figure 4.4: Inland Basin topography, showing the difference in elevation between glaciated and unglaciated areas.

The portions of southern Indiana and Illinois that were not glaciated have a landscape similar to that of southeastern Ohio: a modest degree of relief, but substantially more rugged than the northern (previously glaciated) portions of those states.

An important distinction is that, because much of the bedrock in the Inland Basin is carbonate, this area commonly displays karst features. Caves are not uncommon in Ohio, but many of them are located in the Central Lowland portion of the state. The bedrock of southern Indiana and Illinois is, in areas, riddled with limestone caves.

Highest and Lowest Elevations *(by state)*

Illinois

Charles Mound, Illinois' highest point at 376 meters (1235 feet), is located in the state's extreme northwest and is part of the Driftless Area. The state's lowest point, at 85 meters (280 feet), is the confluence of the Ohio and Mississippi Rivers at the state's southern tip.

Elevations

Indiana
Extreme eastern Indiana is home to Hoosier Hill, which, at 383 meters (1257 feet), is the state's highest point. The confluence of the Ohio and Wabash Rivers is Indiana's lowest point at 97 meters (320 feet).

Iowa
Hawkeye Point, the highest point in Iowa at 509 meters (1670 feet), is just south of the Minnesota border in the northwest. Iowa's lowest point of 146 meters (480 feet), the confluence of the Des Moines and Mississippi Rivers, also marks the southeasternmost point in the state.

Michigan
Michigan's highest point, located on the Upper Peninsula, is Mt. Arvon at 603 meters (1979 feet). Lake Erie is 174 meters (571 feet) above sea level, the lowest elevation in Michigan.

Minnesota
Eagle Mountain is the highest point in Minnesota at 701 meters (2301 feet). Interestingly, it is only 24 kilometers (15 miles) from Lake Superior, which, at 183 meters (601 feet) above sea level, is the state's lowest elevation.

Ohio
Campbell Hill, 472 meters (1550 feet) high, is located in the city of Bellefontaine, in eastern central Ohio, and it is the state's highest point. The southern extreme of the state's border with Indiana, on the Ohio River, is Ohio's lowest point at 139 meters (455 feet).

Wisconsin
At 595 meters (1951 feet) above sea level, Timms Hill, located in the northern central part of Wisconsin, is the highest point in the state. The state's lowest elevation is Lake Michigan at 177 meters (581 feet).

Resources

Books

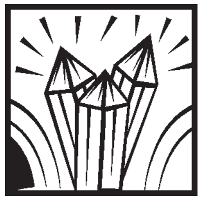
Wyckoff, J., 1999, *Reading the Earth: landforms in the making*. Adastra West, Inc.: Mahwah, NJ.

Websites

Color Landform Atlas of the US (Low resolution shaded relief maps of each state.)
http://fermi.jhuapl.edu/states/states.html.

[Wisconsin] Major landscape features. Wisconsin Geological & Natural History Survey.
http://wgnhs.uwex.edu/wisconsin-geology/major-landscape-features/.

[Wisconsin] Karst and sinkholes. Wisconsin Geological & Natural History Survey.
http://wgnhs.uwex.edu/water-environment/karst-sinkholes/.



Chapter 5: Mineral Resources of the Midwestern US

What is a mineral?

A **mineral** is a naturally occurring solid with a definite chemical composition and crystalline structure. Minerals provide the foundation of our everyday world. Not only do minerals make up the rocks we see around us in the Midwest, they are used in nearly every aspect of our lives. The minerals found in the rocks of the Midwest are used in industry, construction, machinery, technology, food, makeup, jewelry, and even the paper on which these words are printed.

Elements: The Building Blocks of Minerals

Elements are the building blocks of minerals. The mineral quartz, for example, is made of the elements silicon and oxygen. Most minerals present in nature are not composed of a single element, though there are exceptions such as gold (Au). Eight elements make up (by weight) 99% of the Earth's crust, with oxygen being by far the most abundant (46.4%). The remaining elements in the Earth's crust occur in very small amounts, some in concentrations of only a fraction of one percent (*Figure 5.1*). Since silicon (Si) and oxygen (O) are the most abundant elements in the crust by mass, it makes sense that quartz (SiO_2, silicon dioxide or silica) is one of the most common minerals in the Earth's crust and is found all over the Midwest.

Minerals provide the building blocks for rocks. For example, **granite**, an **igneous rock**, is typically made up of crystals of the minerals **feldspar**, **quartz**, **mica**, and **amphibole**. **Sandstone** may be made of cemented grains of feldspar, quartz, and mica. The minerals and the bonds between the crystals define a rock's color and resistance to **weathering**.

Metallic minerals are vital to the machinery and technology of modern civilization. However, metallic minerals occur in extremely small amounts in

granite • *a common and widely occurring type of igneous rock.*

igneous rocks • *rocks derived from the cooling of magma underground or molten lava on the Earth's surface.*

feldspar • *an extremely common, rock-forming mineral found in igneous, metamorphic and sedimentary rocks.*

quartz • *the second most abundant mineral in the Earth's continental crust (after feldspar), made up of silicon and oxygen (SiO_2).*

mica • *a large group of sheetlike silicate minerals.*

amphibole • *a group of dark colored silicate minerals, or either igneous or metamorphic origin.*

CHAPTER AUTHOR

Alex F. Wall

5

Mineral Resources

Review

crust • *the uppermost, rigid outer layer of the Earth, composed of tectonic plates.*

copper • *a ductile, malleable, reddish-brown metallic element (Cu).*

iron • *a metallic chemical element (Fe).*

sulfur • *a bright yellow chemical element (S) that is essential to life.*

diamond • *a mineral form of carbon, with the highest hardness of any material.*

gypsum • *a soft sulfate mineral that is widely mined for its use as fertilizer and as a constituent of plaster.*

erosion • *the transport of weathered materials.*

calcite • *a carbonate mineral, consisting of calcium carbonate ($CaCO_3$).*

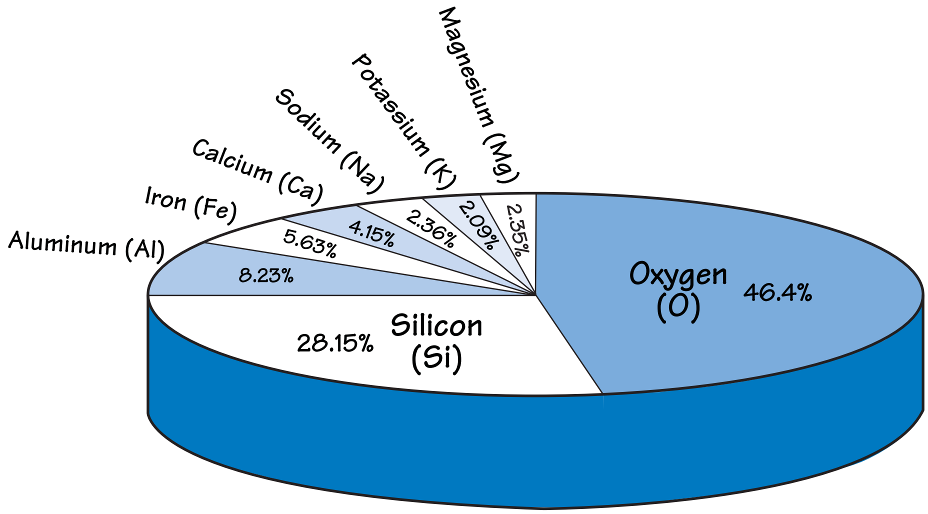


Figure 5.1: Mineral percentage by mass in the Earth's crust.

the **crust**. In addition, it is almost always necessary to process **ore** minerals in order to isolate the useful element. A mineral is called an ore when one or more of its elements can be profitably removed. For example, chalcopyrite ($CuFeS_2$), which contains **copper**, **iron**, and **sulfur**, is referred to as a copper ore when the copper can be profitably extracted from the iron and sulfur.

Non-metallic minerals do not have the flash of a metal, though they may have the brilliance of a **diamond** or the silky appearance of **gypsum** ($CaSO_4 \cdot 2H_2O$). Generally much lighter in color than metallic minerals, non-metallic minerals can transmit light, at least along their edges or through small fragments.

Mineral Identification

Although defined by their chemical composition and crystal structure, minerals are identified based on their physical properties. A variety of properties must usually be employed in identifying a mineral, each eliminating possible alternatives.

Hardness is a very useful property for identification, as a given mineral can only exhibit a narrow range of hardnesses, and it is easily testable, which quickly and simply minimizes the number of possibilities. Hardness is important because it helps us understand why some rocks are more or less resistant to weathering and **erosion**. Quartz, with a rating of 7 on the **Mohs scale**, is a relatively hard mineral, but **calcite** ($CaCO_3$), rating 3 on the Mohs scale, is significantly softer. Therefore, it should be no surprise that quartz sandstone is much more resistant to erosion and weathering than is **limestone**, which is primarily made of the mineral calcite. Quartz is a very common mineral in the Earth's crust and is quite resistant due to its hardness and relative insolubility. Thus, quartz grains are the dominant mineral type in nearly all types of **sand**.

Color is helpful in identifying some minerals like sulfur, but it is uninformative or even misleading in others like garnet. **Luster** describes how light is reflected

Mohs Scale of Hardness

In 1824, the Austrian mineralogist Friedrich Mohs selected ten minerals to which all other minerals could be compared to determine their relative hardness. The scale became known as Mohs scale of hardness, and it remains very useful as a means for identifying minerals or for quickly determining their hardness. A fingernail has a hardness of around 2, a penny 3, window glass 5.5, and a knife blade 6.5.

1	Talc
2	Gypsum
3	Calcite
4	Fluorite
5	Apatite
6	Feldspar
7	Quartz
8	Topaz
9	Corundum
10	Diamond

from a mineral's surface and can range from adamantine, seen in diamonds, to dull or earthy (effectively no luster), like kaolinite. **Crystal form**, if visible, can be diagnostic. For example, **fluorite** and calcite may appear superficially similar, but fluorite forms cubic crystals while calcite forms trigonal-rhombohedral crystals. Relatedly, crystals may have planes of weakness that cause them to break in characteristic ways, called **cleavage**. Or they may not, and instead display **fracture** when broken. Mica and **graphite** have very strong cleavage, allowing them to easily be broken into thin sheets, while quartz and glass (the latter not being a mineral) have no cleavage, instead displaying a distinctive curved fracture form known as conchoidal. The **density** of a mineral may also aid in identifying it (e.g., metals tend to be very dense). Finding the exact density is straightforward, but it does require measuring the volume of the sample. Placing an unknown mineral in water (or other liquid) to find its volume by displacement can be a risky undertaking since several minerals react violently with water, and many more break down with exposure. A mineral's **streak** is obtained by dragging it across a porcelain plate, effectively powdering it. The color of the powder eliminates conflating variables of external weathering, crystal habit, impurities, etc. Some minerals are **magnetic** (affected by magnetic fields), while a few are natural magnets (capable of producing a magnetic field).

Most minerals can be identified by process of elimination after examining a few of these properties and consulting a mineral identification guide. Mineral testing kits often include several common objects used to test hardness: a porcelain streak plate, a magnet, and a magnifying glass. Some minerals have rare properties, which may be more difficult to test. For example, there are minerals that exhibit **luminescence** of all types, giving off light due to a particular stimulus. Some minerals are **radioactive**, usually due to the inclusion of significant amounts of uranium, thorium, or potassium in their structure. **Carbonate** minerals will

Review

sand • *rock material in the form of loose, rounded, or angular grains, and formed as a result of the weathering and decomposition of rocks.*

crystal form • *a physical property of minerals, describing the shape of the mineral's crystal structure.*

fluorite • *the mineral form of calcium fluoride (CaF_2).*

graphite • *a mineral, and the most stable form of carbon.*

density • *a physical property of minerals, describing the mineral's mass per volume.*

streak • *a physical property of minerals, obtained by dragging the mineral across a porcelain plate and effectively powdering it.*

luminescence • *to give off light.*

radioactive • *when an unstable atom loses energy by emitting radiation.*

Review

effervesce • *to foam or fizz while releasing gas.*

double refraction • *the result of light passing through a material that splits it into two polarized sets of rays, doubling images viewed through that material.*

Precambrian • *a geologic time period that spans from the formation of Earth (4.6 billion years ago) to the beginning of the Cambrian (541 million years ago).*

effervesce when exposed to hydrochloric acid. **Double refraction** describes the result of light passing through a material that splits it into two polarized sets of rays, doubling images viewed through that material. For example, a single line on a sheet of paper will appear as two parallel lines when viewed through a clear calcite crystal.

There are many more interesting and distinguishing properties that minerals may possess, and there are many more elaborate and precise means for identifying them. The branch of geology that studies the chemical and physical properties and formation of minerals is called *mineralogy*.

What distinguishes a regular mineral from a gem?

Beauty, durability, and rarity of a mineral qualify it as a gemstone. Beauty refers to the luster, color, transparency, and brilliance of the mineral, though to some degree it is dependent on the skillfulness of the cut. Most gems, including tourmaline, topaz, and corundum, are durable because they are hard, making them scratch-resistant. On the Mohs scale of hardness, the majority of gemstones have values greater than 7. Isolated deposits of semi-precious gemstones can be found in each state in a variety of places, but they are not mined commercially (except as noted below), and precious gemstones are extremely rare in the Midwest.

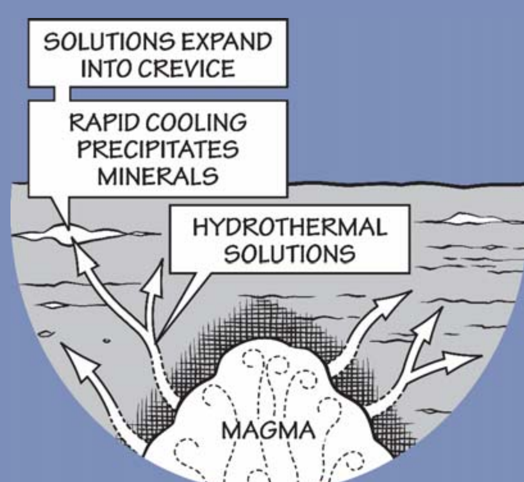
Mineral Formation

Geologists looking for particular minerals do not make haphazard guesses as to the location of ore bodies. The occurrence of minerals in the Earth's crust is due to the geologic processes that formed certain rock types in a given area. An understanding of the environments in which minerals form, the minerals that make up different rocks, and the geologic history of an area, all help geologists ascertain where minerals of interest are concentrated. Metallic minerals are often associated with igneous and metamorphic rocks, which typically occur in either very ancient rocks (**Precambrian**) or in areas of severe deformation of the crust, such as where continents have collided.

Mineral deposits may be formed in several ways: precipitation out of water, crystallization of **magma** or **lava**, **recrystallization** after exposure to heat and pressure, or the dissolution and later precipitation of minerals by hot water moving through cracks and openings in rock located well below the surface. A mineral is not necessarily restricted, however, to one method of concentration or environment of formation. For example, gypsum may form as a precipitate from evaporating water, but it is also associated with **volcanic** regions where limestone and sulfur gases from the volcano have interacted.

What are hydrothermal solutions?

Hot water enriched in salts such as sodium chloride (NaCl), potassium chloride (KCl), and calcium chloride ($CaCl_2$) is called a *hydrothermal solution*, or simply "brine." The brine is as salty or even saltier than seawater and, surprisingly, may contain minute bits of dissolved minerals such as gold, lead, copper, and zinc. The presence of salt in the water stops the metallic minerals from precipitating out of the brine because the chlorides in the salt preferentially bond with the metals. Additionally, because the brine is hot, the minerals are more easily dissolved, just as hot tea dissolves sugar more easily than cold tea does. These hot water brines can have varying origins. As magma cools, it releases its mineral-enriched, super-heated water into surrounding rock. Rainwater becomes a hydrothermal solution by picking up salt as it filters through rocks. Seawater, which is already enriched in salt, often becomes a hydrothermal solution in the vicinity of volcanic activity on the ocean floor where *tectonic plates* are pulling apart. Rapid cooling of the hydrothermal solution over short distances allows concentrations of minerals to be deposited. Water moving quickly through fractures and openings in the rock, experiencing changes in pressure or composition and being diluted with groundwater, can rapidly cool a hydrothermal solution.



Review

magma • *molten rock located below the surface of the Earth.*

lava • *molten rock located on the Earth's surface.*

recrystallization • *the change in structure of mineral crystals that make up rocks, or the formation of new mineral crystals within the rock.*

plate tectonics • *the way by which the plates of the Earth's crust move and interact with one another at their boundaries.*

5 Mineral Resources

Region 1

In the discussions of each region to follow, the focus is on the following: currently mined and other significant minerals; where the minerals are most common (though they may occur in other places as well); and how the minerals formed in each particular area relate to the surrounding rocks and geologic history.

***Canadian Shield* •** *the stable core of the North American continental landmass, containing some of the oldest rocks on Earth.*

***mantle* •** *the layer of the Earth between the crust and core.*

***basalt* •** *an extrusive igneous rock, and the most common rock type on the surface of the Earth.*

***gabbro* •** *a usually coarse-grained, mafic and intrusive igneous rock.*

***sedimentary rock* •** *formed through the accumulation and consolidation of grains of broken rock, crystals, skeletal fragments, and organic matter.*

Mineral Resources of the Superior Upland

Region 1

The Superior Upland portion of the **Canadian Shield** is composed mostly of igneous and metamorphosed Precambrian rock. Plumes of magma that welled up from the **mantle** (and then cooled) formed expanses of igneous rocks like granite, **basalt**, and **gabbro**. **Sedimentary rock**, including **banded iron formations**, formed as sediment slowly accumulated under the ancient ocean. Later, **metamorphism** converted much of the igneous rock into **gneiss** and the sedimentary rock into **quartzite**. Some **nickel**, copper, and platinum are produced in the region, but these are secondary products in the mining of the Superior Upland's dominant mineral resource: iron. Minnesota and Michigan are the states that produce, respectively, the most and second most iron ore in the US. The ore, primarily **hematite** (Fe_2O_3) and **magnetite** (Fe_3O_4), is mined from banded iron formations (*Figure 5.2*).

Banded iron formations (BIFs) are rocks with regular, alternating thin layers of iron oxides (e.g., hematite and magnetite) and either shale or silicate minerals (e.g. chert, jasper, and agate). For example, BIFs in Michigan are composed of jasper between layers of hematite/magnetite and are found on Jasper Knob near Marquette. They are a primary source of iron ore, and their formation is discussed in Chapter 9: Climate.

In Minnesota, iron is principally produced from the aptly named Biwabik Iron Formation in Itasca and Saint Louis Counties. Two large open pit mines operate in Marquette County, in the Marquette Range found in the north central portion of Michigan's Upper Peninsula. Most of the iron is used to make steel. The portion of the Superior Upland found in Wisconsin is not yet used for mineral resources. It is, however, quarried for stone used in construction and industry.

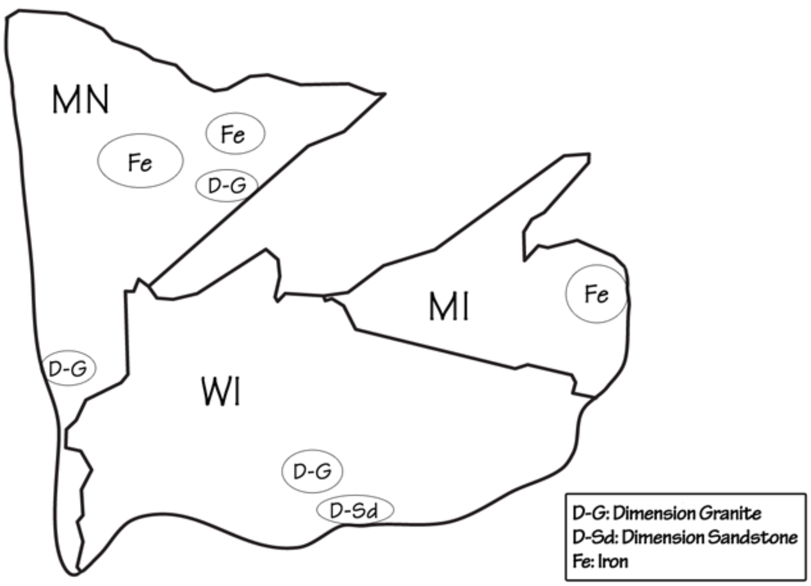


Figure 5.2: Principal mineral-producing localities in the Superior Upland, associated particularly with crystalline Precambrian basement rocks and sedimentary banded iron formations (see Chapter 1: Geologic History and Chapter 2: Rocks).

Mineral Resources of the Central Lowland
Region 2

The Central Lowland is not widely exploited for mineral resources because its near-surface minerals are not commercially valuable. Nearly all of the bedrock in this large region formed as sediment under shallow seas. Limestone and **shale**, the most common rocks, do not tend to be rich in commercially significant minerals, though the rocks themselves are often quarried for building materials. The ancient seas, like the modern ocean, contained dissolved **salts** that were eventually preserved in rocks around the Central Lowland. These **evaporite** minerals, formed by precipitation out of solution in water, are mined commercially in Michigan's Lower Peninsula, and, to a lesser extent, in Iowa.

Wells in Manistee County tap into deposits of **brine** rich in magnesium oxide, allowing Michigan to produce more magnesium compounds than any other state. Magnesium is relatively abundant in seawater, and the brines deposited under Michigan are the remains of an ancient sea that once covered Michigan and much of the Central Lowland. Marine deposits in Manistee County and Osceola County are also mined for **halite** (salt) and **potash** (in Osceola County alone), making the state a leading producer of those minerals as well (*Figure 5.3*).

metamorphic rocks • *rocks formed by the recrystallization and realignment of minerals in pre-existing sedimentary, igneous, and metamorphic rocks when exposed to high enough temperature and/or pressure.*

gneiss • *a metamorphic rock that may form from granite or layered sedimentary rock such as sandstone or siltstone.*

quartzite • *a hard metamorphic rock that was originally sandstone.*

nickel • *a ductile, silvery-white metallic element (Ni).*

evaporite • *a sedimentary rock created by the precipitation of minerals directly from seawater, including gypsum, carbonate, and halite.*

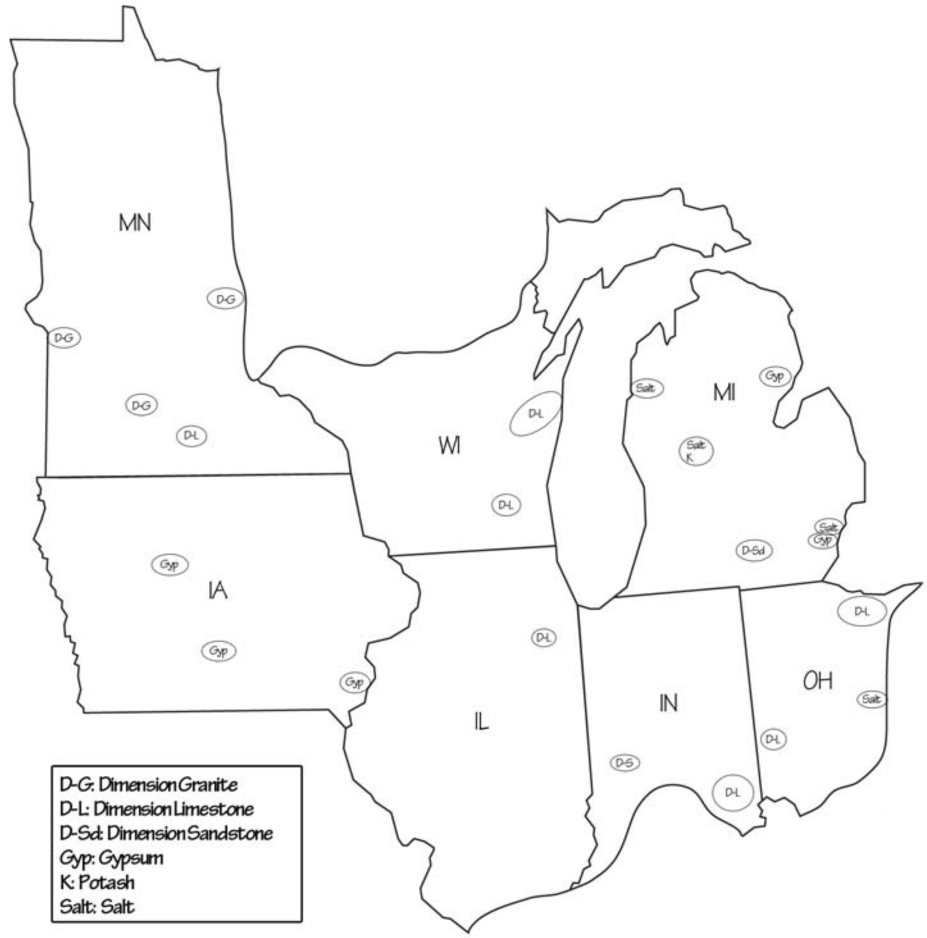


Figure 5.3: Principal mineral-producing localities in the Central Lowland, associated primarily with Paleozoic deposition of sand, carbonate sediments, and occasionally evaporates in warm shallow continental seas of the Paleozoic (see Chapter 1: Geologic History and Chapter 2: Rocks).

Halite (NaCl) is mined in two ways. When deposited in thick beds, salt can be excavated by mechanically carving and blasting it out. This method, called "room and pillar" mining, usually requires that pillars of salt be left at regular intervals to prevent the mine from collapsing (*Figure 5.4*). Another method, called solution mining, involves drilling a well into a layer of salt. In some cases, the salt exists as part of a brine that can then be pumped to the surface and the water removed, leaving salt. In others, fresh water is pumped down to dissolve the salt, and the solution is brought back to the surface where the salt is removed (*Figure 5.5*).

Potash is a name used for a variety of salts containing potassium, with mined potash being primarily potassium chloride (KCl). The majority of potash is used as fertilizer, but an increasing amount is being used in a variety of other ways: water softening, snow melting, a variety of industrial processes, as a medicine, and to produce potassium carbonate (K_2CO_3).

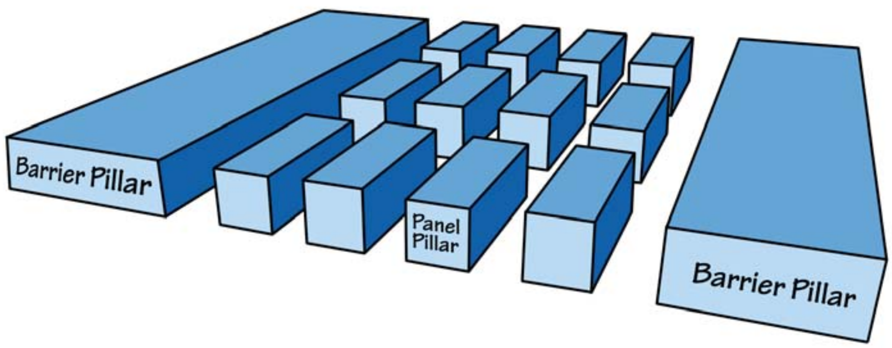


Figure 5.4: In pillar and room mining, the mine is divided up into smaller areas called "panels." The panels are separated from one another by extra-large (barrier) pillars that are designed to prevent total mine collapse in the event of the failure of one or more regular-sized (panel) pillars.

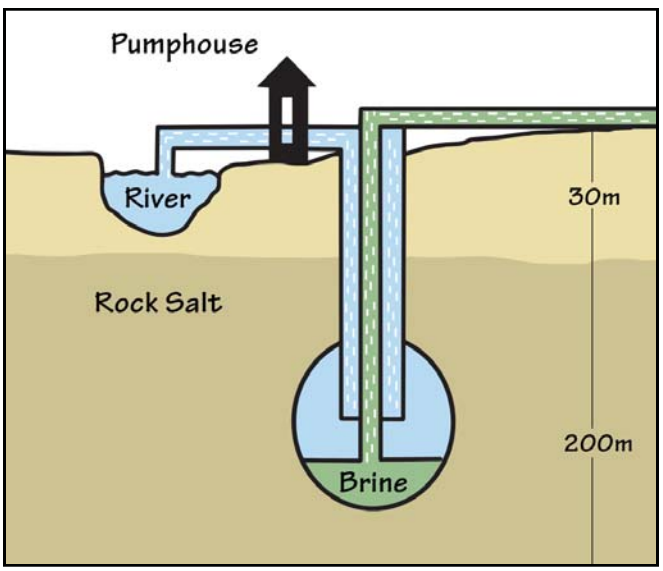


Figure 5.5: An example of solution mining that involves the pumping of fresh water through a borehole drilled into a subterranean salt deposit.

Region 2

Michigan Formation *• a ring-like stratum in the rock of the Michigan Basin, where most of the state's gypsum is mined.*

Gypsum, ($CaSO_4$-H_2O) another evaporite mineral, is mined in Michigan and is currently the only mineral resource exploited in all parts of the Central Lowland, especially Iowa. Iosco and Kent Counties in Michigan both lie on the **Michigan Formation**, the source of their gypsum. Iowa is typically the second or third largest producer of gypsum in the country. Deposits are found along the Des Moines River Valley running from north central to the southeastern corner of the state. The Fort Dodge Beds are mined in Webster County, the Saint Louis Formation in Marion County, and the Wapsipinicon Formation in Des Moines County. Gypsum is used in plaster and wallboard. It is the mineral assigned the value of 2 on the Mohs scale of mineral hardness, meaning that it is softer than a fingernail.

5 Mineral Resources

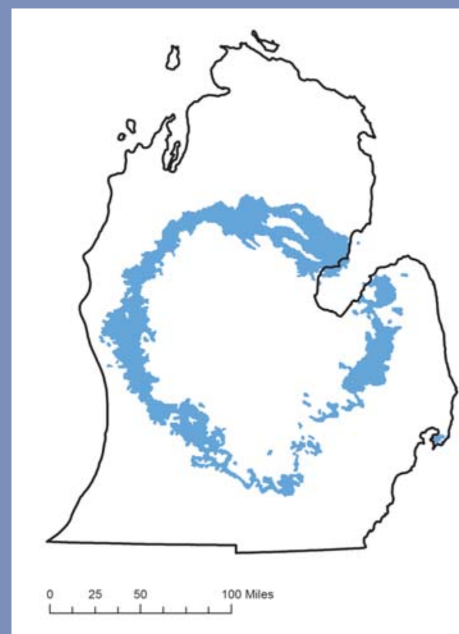
Regions 2–3

inland basin • *a depression located inland from the mountains, and formed by the buckling (downwarping) of the Earth's crust.*

Mississippian • *a subperiod of the Carboniferous, spanning from 359 to 323 million years ago.*

The Michigan Formation

The bedrock of Michigan's Lower Peninsula forms a basin where older rocks can be imagined curving up from below to cup the younger strata in the center. This produces some formations that appear as rings on geologic maps. For example, the Michigan Formation, where most of the state's gypsum is mined, can be found in a nearly continuous band around, but at least 64 kilometers (40 miles) from, the center of the Lower Peninsula. The formation of Michigan's *inland basin* is described in Chapter 1: Geologic History.



Mineral Resources of the Inland Basin

Region 3

Because the Inland Basin is represented in a relatively small area in the Midwest and its rocks are not particularly rich in minerals, this region contains little in the way of exploitable mineral resources. The ancient seas of the **Mississippian** era, during which the rocks formed, provided some evaporite minerals, but they are commercially viable to mine in only a few places. Rock salt is mined in northeastern Ohio, beginning in Cuyahoga, Lake, Wayne, and Summit Counties, and sometimes going deep under Lake Erie. Farther south, Licking County also produces salt. The only other mineral resource produced in the Inland Basin of the Midwest is in Martin County, Indiana, where gypsum is mined (*Figure 5.6*).

Region 3

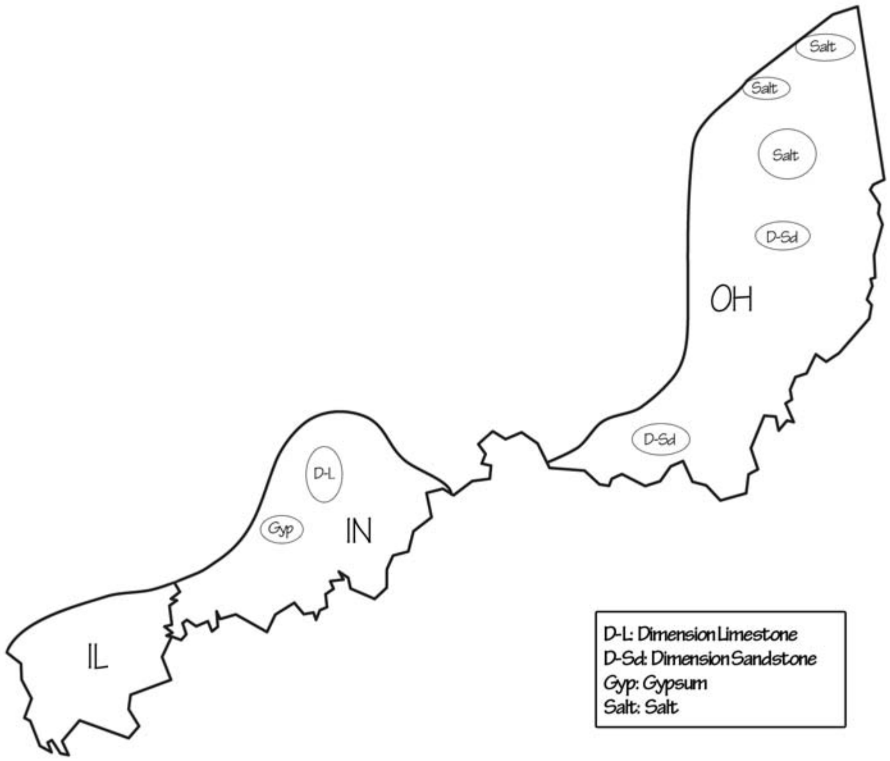


Figure 5.6: Principal mineral-producing localities in the Inland Basin, associated primarily with Paleozoic deposition of sand, carbonate sediments, and occasionally evaporates in the warm shallow continental seas filling the Appalachian Basin (see Chapter 1: Geologic History and Chapter 2: Rocks).

Mississippian rocks in Illinois host Illinois' state mineral: fluorite (CaF_2). During the **Jurassic**, more than 100 million years after the limestone bedrock was laid down, geothermally heated water full of dissolved chemicals was forced through existing cracks. Fluorite crystals precipitated onto the walls of these cracks, forming Illinois' famous deposits. Fluorite is mined primarily to be converted into hydrogen fluoride (HF), a chemical with a wide range of applications. While colorful and translucent, fluorite is too soft to see extensive use as a semiprecious gemstone.

Jurassic • *the geologic time period lasting from 201 to 145 million years ago.*

Resources

Books

Skinner, B. J., 1989, Mineral Resources of North America, In: Bally, A.W. & Palmer, A.R. (eds.), *The Geology of North America – An overview*. The Geology of North America, vol. A, Geological Society of America, Boulder, CO, pp. 575–584.

State-based Resources

USGS Minerals Yearbook, Volume II – Area Reports: Domestic, State and Territory chapters, http://minerals.usgs.gov/minerals/pubs/state/index.html#pubs. (State-by-state information about mineral mining and production.)

Minerals of Wisconsin, Wisconsin Geological and Natural History Survey. http://wgnhs.uwex.edu/wisconsin-geology/minerals-wisconsin/.

Economic Minerals Prominent in the Midwest

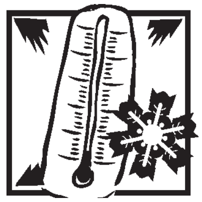
Fluorite: The Illinois State Mineral, Illinois Department of Natural Resources. http://dnr.state.il.us/mines/education/indus2.htm.

Gypsum the Commodity, Indian Geological Survey. http://igs.indiana.edu/MineralResources/Gypsum.cfm.

Rock Salt Mining, Michigan State University. http://web2.geo.msu.edu/geomich/saltminingM.html.

Salt Mining, How Stuff Works. http://science.howstuffworks.com/innovation/edible-innovations/salt.htm.

Iron mining. http://wgnhs.uwex.edu/wisconsin-geology/iron-mining.



Chapter 6: Glaciers of the Midwestern US

The ancient geologic history of the Midwest is often disguised by its more recent geologic history, one that was dominated by **glaciers**. During the **Quaternary** period, which began just 2.6 million years ago and extends to the present, ice at times extended southward from the Hudson Bay area and began to encroach on the northern United States. At different points during the Quaternary period, ice has covered all of the Midwest except for the extreme southern parts of Illinois, Indiana, Ohio, and a unique region called the **Driftless Area** (*Figure 6.1*). These **ice sheets** scraped away and ground up whatever rock was at the surface. When the ice finally retreated, it dropped its load of rock and dirt, forming much of the landscape we see today and obscuring the bedrock below in many feet of sediment. More than any other force, the glaciers are responsible for the landscape of the Midwest: they smoothed peaks, filled valleys, pocked the area with ponds, and carved the **Great Lakes**. Because the ice sheets affected the Superior Upland, Central Lowland, and Inland Basin similarly, this chapter discusses the Midwest as a whole.

Fig 6.1: Extent of glaciation over North America at the Last Glacial Maximum.

glacier • *a body of dense ice on land that does not melt away annually and has sufficient mass to move under its own weight.*

Quaternary • *a geologic time period that extends from 2.6 million years ago to the present.*

Driftless Area • *a region that did not experience glaciation, located in parts of southwestern Wisconsin, eastern Minnesota, and northeastern Illinois and Iowa.*

ice sheet • *a mass of glacial ice that covers part of a continent and has an area greater than 50,000 square kilometers (19,000 square miles).*

Great Lakes • *the largest group of freshwater lakes on Earth (by total surface area and volume), located on the US-Canadian border.*

CHAPTER AUTHOR

Alex F. Wall

6 Glaciers

Review

climate • *a description of the average temperature, range of temperature, humidity, precipitation, and other atmospheric/hydrospheric conditions a region experiences over a period of many years (usually more than 30).*

firn • *compacted glacial ice, formed by the weight of snow on top.*

topography • *the landscape of an area, including the presence or absence of hills and the slopes between high and low areas.*

Glaciers will only form under certain conditions and in specific environments. A cold **climate** and sufficient moisture in the air for the precipitation of snow are both necessary factors that permit at least some snow to last year-round. This allows for the build-up and compaction of snow that will eventually become glacial ice. Sufficiently cold climate conditions exist at high altitudes and high latitudes.

Glacial ice is formed as snow is buried; the weight of more snow above causes lower layers to compact. Individual flakes break down by melting, refreezing, and bonding to the snow around them, eventually forming grains called **firn**. This process can be facilitated with water filling the space between flakes, but the pressure alone will cause the flakes to melt and refreeze. Air is forced up and out, or into bubbles, increasing the density of the ice. As more snow falls at the surface, adding more weight, the firn becomes denser and denser until the ice crystals interlock, effectively leaving no space between them—this is known as glacial ice. At a depth greater than about 50 meters (165 feet), the pressure is high enough for plastic flow to occur. Ice flow is driven by gravity, and it causes movement downhill and out from the center.

Most broadly, there are two types of glaciers: smaller alpine glaciers and larger continental glaciers. Found in mountainous regions, alpine glaciers have a shape and motion that is largely controlled by **topography**, and they naturally flow from higher to lower altitudes. Continental glaciers are much larger, and they are less controlled by the landscape, tending to flow outward from their center of accumulation.

It is not surprising that today's continental glaciers, also called ice sheets, are located in the high latitude polar regions of Greenland and Antarctica, where temperatures are low most of the year. There must be landmasses at high latitudes for continental glaciers to occur, as they cannot form over open water. While persistent sea ice can and does form, because it floats, it does not flow as a glacier does. The glaciers that stretched over North America 20,000 years ago were primarily continental ice sheets.

Alpine glaciers are found at high altitudes, and they sometimes occur relatively close to the equator. They accumulate snow at their tops and flow downhill. Alpine glaciers may fill part of a single valley, or they may cap an entire mountain range.

While only the two broadest categories of glaciers are discussed here, glaciers exist in a diversity of forms. Even this broadest of distinctions is not completely clean-cut (e.g., continental glaciers often have tongues that feed into valleys, which may become alpine glaciers).

In general, glaciers grow when it is cool enough for the ice sheet to accumulate snow more quickly than it melts. As they grow, ice sheets become so massive that they flow outwards, covering an increasing area until melting at the margins catches up to the pace of accumulation. Glaciers in the Midwest flowed from centers of accumulation to the north (now Canada), and glacial growth southward through the Midwest was more a result of this lateral flow than of direct precipitation from falling snow.

Glacial Landscapes

The interaction of the glaciers with the landscape is a complex process. **Scouring** abrades bedrock and removes sediment, while melting causes the ice to deposit sediment. Glacial features like **moraines**, **drumlins**, and **kettles** occasionally break the pattern of gently rolling hills found in most of the Midwest. Even in southernmost Illinois, Indiana, Ohio, and the Driftless Area where the glaciers did not reach, glacial runoff changed the landscape: meltwater loaded with abrasive sediment carved the landscape, making it more rugged.

Erosion

Thousands of years of scraping by ice can have dramatic, and sometimes dramatically varied, effects on a landscape. An important factor determining the effect is the kind of rock being **eroded**. Harder bedrock will be scratched and polished by sediment stuck in the ice, while **frost wedging**, when water freezes and expands in cracks, can eventually break chunks of rock away. Softer bedrock is much more easily carved and crushed.

The flowing ice cracks and breaks rock as it passes over, pieces of which become incorporated in the sheet or bulldozed forward, in front of the glacier's margin. The process of glaciers picking up sediment in this way is called **plucking**. The less resistant rock over which glaciers move is often eroded and ground-up into very fine **sand** and **clay** (called **rock flour**). More resistant **igneous** and **metamorphic rock** is often polished and scratched by the grinding action of the sediments in the glacial ice. Streams of meltwater from the glacier, frequently gushing and full of sediment, cause significant amounts of scour as well. The abrasive sediments in the flowing water create **potholes** in the bedrock and

How do we know the mark of glaciers?

How do we know that striations, polish, scoured basins, U-shaped valleys, and the variety of deposits attributed to glaciers are in fact a result of glacial action? Before the modern understanding of the ice ages, many believed that the features now attributed to glaciers were the result of a great flood similar to the one found in the Biblical story of Noah and the Ark. By studying modern glaciers, however, geologists have come to understand the resulting features of glacial scour and deposition that are readily identified in much of the Midwest. Modern glaciers include the large-scale ice sheets in Greenland and Antarctica as well as the small-scale valley glaciers found in mountain ranges in places such as Alaska, Canada, and the Alps.

Landscapes

scouring • *erosion resulting from glacial abrasion on the landscape.*

moraine • *an accumulation of unconsolidated glacial debris (soil and rock) that can occur in currently glaciated and formerly glaciated regions.*

drumlin • *a teardrop-shaped hill of till that was trapped beneath a glacier and streamlined in the direction of the flow of the ice moving over it.*

kettle • *a lake formed where a large, isolated block of ice became separated from the retreating ice sheet.*

frost wedging • *weathering that occurs when water freezes and expands in cracks.*

plucking • *process in which a glacier "plucks" sediments and larger chunks of rock from the bedrock.*

pothole • *a shallow, rounded depression eroded in bedrock by a glacier.*

plunge pool • *a stream pool, lake, or pond that is small in diameter, but deep.*

silt • *fine granular sediment most commonly composed of quartz and feldspar crystals.*

till • *unconsolidated sediment that is eroded from the bedrock, then carried and eventually depositied by glaciers as they recede.*

plunge pools at the base of waterfalls. At the edge of the sheet, where the ice at last succumbs to melting, the rock is finally deposited. Piles of this rock form many of the distinctive landforms found in the Midwest today.

The nature of the glacier causing the erosion is also crucial. Because continental glaciers spread from a central accumulation zone, they can't go around peaks in their path, so they instead slowly crush and scrape them away. For the most part, this results in flatter landscapes. Conversely, alpine glaciers tend to follow the existing topography, flowing downhill. This frequently causes them to scour existing low places, making them lower still. While this gouging increases the overall relief of an area, anything directly in the path of the ice is flattened. For example, a glacier might deepen a valley while surrounding peaks remain high, yet the valley itself, initially cut by a narrow stream into a sharp V-shape, is smoothed into a distinctive U-shape by the wider glacier.

Deposition

As glaciers scrape over the earth, sediment is incorporated into or shoved ahead of the advancing ice (*Figure 6.2*). The unsorted mixture of boulders, gravel, sand, **silt**, and clay that is picked up and later deposited by glaciers is called **till**. It is important to note that whether a glacier is advancing, in equilibrium, or retreating, its ice is still flowing forward, like a conveyor belt that is constantly depositing till at its margin. Where a glacier stopped its advance and then melted back, a ridge of till that had been pushed in front of it is left behind,

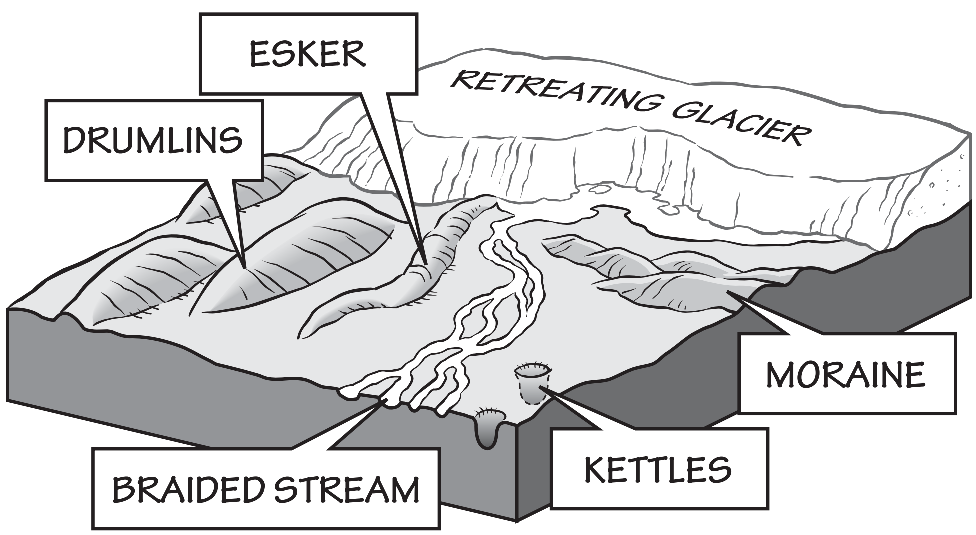


Figure 6.2: Glacial features.

marking the farthest extent of its margin, or terminus. A ridge of till formed this way is called a moraine, and it may range in length from hundreds to thousands of meters. A drumlin is a teardrop-shaped hill of till that was trapped beneath a glacier and streamlined in the direction of the flow of the ice moving over it. The elongation of a drumlin is an excellent clue to the direction of flow during an ice sheet's most recent advance.

Landscapes

Meltwater flowing off a glacier also leaves behind deposits. Unlike till deposits, meltwater deposits are well-sorted: large rocks can only be moved by high-energy water, while finer sand and mud are washed downstream until enough energy is lost that even they are dropped. In other words, the faster the water is moving, the coarser the sediment deposited (*Figure 6.3*). As a glacier melts, streams of sediment-laden meltwater often create networks of **braided streams** in front of the glacier. Streams of meltwater flowing under a glacier can deposit sand and gravel. When an ice sheet retreats, these snaking ridges of stream deposits, known as **eskers**, are left standing.

Other glacial features include kettles, **kames**, and **erratics**. Kettles are depressions left behind by the melting glacier. Blocks of ice may be broken off from the glacier and buried or surrounded by meltwater sediments (*Figure 6.4*). When the ice eventually melts, the overlying sediments have no support, so they frequently collapse and form a depression that often fills with water to become a lake. Many kettle lakes and ponds are found throughout the Midwest, particularly the 10,000 lakes area of Minnesota, and most of the inland lakes of Wisconsin and Michigan formed in this way as well. Kames are formed in nearly the opposite way; layers of sediment fill in depressions in the ice, leaving mound-like deposits of sorted sediment after the glacier retreats (*Figure 6.5*). Often the kettles and kames occur near one another. Erratics are rocks that the ice sheet picked up and transported further south, sometimes hundreds of miles from their origin.

braided stream • *a stream consisting of multiple, small, shallow channels that divide and recombine numerous times, forming a pattern resembling strands of braided hair.*

kame • *an irregularly shaped mound made up of sediment that accumulated in a depression on a retreating glacier.*

erratic • *a piece of rock that differs from the type of rock native to the area in which it rests, carried there by glaciers often over long distances.*

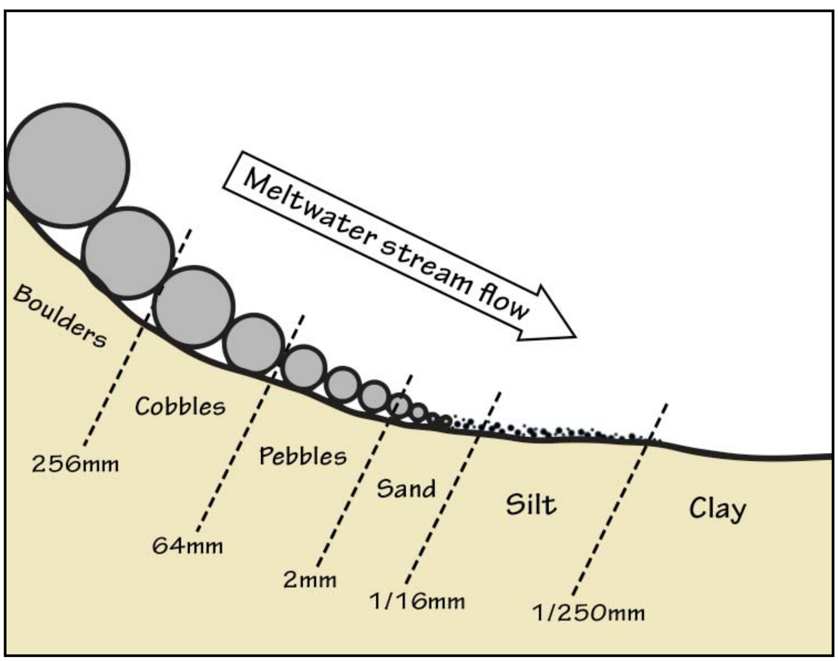


Figure 6.3: Moving water deposits sediments in what is known as a horizontally sorted pattern. As the water slows down (i.e., loses energy), it deposits the larger particles first.

A well-sorted deposit has a relatively uniform grain size.

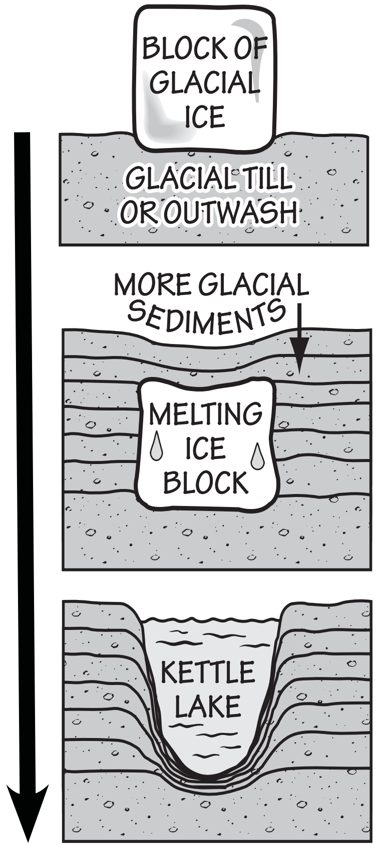


Figure 6.4: Steps in the formation of a kettle lake.

Erratics **are often distinctive because they are a different type of rock than the bedrock in the area to which they've been transported. For example, boulders and pebbles of igneous and metamorphic rocks are often found in areas where the bedrock is sedimentary; it is sometimes possible to locate the origin of an erratic if its composition and textures are highly distinctive. Anyone who has tried to till a field or garden in the Midwest is familiar with rocks like this.**

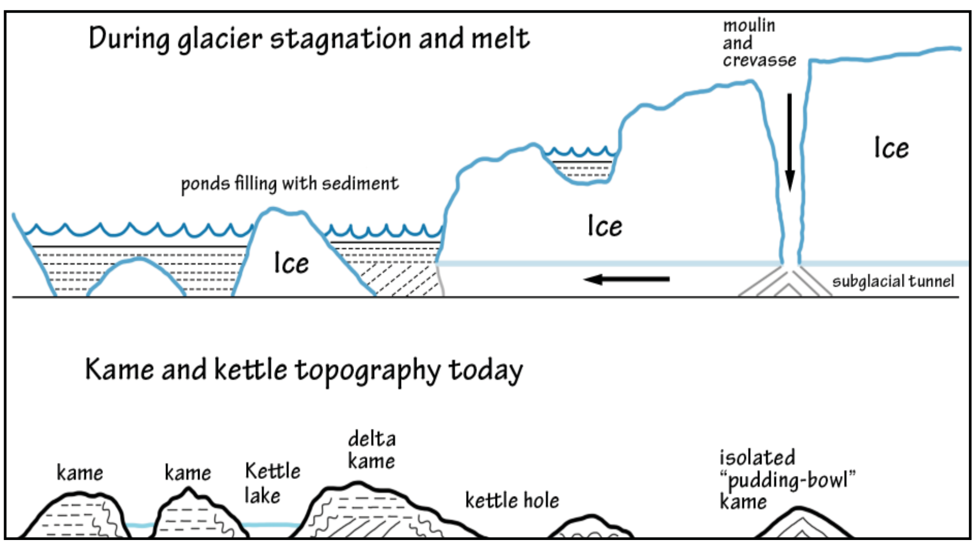


Figure 6.5: Glacial sediment deposits and the resulting hills called kames.

Periglacial Environments

Though a few areas in the Midwest were never covered by the ice sheet, the entire area felt its effects. The portion covered by the ice sheet was scoured and covered with glacial deposits; the area south of the ice sheet has its own distinctive landscape and features because it was next to the ice margin. This unglaciated but still affected zone is called a **periglacial zone**.

> **The average annual air temperature in a periglacial area is between -12° and 3°C (10° and 37°F). Though the surface of the ground may melt in the summer, it refreezes in the winter.**

There are a variety of features associated with a periglacial zone that also provide clues to the extent of the most recent ice sheet. In the tundra-like environment of a periglacial zone, **aeolian**, or windblown deposits are common. Sand dunes and **wind**-transported sediments are found in former periglacial areas and in glacial lake bottoms of the Midwest.

The **permafrost** associated with the periglacial area, in which the ground is frozen much of the year, can cause mass movement of sediment. When the surface layer of the permafrost ground thaws, it is full of moisture. This water-heavy layer of **soil** may move rapidly down a hill in a process called **solifluction**.

Physical **weathering** of the bedrock is magnified in the periglacial environment because of the freeze-thaw cycles associated with permafrost. When water enters the cracks and fissures in the ground and subsequently freezes, the ice wedges the cracks farther and farther apart (*Figure 6.6*). Freeze-thaw is important in any climate that vacillates above and below the freezing point of water. Because ice takes up more space than water, the pre-existing cracks and fractures are widened when the water freezes. Along ridges, rocks are eventually broken off as ice wedges continue to expand in joints and fractures. The boulders and blocks of bedrock roll downhill and are deposited along the slope or as fields of **talus**. Frost action also brings cobbles and pebbles to the surface to form nets, circles, polygons, and garlands of rocks. These unusual patterns of sorted rock are known as **patterned ground**. Solifluction and ice wedging are found exclusively where the ground remains perennially frozen, yet is not insulated by an ice sheet. Such conditions only occur in areas adjacent to ice sheets. While conditions like these existed in the Midwest at this time and led to the formation of patterned ground, any evidence was subsequently covered with glacial sediment or eroded away.

> ***Physical weathering* is the break-up of rock due to physical processes (such as erosion by wind, water, and ice) rather than chemical processes.**

wind • *the movement of air from areas of high pressure to areas of low pressure.*

permafrost • *a layer of soil below the surface that remains frozen all year round. Its thickness can range from tens of centimeters to a few meters.*

soil • *the collection of natural materials that collect on Earth's surface, above the bedrock.*

solifluction • *a type of mass wasting where waterlogged sediment moves slowly downslope, over impermeable material.*

talus • *debris fields found on the sides of steep slopes, common in periglacial environments.*

Ice Ages

last glacial maximum • *the most recent time the ice sheets reached their largest size and extended farthest towards the equator, about 26,000 to 19,000 years ago.*

Neogene • *the geologic time period extending from 23 to 2.6 million years ago.*

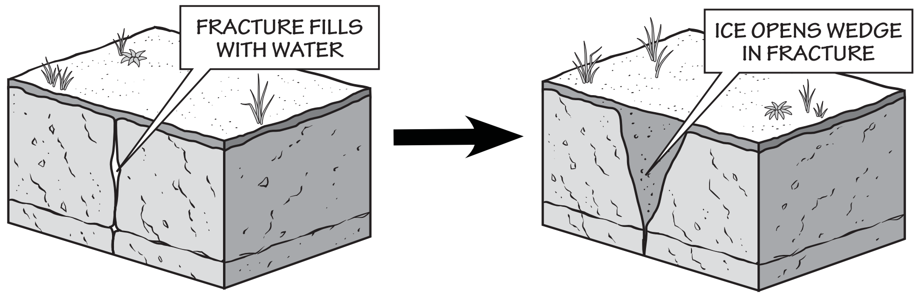


Figure 6.6: Physical weathering from a freeze-thaw cycle.

Ice Ages Over Time

As discussed in Chapter 9: Climate, for much of Earth's history there have not been persistent ice sheets in high latitudes. Any time that the world is cool enough to allow them to form is called an "**ice age**." We are therefore living in an ice age right now! The current ice age began about 34 million years ago when ice sheets were first forming on Antarctica, followed by Greenland at least 18 million years ago, and finally on North America, which defined the beginning of the Quaternary period (about 2.6 million years ago). When most people use the phrase "the ice age," however, they are referring to the **last glacial maximum** that saw much of North America and Europe covered in ice thousands of meters / feet thick, while many kinds of large, wooly mammals roamed the unfrozen portions of those continents.

Age of the Quaternary

In 2009, scientists at the International Commission on Stratigraphy voted to move the base of the Quaternary period to 2.6 million years ago, bumping it to 0.8 million years earlier than the previous date of 1.8 million years ago—a date set in 1985. They argued that the previous date was based on data that reflected climatic cooling that was only local to the region in Italy where it was first observed. On the other hand, the 2.6 million year mark shows a global drop in temperature, and it includes the entirety of North American and Eurasian glaciation, rather than dividing it between the Quaternary and the earlier *Neogene* period.

Ice Ages

plates *• large, rigid pieces of the Earth's crust and upper mantle, which move and interact with one another at their boundaries.*

The Quaternary period is divided into two epochs. The earlier **Pleistocene** encompasses the time from 2.6 million to 11,700 years ago, including all of the Quaternary up until the most recent episode of glacial retreat. Most of the glacial features in the Midwest were created during the Pleistocene, because by the beginning of the **Holocene** 11,700 years ago, the glaciers had already retreated from much of the area.

Ice on a Schedule

The enormous continental glaciers that define an ice age are so large that their extent is most directly affected by global trends, while mountain glaciers are much more susceptible to local and short-term changes in climate. Continental ice sheets advance and retreat in cycles that last tens of thousands of years, controlled to a large extent by astronomic cycles.

Astronomic Cycles and Ice Sheets

The cyclical movements of ice sheets seem primarily to be caused by specific astronomic cycles called *Milankovitch cycles*, which change the amount of light the Earth receives, particularly when comparing the summer to the winter. The cycles, predicted through principles of physics a century ago, are related to the degree of tilt of the Earth, the Earth's distance to the sun, and the point in the Earth's revolution around the sun that the Northern Hemisphere experiences summer. When the cycles interact such that there are cool summers at high latitudes in the Northern Hemisphere (milder rather than extreme seasonality), glaciers can accumulate and thus advance. The cyclicity of glacial-interglacial advances was about 40,000 years from before the start of the Quaternary until about a million years ago. For reasons that aren't clear, however, the cycles changed to about 100,000 years. If not for human-induced climate change, we might expect glaciers to cover the Midwest again in about 80,000 years!

Scientists continue to debate the particular causes of the onset of glaciation in North America over two million years ago. Movement of the Earth's tectonic **plates** may have been a direct or indirect cause of the glaciation. As plates shifted, continents moved together and apart, changing the size and shape of the ocean basins. This, in turn, altered oceanic currents. Mountain building, which occurred when continents collided, erected obstacles to prevailing winds

Ice Ages

Wisconsinian glaciation *• the most recent interval of glaciation, which occurred during the Pleistocene, 85,000 to 11,000 years ago.*

Illinoian *• a period of glaciation that occurred during the Pleistocene, 191 to 131 thousand years ago.*

and changed moisture conditions. The freshly exposed rock from the rising of the Himalayas also combined with atmospheric carbon dioxide through chemical weathering; this consequent decrease in levels of atmospheric carbon dioxide was at least partially responsible for global cooling. Finally, the presence of continental landmasses over one pole and near the other was also a major factor enabling the development of continental glaciers.

While they have advanced over and retreated from the Midwest many times during the Quaternary, each advance, called a glacial period, scrapes away and reworks much of what was previously left behind, making it difficult to reconstruct the precise course of events. The two most recent glaciations, the **Wisconsinian** and the **Illinoian** stages respectively, are relatively well understood, while researchers believe there have been approximately 10 previous Midwestern glacial periods that are generally lumped together as "**Pre-Illinoian**." After all that ice, it's little wonder most of the Midwest has been worn nearly flat!

Seeking Detailed Records of Glacial-interglacial Cycles

When glaciers advance over the land, the historical rock records are largely erased with each glacial advance. Therefore, to investigate the details of any associated climate change we must seek environments that record climate change but are preserved. Since the 1970s, the international Deep Sea Drilling Project has provided a treasure trove of data on coincident changes in the ocean, preserved in sediments at the ocean bottom (*Figure 6.7*). In the 1980s, coring of ice sheets in Greenland and Antarctica provided similarly high-resolution data on atmospheric composition and temperature back nearly one million years (*Figure 6.8*). The data from these programs have revealed that the Earth, particularly the Midwest, experienced dozens of warming and cooling

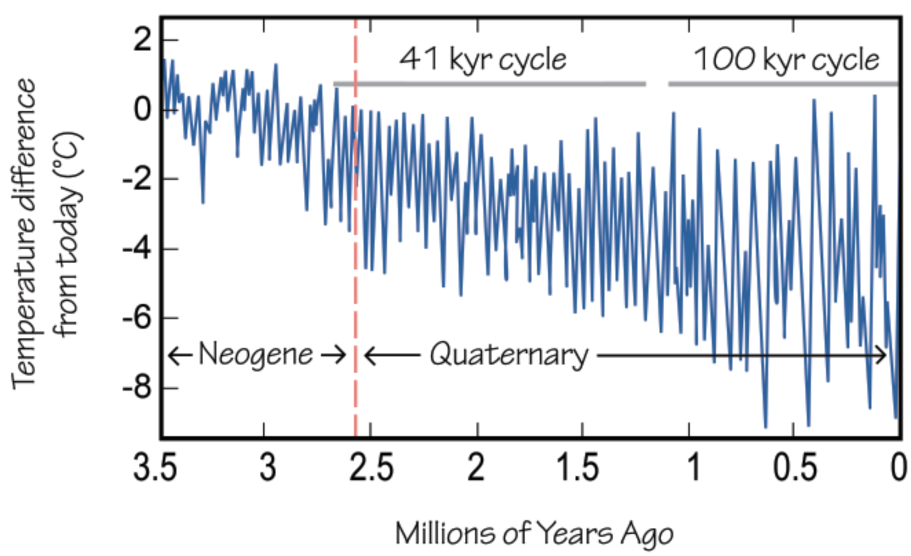


Figure 6.7: Ocean bottom temperatures from 3.6 million years ago to present, based on chemical analyses of foraminifera shells. Notice how the amplitude of glacial-interglacial variations increases through time, and how the length of cycles changes.

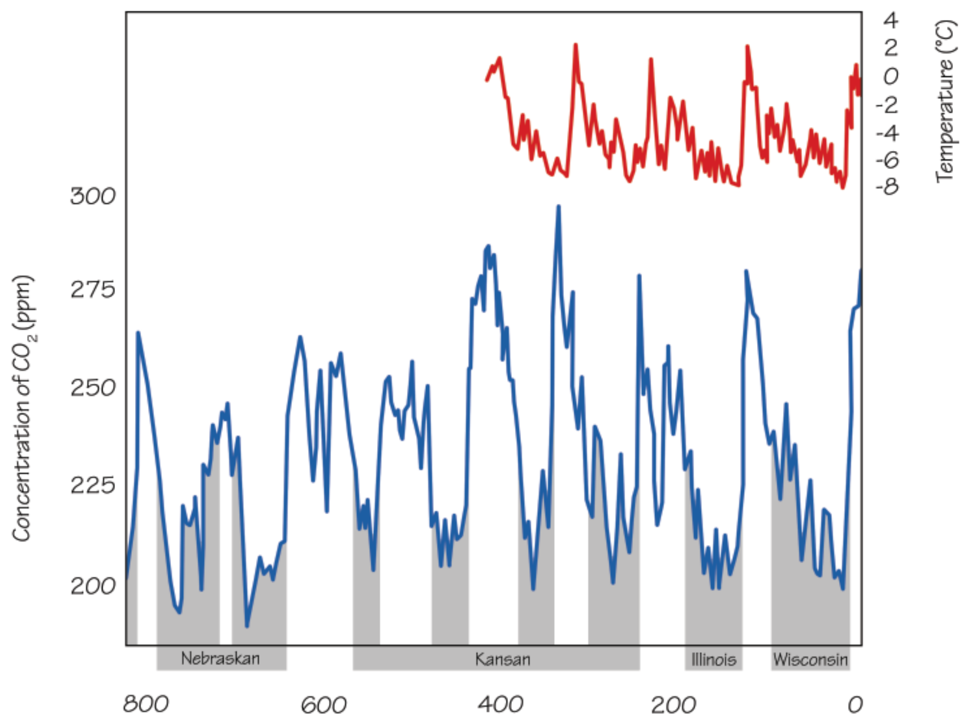


Figure 6.8: Atmospheric temperature and carbon dioxide concentrations from an ice core taken in Vostok in Antarctica and CO_2 data from several cores. Midwest glacial deposits are represented in gray at the bottom. Note that Kansan and Nebraskan deposits represent more than one glacial advance.

cycles over the course of the Quaternary period. Most of the earlier and less extensive Pleistocene glacial advances that occurred in the Midwest have been completely erased on land and so were unknown before records from deep-sea cores and ice cores revealed them.

From the Pleistocene to the Present

A cooling climate triggered the start of a series of glacial advances shortly before the Pleistocene began. The most recent glacial period, prior to the present **interglacial** period, began 65,000 years ago and affected the Midwest until about 10,000 years ago. Initially, the ice that covered the Midwest spread from a single **dome** located in northern Canada over the Hudson Bay. Approximately 20,000 years ago, this ice sheet reached its maximum extent, reaching as far south as northernmost Kansas and Kentucky (*Figure 6.9*).

The formation of glaciers comes from the precipitation of water that originates from the evaporation of ocean water. Thus, significant glacial build-up ties up water in ice sheets, causing a sea level drop. During the Pleistocene glacial advances, the sea level dropped an estimated 110 meters (360 feet)!

Pleistocene

interglacial • *a period of geologic time between two successive glacial stages.*

ice dome • *the spreading center of an ice sheet.*

crust • *the uppermost, rigid outer layer of the Earth, composed of tectonic plates.*

mantle • *the layer of the Earth between the crust and core.*

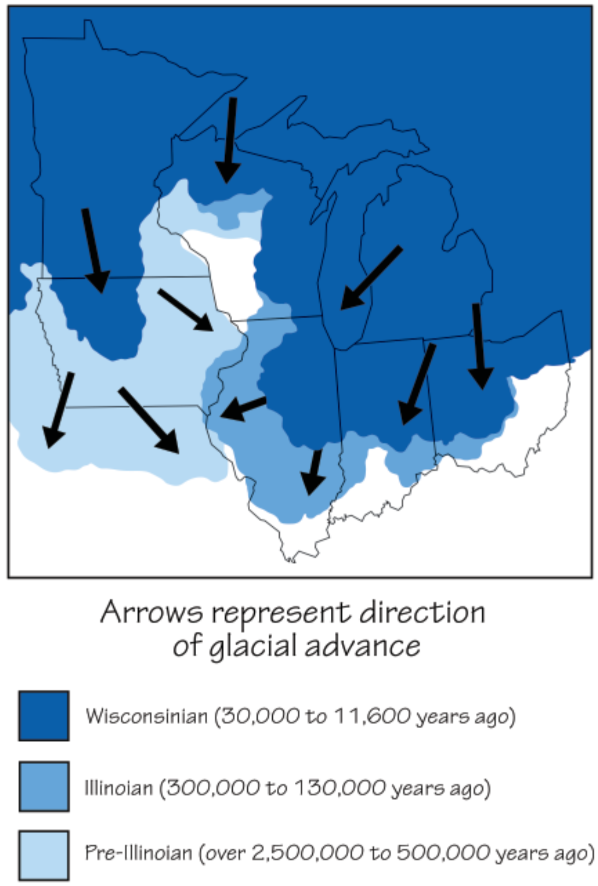


Figure 6.9: Glaciers flowed south during glacial advances; each advance differed slightly and left different sets of deposits.

By 18,000 years ago, the ice sheet was in retreat because of a slight warming of the climate. Though the ice sheet alternately moved forward and melted backward, overall it was on the retreat. Even during glacial advance, the glacier was always melting at its fringes. During times of glacial retreat, the ice sheet was not actually flowing backwards: the glacier continued to flow forward, but it was melting faster than it was advancing.

Rebounding of the Crust

The ice sheets could exceed two kilometers (1.2 miles) in thickness. The enormous weight of all of that ice over the continent depressed the **crust** into the **asthenosphere** (the uppermost part of the **mantle**) just as the weight of a person in a canoe causes the boat to ride lower in the water. When the person steps out of the canoe, the buoyancy of the canoe allows it to once again rise. As the ice sheet retreated from the Midwest during the current interglacial period, the crust rebounded, and it continues to do so today. The equilibrium achieved between the crust and mantle is known as **isostasy** (*Figure 6.11*). This rebound is thought to be a cause of infrequent, but occasionally severe, seismic activity in the Midwest.

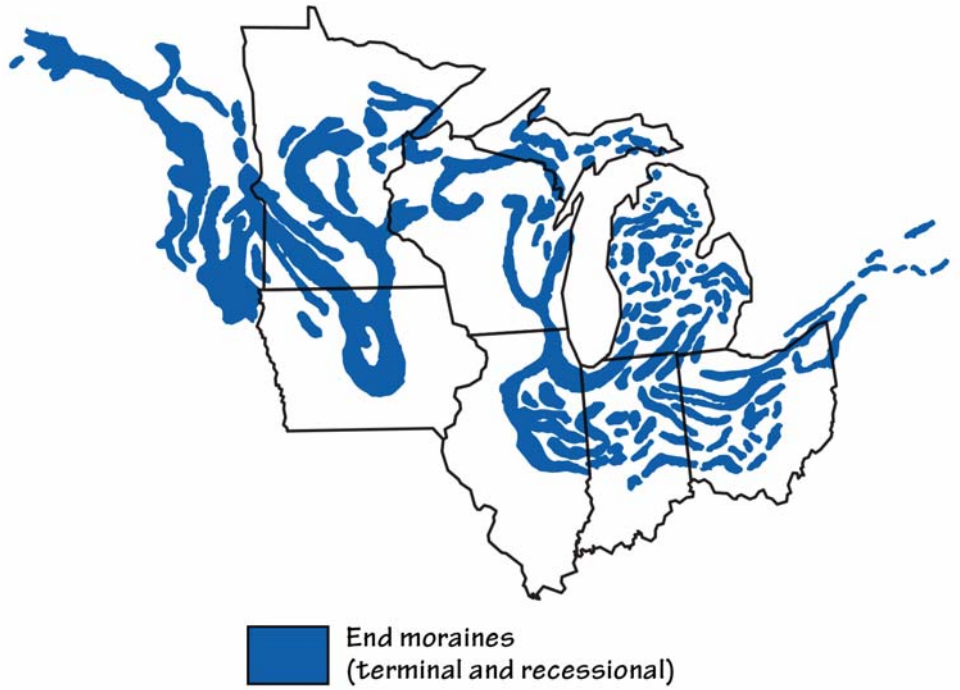


Figure 6.10: In addition to other deposits, glaciers resulted in moraine deposits through the Midwest, in some cases adding topographic relief to otherwise flat terrain. The moraines help define the extent of glacial advances.

The *Iowa Pleistocene snail* was abundant throughout the Midwest during much of the Pleistocene epoch. At one time it was only known from the fossil record and thought to have gone extinct after the last glacial maximum, but it was discovered alive and well in 1955. It survives today scattered among a few dozen algific talus slopes in five counties in Iowa and one in Illinois. It is currently classified as an endangered species.

Iowa Pleistocene snail* (Discus macclintocki), *found only in specific types of karst habitats. Adult shell width about 7 mm (0.25 inch).

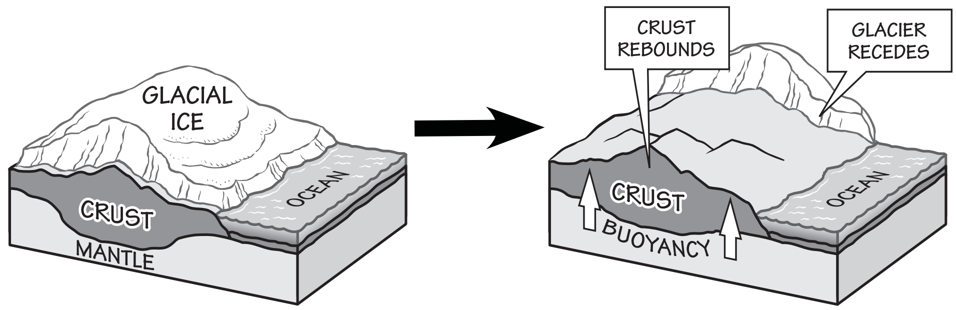


Figure 6.11: Through isostacy, glaciers push the crust down, and, when they melt, the crust rebounds upward.

The Great Lakes

The Great Lakes are a prominent geologic feature of the Midwest and include three of the five largest lakes in the world. In fact, they contain 21% of the world's fresh water. And 20,000 years ago, they did not exist. At that time, the ice sheets extended well past where the lakes would come to be prior to glaciation. The Great Lakes were actually river valleys that had been scoured and deepened repeatedly by the numerous ice advances during the Quaternary period. Many sizable glacial lakes were formed at the edge of the melting glacier, yet they no longer exist today or have significantly shrunk in size. As the glacier retreated and the basins filled with glacial runoff, the still-forming lakes drained southward, eventually into the Mississippi River (*Figure 6.12*).

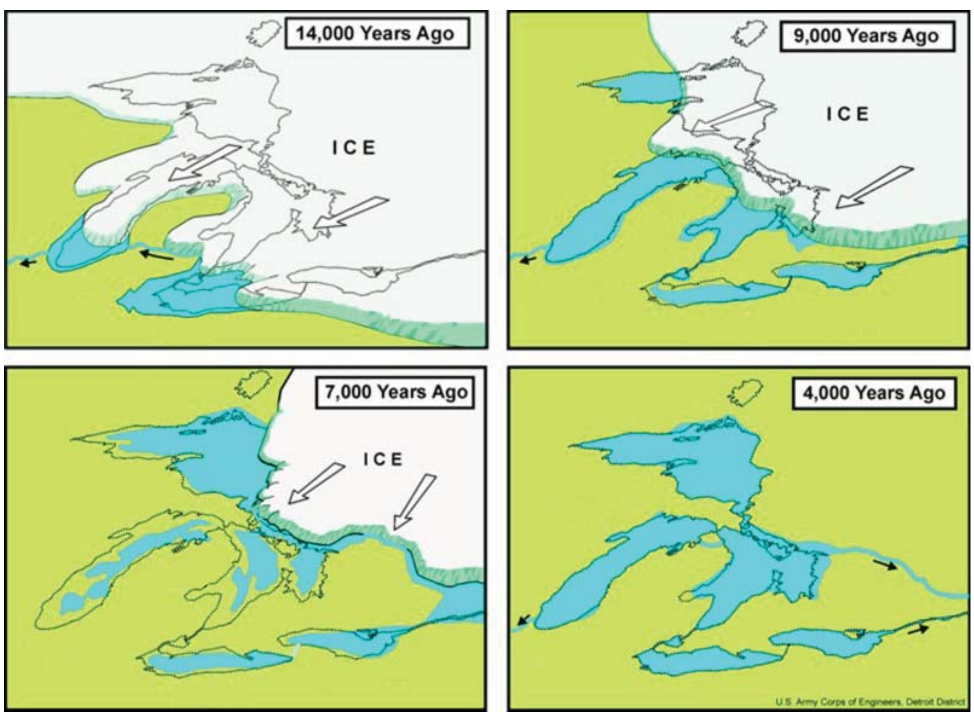


Figure 6.12: Glaciers over the Midwest retreated over the course of 10,000 years after the Last Glacial Maximum, leaving behind the Great Lakes, among other features.

The Loess Hills

The Loess Hills of extreme western Iowa, extending into northwesternmost Missouri, are named after a glacial deposit formed of windblown rock flour: **loess**. This type of glacial feature is found in only a few places on Earth. Loess deposits are found in parts of Wisconsin, Minnesota, Illinois, and Iowa, but the loess hills in Iowa represent the most prominent of all the loess deposits. While these hills form only a very narrow, 320-kilometer (200-mile) long, north-south band immediately east of the Missouri River **floodplain**, they are an important part of the story of the glaciation of the Midwest (*Figure 6.13*). The hills stand more than 60 meters (200 feet) above the surrounding low farmland and often display very sharp profiles, having been cut away into steep bluffs. They were formed during several glacial/interglacial cycles when glaciers ground down the bedrock. Then, as the ice retreated, meltwater deposited the fine sediments in expansive mudflats. When the mudflats dried, strong westerly winds blew the sand into great dunes, and the finest material (silt and clay) was carried farther in massive dust clouds. The dunes were eventually stabilized by vegetation and matured into the hills, but the loose material of the hills can still be easily eroded and carved. Slumping, mudslides, and undercutting caused by wind and water have produced steep slopes and a landscape of narrow ridges.

floodplain • *the land around a river that is prone to flooding.*

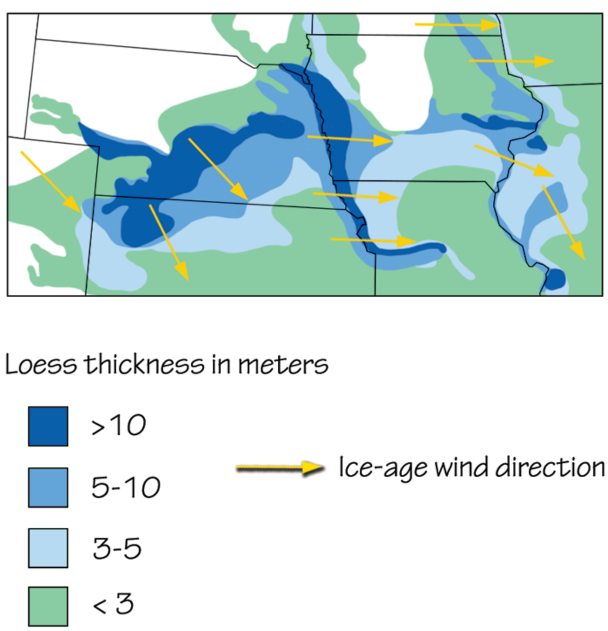


Fig 6.13: Thickness of loess deposits in Midwest.

Much of the soil throughout the Midwest is composed, in part, of sediment blown from the huge mudflats on the banks of the ancient Missouri River, which was a major channel for floods of glacial meltwater.

karst topography • *a kind of landscape defined by bedrock that has been weathered by dissolution in water, forming features like sinkholes, caves, and cliffs.*

Driftless Area

The Driftless Area, also known as the Paleozoic Plateau, is located around the upper Mississippi River valley where Minnesota, Wisconsin, Iowa, and Illinois meet. It is a place that beautifully contrasts with the surrounding glacial landscape because the Driftless Area was completely missed by the advancing ice during the Pleistocene. Its deep valleys, steep bluffs, and high hills stand in stark relief to the flat plains surrounding it, and it is suggestive of what the rest of the Midwest might have looked like before glaciers leveled it. The Driftless Area's topography is largely controlled by the water flowing through it, which has been carving into its rock for millions of years. Other creeks and rivers in the Midwest have been following their current courses for a few tens of thousands of years at most—orders of magnitude less time in which to shape their landscapes. As they scraped over the area, the ice sheets covered river valleys and filled them with sediment, forcing water to flow around their margins, effectively shoving the rivers out ahead of them. Much of the Missouri, Ohio, and Mississippi Rivers outline the farthest extent of ice sheet advances. This underscores the importance of glaciers to the Midwest: the borders of several states, defined by these rivers, are the direct result of glacial action!

The Driftless Area is an example of **karst topography**, a kind of landscape defined by bedrock that has been weathered by dissolution in water, forming features like sinkholes, caves, and cliffs (*Figure 6.14*). Here, cold underground lakes create a kind of natural air conditioning that cycles air into cracks and caves in the rock where it is cooled by the water before returning to the surface. This unique geologic phenomenon, coupled with cliffs that block much of the sunlight, make microhabitats that are tens of degrees cooler than the surrounding area just yards away. These habitats, called algific talus slopes, tend to occur only on the northern slopes of hills where they receive very little sunlight, and they are scattered across the Driftless Area. Furthermore, they do not occur anywhere else on Earth. They are home to unique flora and fauna, many members of which are usually only found much farther north, and some of which are no longer found anywhere else. In short, in many ways the Driftless Area is like a time capsule of the ancient Midwest.

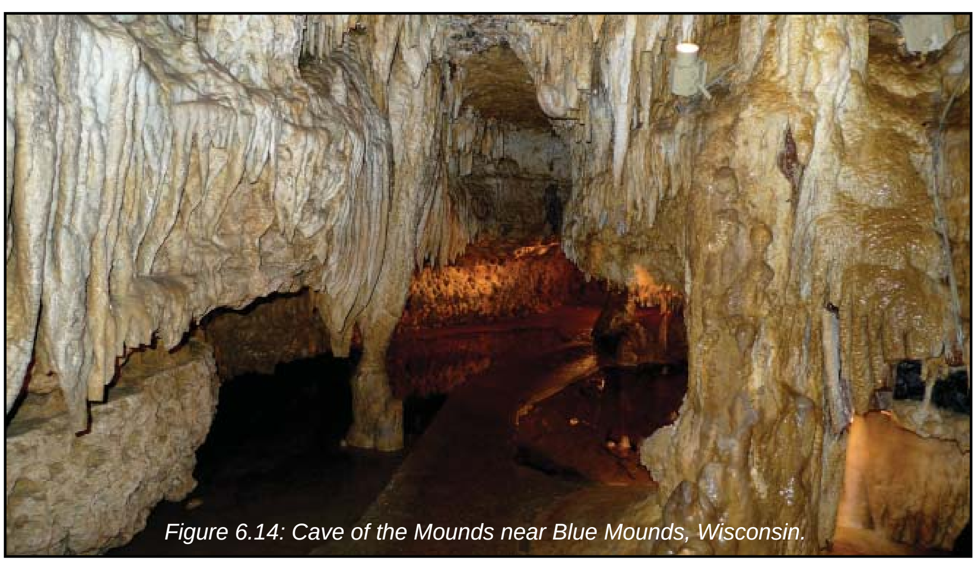


Figure 6.14: Cave of the Mounds near Blue Mounds, Wisconsin.

Resources

Books

Alley, R. B., 2000, The two-mile time machine: ice cores, abrupt climate change, and our future. Princeton University Press: Princeton, NJ.

Benn, D. I., & Evans, D. J.,2010, Glaciers & glaciation, (2nd ed), Arnold: London.

Fagan, B. M., 2009, The complete Ice Age: how climate change shaped the world. Thames & Hudson: New York.

Imbrie, J., & Imbrie, K. P.,1979, *Ice ages: solving the mystery*. Enslow Publishers: Short Hills, N.J.

Macdougall, J. D., 2004, *Frozen Earth: the once and future story of ice ages.* University of California Press: Berkeley, CA.

Mickelson, D.M., Maher Jr., L.J., and Simpson, S.L., 2011, *Geology of the Ice Age National Scenic Trail*, University of Wisconsin Press: Madison. 305 p.

Pidwirny, M., 2006, Landforms of Glaciation. In: *Fundamentals of Physical Geography* (2nd ed.). http://www.physicalgeography.net/fundamentals/10af.html.

Ruddiman, W. F., 2001, *Earth's climate: past and future*. W.H. Freeman: New York.

White, C., 2013, *The Melting World: A Journey Across America's Vanishing Glaciers.* St. Martin's Press: New York.

State-focused Resources

Glacial Deposits of Wisconsin, Sand and Gravel Resource Potential, 1976, Map #10, WGNHS Publications.

[Illinois] Quaternary Deposits Map, Illinois State Geological Survey. (Map showing the extent of the Quaternary glacial deposits covering Illinois.) http://isgs.illinois.edu/sites/isgs/files/maps/statewide/quaternary-deposits-8x11.pdf.

Iowa Pleistocene Snail (*Discus macclintocki*) Fact Sheet, US Fish and Wildlife Service, Midwest Region. http://www.fws.gov/midwest/endangered/Snails/iops_fct.html.

Landscapes of Wisconsin, 2001, Map #142, Wisconsin Geological and Natural History Survey Publications.

Chapter 7: Energy in the Midwestern US

Everything we do depends upon **energy**—without it there would be no civilization, no sunlight, no food and no life. Energy moves people and goods, produces electricity, heats our homes and businesses, and is used in manufacturing and other industrial processes. But what *is* energy? Energy is the **power** derived from the utilization of physical or chemical resources. In this chapter, we are especially interested in the energy used to provide light and **heat**, or to work machines.

For most of human history, the way we captured and used energy changed little. With very few exceptions, materials were moved by human or animal power, and heat was produced largely through the burning of wood. Nearly all the energy to power human society was, in other words, **biomass**. But the transition from brute force and wood burning to the various industrial sources of energy—and the accompanying adoption of energy-intensive lifestyles—has occurred remarkably quickly, in the course of just the last several generations. This has caused changes in virtually every aspect of human life, from economics to war to architecture. Much of the rural US was without access to electricity until the 1930s, and cars have been around only slightly longer. Our energy **system** (how we get energy and what we use it for) has changed and is changing remarkably quickly, though some aspects of the energy system are also remarkably resistant to change.

Exceptions include the use of sails on boats by a very small percentage of the world's population to move people and goods, and the Chinese use of natural gas to boil brine in the production of salt beginning roughly 2,000 years ago.

The use of **wind** to generate electricity, for example, grew very quickly in the late 2000s and early 2010s. In 2002, wind produced less than 11 million megawatt hours (MWh) of electricity in the US. In 2011, wind produced more than 120 million MWh—more than 1000% growth in ten years! That aspect of change stands in contrast to our long-lasting reliance on **fossil fuels**, **coal**, oil, and **natural gas**. Our reliance on fossil fuels is driven by a number of factors: the low upfront cost, very high energy densities, and the cost and durability of the infrastructure built to use fossil fuels.

power • *the rate at which energy is transferred, usually measured in watts or, less frequently, horsepower.*

heat • *the transfer of energy from one body to another as a result of a difference in temperature or a change in phase.*

biomass • *organic material from one or more organisms.*

wind • *the movement of air from areas of high pressure to areas of low pressure.*

fossil fuels • *fuel for human use that is made from the remains of ancient biomass.*

coal • *a combustible, compact black or dark-brown carbonaceous rock formed by the compaction of layers of partially decomposed vegetation.*

CHAPTER AUTHOR

Carlyn S. Buckler

7

Energy

Review

degrade (energy) • *the transformation of energy into a form in which it is less available for doing work, such as heat.*

watt • *a unit of power measuring the rate of energy conversion or transfer designated by the International System of Units as one joule per second.*

Energy production and use not only changes across time, but also with geography, as we'll see by looking at energy production and use across the different regions of the US.

Electricity is a good example of an *energy carrier*: a source of energy that has been subject to human-induced energy transfers or transformations.

Wind power, on the other hand, is a *primary energy source*: a source of energy found in nature that has not been subject to any human manipulation.

What do different units of energy mean?

Heat is energy, and heat is at the root of all the ways that we move materials or generate light, so measurements of heat can be thought of as the most basic way to measure energy. The **British Thermal Unit** (abbreviated Btu or BTU) is the most commonly used unit for heat energy and is approximately the amount of heat required to raise one pound of water by one degree Fahrenheit. A Btu is also about the amount of energy released by burning a single wooden match. One Btu is also equal to 1055 joules. A **joule** is the energy expended (or work done) to apply a force of one newton over a distance of one meter. A typical apple weighs about a newton, so lifting an apple one meter takes about a joule of energy. That means that one Btu—the energy contained in a wooden match—would be all the energy required to lift an apple 1000 meters, or one kilometer.

The principle of *Conservation of Energy* tells us that energy is neither created nor destroyed, but can be altered from one form to another.

This comparison of the energy of heat to the energy of motion (**kinetic energy**) might be a little confusing, but energy is transformed from one type to another all the time in our energy system. This is perhaps most obvious with electricity, where electrical energy is transformed into light, heat, or motion at the flip of a switch. Those processes can also be reversed—light, heat, and motion can all be transformed into electricity. The machines that make those transitions in either direction are always imperfect, so energy always **degrades** into heat when it is transformed from one form to another. A kilowatt-hour (kWh) is the amount of energy required to light ten 100-**watt** light bulbs for one hour. *Figure 7.1* compares different ways to make and use one kWh.

Review

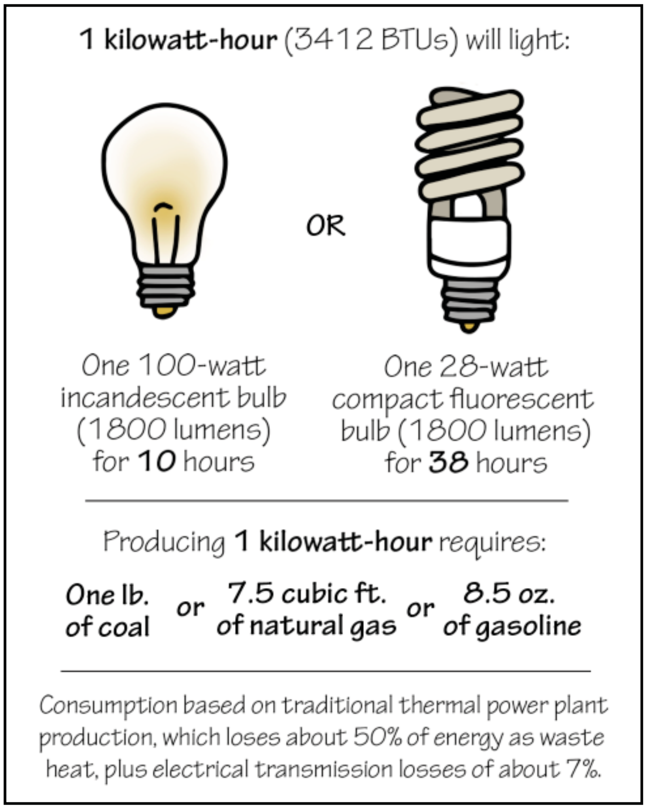


Figure 7.1: Examples of uses and sources of 1 kilowatt-hour.

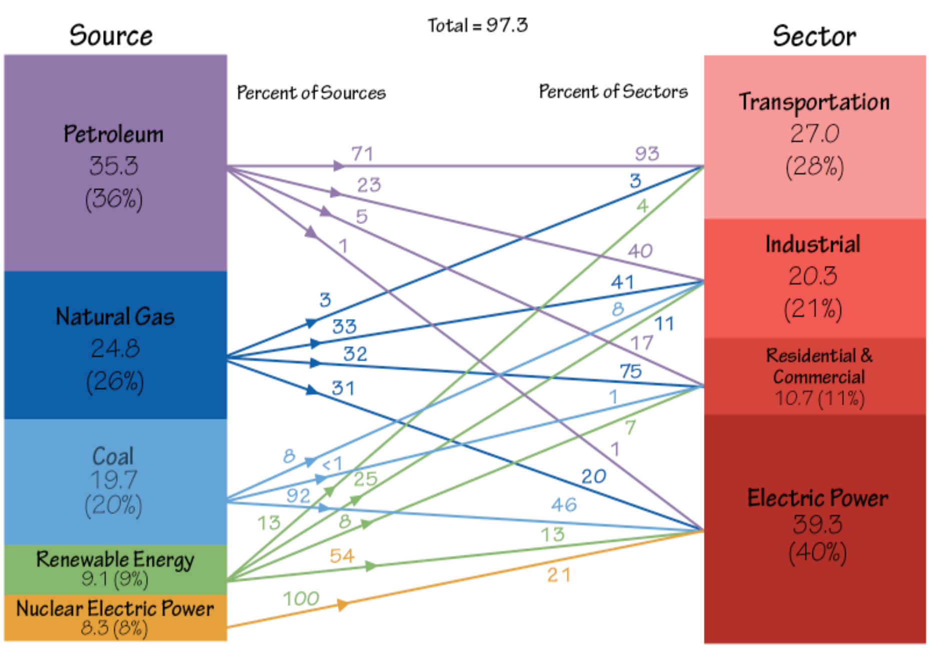


Figure 7.2. US energy production sources and use sectors for 2011. Petroleum provides more energy than any other source, and most of it is used for transportation. More energy is used to generate electricity than for any other use, and electricity is generated by all five energy sources. Nuclear is unique among sources in that all of the energy it generates goes to a single sector: electric generation.

7 Energy

Review

chemical reaction • *a process that involves changes in the structure and energy content of atoms, molecules, or ions but not their nuclei.*

petroleum • *a naturally occurring, flammable liquid found in geologic formations beneath the Earth's surface.*

renewable energy • *energy obtained from sources that are virtually inexhaustible (defined in terms of comparison to the lifetime of the Sun) and replenish naturally over small time scales relative to human life spans.*

nuclear • *a reaction, as in fission, fusion, or radioactive decay, that alters the energy, composition, or structure of an atomic nucleus.*

How do we look at energy in the Earth system?

The concepts used to understand energy in the Earth system are fundamental to all disciplines of science; energy is an interdisciplinary topic. One cannot study physics or understand biomes, photosynthesis, fire, evolution, seismology, **chemical reactions**, or genetics without considering energy. In the US, every successive generation has enjoyed the luxury of more advanced technology (e.g., the ability to travel more frequently, more quickly, and over greater distances), and we require more and more energy to maintain these new lifestyles and to power new technologies.

Figure 7.2 shows the sources and uses of energy in the US, by sector. The Energy Information Administration (EIA) categorizes energy as coming from one of five sources (**petroleum**, natural gas, coal, **renewable energy** and **nuclear** electric power) and being used in one of four energy sectors (transportation, industrial, residential & commercial, and electric power). All of the energy that powers our society comes from one of these five sources and is used in one of these four sectors.

The more we come to understand the Earth system, the more we realize that there is a finite amount of consumable energy, and that harvesting certain resources for use in energy consumption may have wide ranging and permanent effects on the planet's life. Understanding energy within the Earth system is the first step to making informed decisions about energy transitions.

Becoming "Energy Literate"

Energy is neither lost nor gained within the universe, but rather is constantly flowing through the Earth system. In order to fully understand energy in our daily lives—and make informed decisions—we need to understand energy in the context of that system. Becoming energy literate gives us the tools to apply this understanding to solving problems and answering questions. The Seven Principles of Energy, as detailed in "*Energy Literacy: Energy Principles and Fundamental Concepts for Energy Education*" are:

Energy Literacy: Energy Principles and Fundamental Concepts for Energy Education **is a publication of the US Department of Energy. It can be accessed for free online; see Resources for more information.**

1	**Energy is a physical quantity that follows precise natural laws.**
2	**Physical processes on Earth are the result of energy flow through the Earth system.**
3	**Biological processes depend on energy flow through the Earth system.**

4	**Various sources of energy can be used to power human activities, and often this energy must be transferred from source to destination.**
5	**Energy decisions are influenced by economic, political, environmental, and social factors.**
6	**The amount of energy used by human society depends on many factors.**
7	**The quality of life of individuals and societies is affected by energy choices.**

Each principle is defined by a set of fundamental concepts that can help clarify ties to curriculum. Keeping these energy principles in mind when we teach others about energy can help us contextualize and make relevant our own energy consumption and its effect on the Earth system.

Energy in the Midwestern Regions

The primary energy resources in the Midwest come from fossil fuels. Illinois, Indiana, and Ohio combined represent 13% of the total coal production in the US, and it is the primary source of energy. Illinois was once a major producer of oil, and natural gas production has been increasing in Ohio.

Fossil Fuels

Fossil fuels—oil, natural gas, and coal—are made of the preserved organic remains of ancient organisms. Petroleum typically forms from the remains of aquatic life, primarily one-celled photosynthetic organisms, which can accumulate in sediments. Coal forms primarily from the accumulation of land plants. In either case, organic matter only preserves when the rate of accumulation is higher than the rate the rate of decay. This happens most often when the oxygen supply is sufficiently low that oxygen-loving bacteria cannot thrive, greatly slowing breakdown of organic matter. In this way, the organic matter can be incorporated into the buried sediment. The organics are compacted and heated with the rest of the rock, eventually transforming into fossil fuels.

Regions

biofuel • *carbon-based fuel produced from renewable sources of biomass like plants and garbage.*

Pennsylvanian • *a subperiod of the Carboniferous, spanning from 323 to 299 million years ago.*

Illinois Basin • *an inland basin centered in the state of Illinois, which formed when Baltica approached North America in the Ordovician.*

sulfur • *a bright yellow chemical element (S) that is essential to life.*

Fossil Fuels (continued)

The history of surface environments, evolution of life, and geologic processes beneath the surface have all influenced where fossil fuel deposits formed and accumulated. The largest oil and gas reserves were at one time nutrient-rich seas with abundant surface phytoplankton and organic-rich bottom sediments; the largest coal beds were swampy environments where fallen forest trees and leaves were buried in stagnant muds.

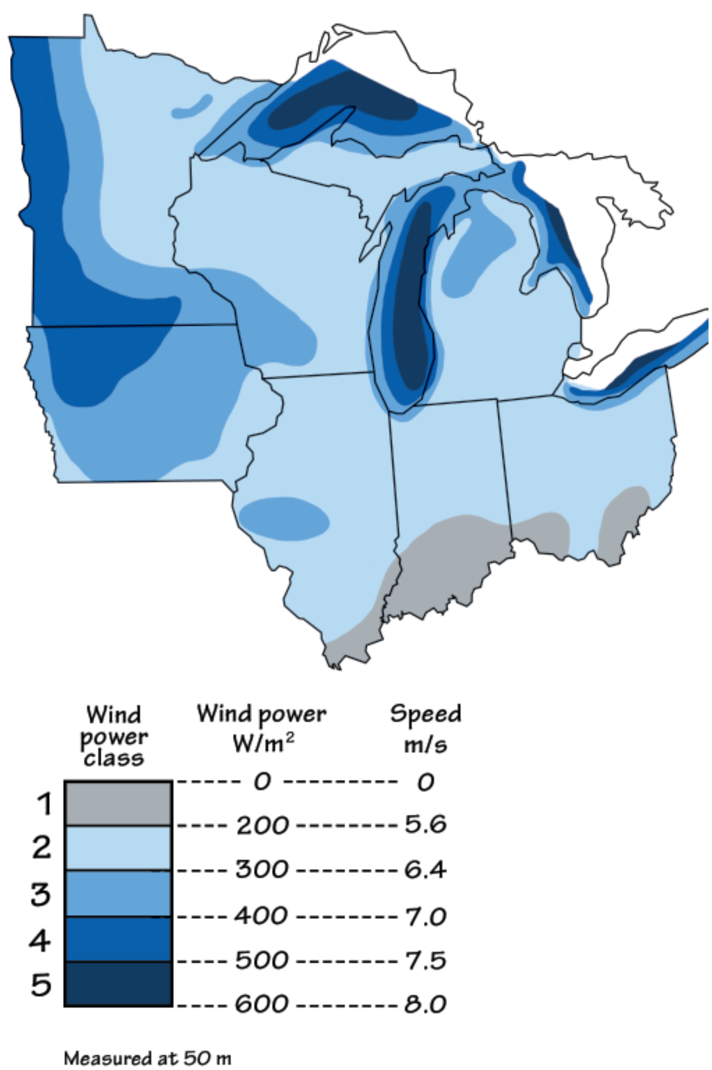


Figure 7.3: Average annual wind power distribution in the Midwest.

Energy

7

Regions 1–2

While fossil fuels represent both the majority of energy produced and consumed within the Midwest, growth of renewables has been substantial in the last several years. Between 2011 and 2012, electricity produced from wind increased 30% in the area. While Iowa leads the Midwest in production, both Michigan and Ohio much more than doubled their production in this timeframe. In 2012, wind produced 25% of Iowa's electricity and 15% of Minnesota's (*Figure 7.3*).

Biofuels (from biomass) also represent a significant energy resource throughout the Midwest, with production and consumption rapidly rising. Between 2001 and 2011, ethanol grew from less than 1% (by volume) of US gasoline to 10%. Most gasoline in the US is now blended with 10% ethanol (E10). Ethanol is not as energy dense as gasoline, so it provides about 6% of the energy in E10 gasoline. The Midwestern states are major producers of both ethanol and biodiesel, and production of both has much more than doubled in the last ten years. Liquid biofuels now provide about 1% of US energy while wind provides about 1.5%. As biofuels are produced from many different crops and through a range of different processes, their environmental impact is difficult to measure.

Energy in the Superior Upland
Region 1

Coal is the number one source of energy for this region, but it is all mined outside the Superior Upland. The abundant water resources of this "Land of 10,000 Lakes," however, allow for abundant hydropower. The harvest of oil and natural gas for energy is not significant in the Superior Upland, yet imports of petroleum provide a significant source of power to the region.

Energy in the Central Lowland
Region 2

The use and production of coal is big in this region, providing the majority of power, followed by hydropower and petroleum. The most important sources of coal come from **Pennsylvanian** period deposits in the **Illinois Basin** in Southern Illinois and part of southern Indiana (*Figure 7.4*). Coal from these deposits is relatively **sulfur**-rich **bituminous coal**.

The use of coal has declined in recent decades, associated with environmental concerns about **acid rain**. However, through the widespread use of technology that removes sulfur dioxide at coal-fired plants, mining from these deposits has recently begun to increase again. There are also small Pennsylvanian-age coal deposits in central Michigan.

The largest producer of oil in the region is also the Illinois Basin, which generates about 12,000 barrels a year (*Figure 7.5*). Michigan increased its gas production in the late 1990s with extraction from Late **Devonian** period **sedimentary rocks** of the Antrim Shale, which is part of the **Michigan Basin**. Michigan produces about 1% of the US total, extracting 300 billion cubic feet

bituminous coal • *a relatively soft coal containing a tarlike substance called bitumen, which is usually formed as a result of high pressure on lignite.*

acid rain • *rain or other precipitation that contains high amounts of sulfuric and nitric acid.*

Devonian • *a geologic time period spanning from 419 to 359 million years ago.*

sedimentary rock • *formed through the accumulation and consolidation of grains of broken rock, crystals, skeletal fragments, and organic matter.*

Michigan Basin • *an inland basin centered on Michigan's Lower Peninsula, which formed when Baltica approached North America in the Ordovician.*

7 Energy

Region 2

Figure 7.4: Distribution of coal mining in the Midwest.

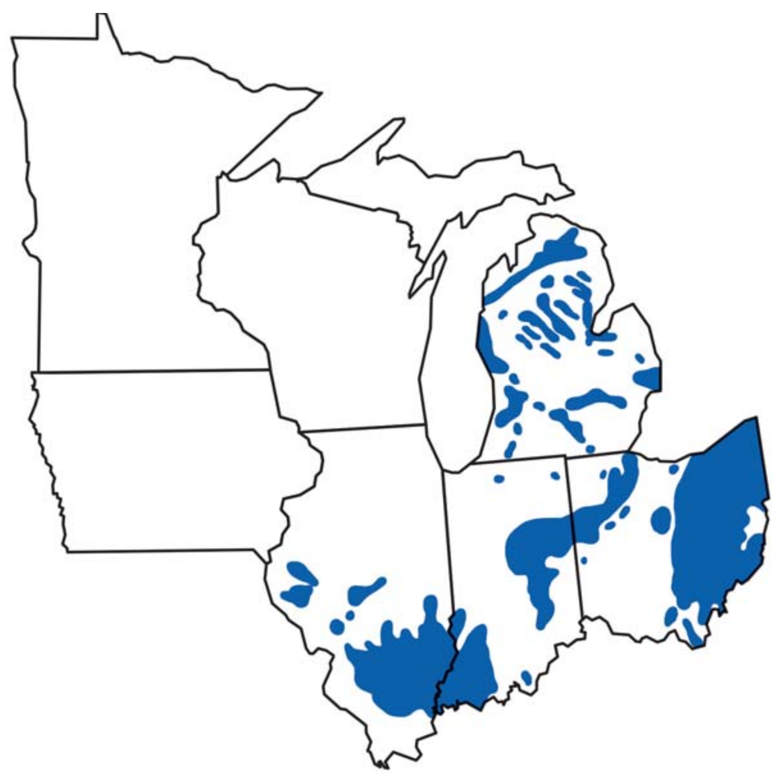


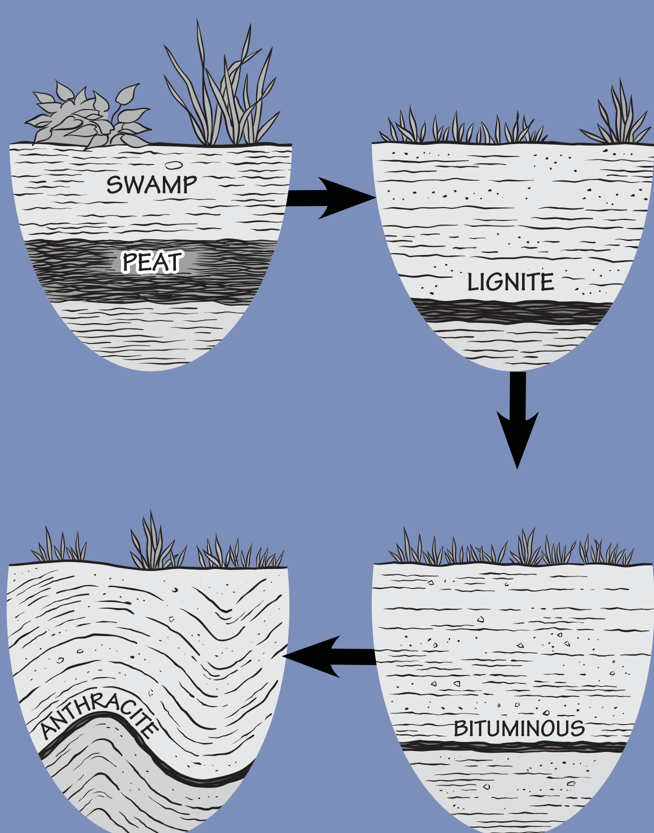
Figure 7.5: Distribution of oil and natural gas drilling in the Midwest.

Region 2

Coal

As leaves and wood are buried more and more deeply, pressure on them builds from overlying sediments, squeezing and compressing them into coal. The coal becomes gradually more enriched in carbon as water and other components are squeezed out: *peat* becomes *lignite*, bituminous and eventually *anthracite* coal, which contains up to 95% carbon. Anthracite has the fewest pollutants of the four types of coal, because it has the highest amount of pure carbon. By the time a peat bed has been turned into a layer of anthracite, the layer is one-tenth its original thickness.

The *Carboniferous* period takes its name from the carbon in coal. A remarkable amount of today's coal formed from the plants of the Carboniferous, which included thick forests of trees with woody vascular tissues.



peat • *an accumulation of partially decayed plant matter.*

lignite • *a soft, brownish-black coal in which the alteration of plant matter has proceeded farther than in peat but not as far as in bituminous coal.*

anthracite • *a dense, shiny coal that has a high carbon content and little volatile matter.*

Carboniferous • *a geologic time period that extends from 359 to 299 million years ago.*

Regions 2–3

***Appalachian Basin* •** *an inland basin, formed by the Taconic and Acadian mountain-building events.*

***Ordovician* •** *a geologic time period spanning from 485 to 443 million years ago.*

***Utica Formation* •** *an organic-rich black shale from the Middle Ordovician.*

of natural gas per year. Natural gas is also produced in Illinois, Indiana, and western Ohio, but not to a significant degree.

Biofuels (from biomass) also represent a significant energy resource in this region, with production and consumption on the rise. The Central Lowland is also a major oil-refining region. The Chicago area has one of the largest oil refineries in the country, with a capacity of nearly one million barrels a day.

Energy in the Inland Basin
Region 3

The eastern edge of Ohio is a coal-producing region, where mining occurs in the same Pennsylvanian period deposits of the **Appalachian Basin** that have long been famous in Pennsylvania, Kentucky, and West Virginia. Deposits in Ohio are high in sulfur compared to those further east and so have been in less demand since environmental regulations began in the 1990s.

Recently the rate of natural gas production in the region has greatly increased, from both the Appalachian Basin deposits in eastern Ohio and much older **Ordovician** period marine deposits. This production increase has occurred through use of a particular extraction technique, high-volume slickwater hydraulic fracturing, in the **Utica Formation**.

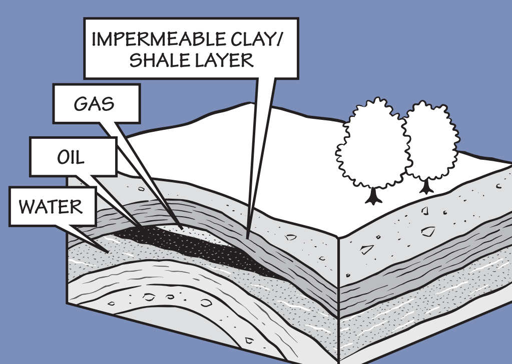
As in the Central Lowlands, because of the significant farming industry in this region, biomass also provides a significant amount of energy in the form of biofuels.

Oil and Gas

Oil and gas form from organic matter in the pores of sedimentary rocks. Shale in particular is often organic-rich, because organic matter settles and accumulates in the same places that fine *clay* and *silt* particles settle out of the water. Further, such quiet waters are often relatively stagnant and low in oxygen, thus organic matter decay is slow. Because oil and gas are under pressure, they will move to areas of lower pressure, gradually upward, through tiny connections between pores spaces and natural fractures in the rocks.

Often, natural gas and oil are trapped below the surface under impermeable layers that do not have sufficient spaces for liquids and gases to travel through. Folds or "arches" in impermeable layers, or faults in rock layers, are common ways of trapping oil and gas below the surface. Most oil and gas has been extracted using the "conventional" technique of seeking such reservoirs and drilling into them, allowing the gas or oil to come to the surface through a vertical well.

Some impermeable layers contain oil and gas that has never escaped. In the 2000s the fossil fuel industry began to access these resources through a method, known as high-volume slickwater hydraulic fracturing, that creates thousands of small fractures along impermeable rock layers. The method has greatly increased oil and gas production, but has also been a very controversial topic involving the issues of environmental impact and carbon emissions.



clay • *the common name for a number of very fine-grained, earthy materials that become plastic (flow or change shape) when wet.*

silt • *fine granular sediment most commonly composed of quartz and feldspar crystals.*

Energy

Energy Facts by State

Because of many local laws and guidelines, energy production and use is highly dictated by each state government. Below is a state-by-state assessment of energy production and use in the Midwestern US (from http://www.eia.gov/state/).

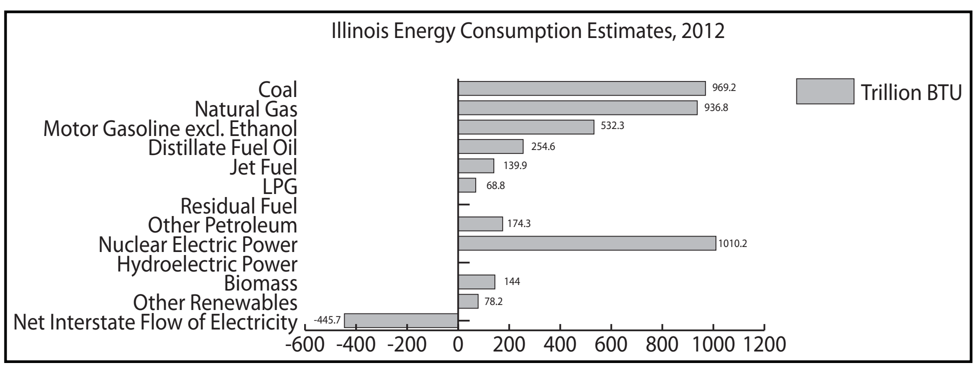
Illinois

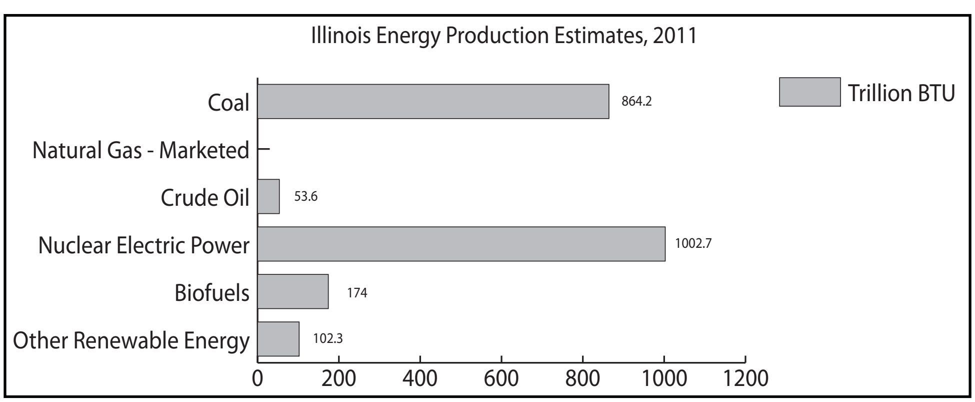
- Illinois is a key transportation hub for crude oil and natural gas moving throughout North America, with over a dozen interstate natural gas pipelines, two natural gas market centers, several petroleum and petroleum product pipelines, and an oil port.

- In 2010, Illinois' producing coal mines had the third largest recoverable coal reserves in the nation. It also ranked first in the nation for both generating capacity and net electricity generation from nuclear power; generation from its nuclear power plants accounted for 12% of the nation's total.

- In 2011, Illinois led the Midwest in crude oil refining capacity and ranked fourth in the nation.

- With a production capacity of 1.5 billion gallons per year, Illinois is a top producer of ethanol; it ranked third in the United States in 2011.





Energy

7

State Facts

Indiana

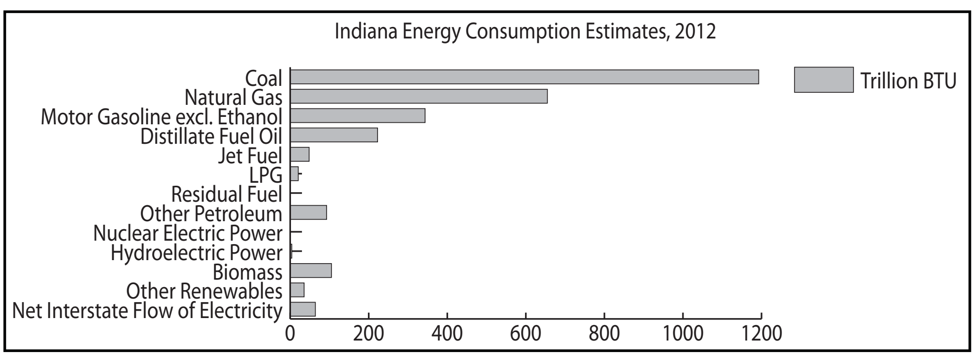
- Indiana’s industrial sector, which includes manufacturers of aluminum, chemicals, glass, metal casting, and steel, consumed more energy in 2010 than the residential and commercial sectors combined.

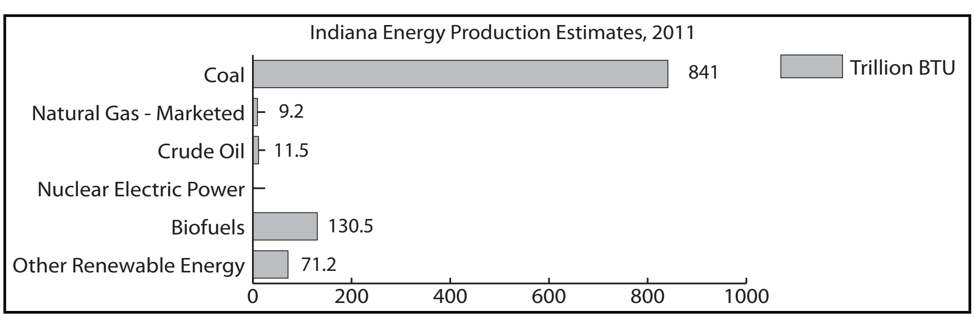
- The largest geothermal heating and cooling system in the United States is being built in Muncie, Indiana.

- Indiana ranked seventh among all states in coal production in 2010, and coal-fired electric power plants provided 83% of Indiana’s net electricity generation in 2011.

- In 2011, the Whiting oil refinery had the largest processing capacity of any refinery outside of the Gulf Coast region.

- Indiana is a major producer of ethanol; in 2011, it had 13 ethanol plants capable of producing 906 million gallons per year.



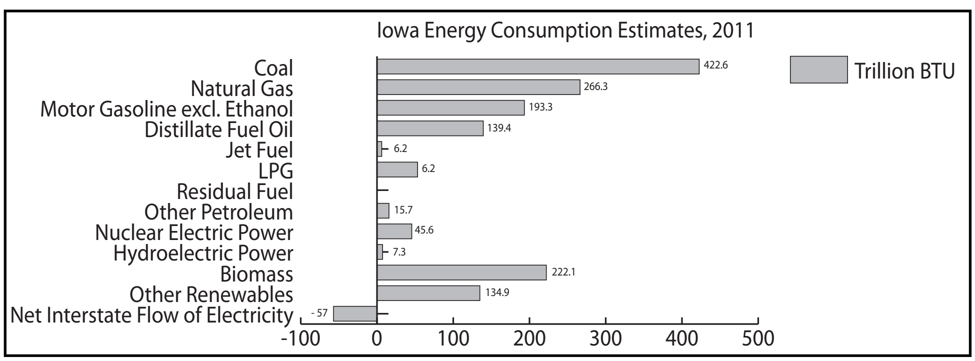


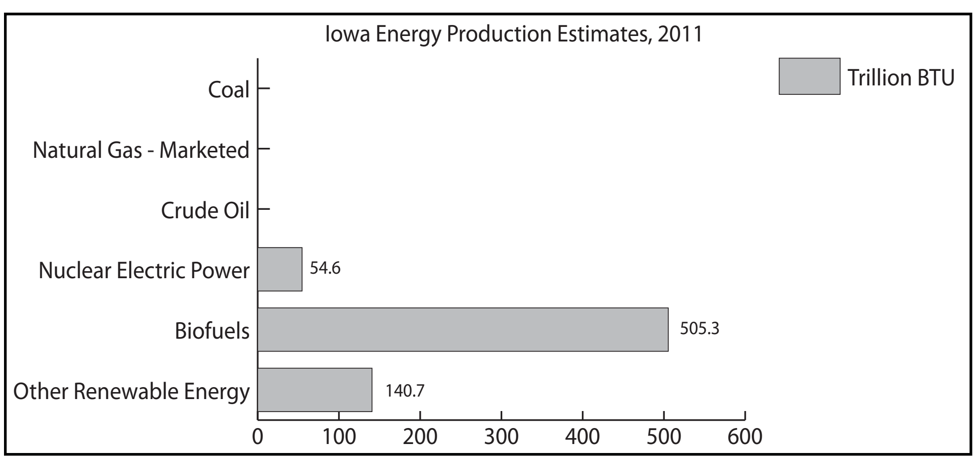
7 Energy

State Facts

Iowa

- The use of liquefied petroleum gases (LPG) in the residential and industrial sectors contributes to Iowa's relatively high consumption of LPG.
- Iowa was the largest producer of ethanol in the United States in 2011, accounting for 27% of the nation's fuel ethanol production.
- Seventy-seven percent of Iowa's 2011 net electricity generation came from electric utilities; most of the rest came from independent power producers.
- In 2011, Iowa was ranked third in the share of net electricity generation from non-hydroelectric renewable energy resources.
- Wind provided 19% of Iowa's total electricity generation in 2011; it was second only to coal as an energy source for electricity generation in the state.

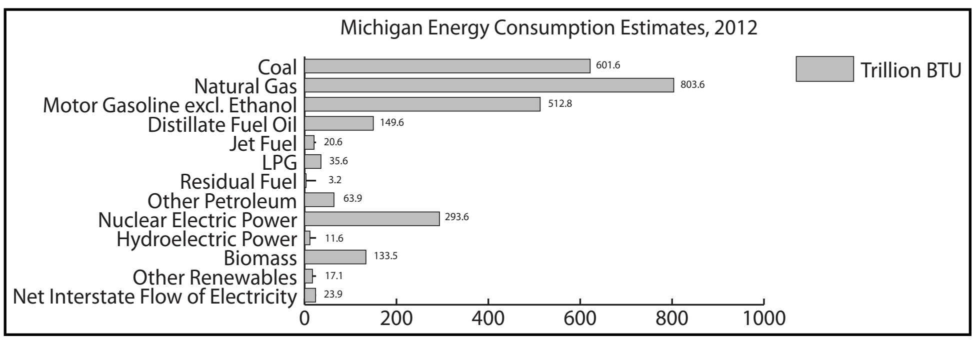


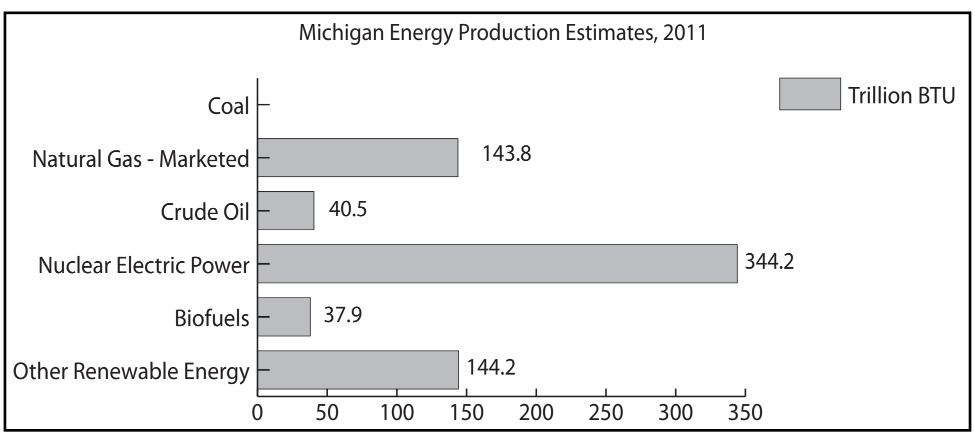


State Facts

Michigan

- In 2010, Michigan had more underground natural gas storage capacity—1.1 trillion cubic feet—than any other state in the nation.
- The Antrim Gas Field, located in Michigan's Lower Peninsula, was ranked 15th in the nation in estimated wet natural gas reserves as of 2009 and produced an estimated 126 billion cubic feet of gas that year.
- In 2011, Michigan's three nuclear power plants, with four reactor units, provided 30% of the state's net electricity generation.
- Michigan used coal for 54% of its net electricity generation in 2011; much of its coal is imported from Wyoming.
- Biomass from Michigan's almost 8 million hectares (19 million acres) of forest land provided fuel for 54% of Michigan's renewable net electricity generation in 2011.





7 Energy

State Facts

Minnesota

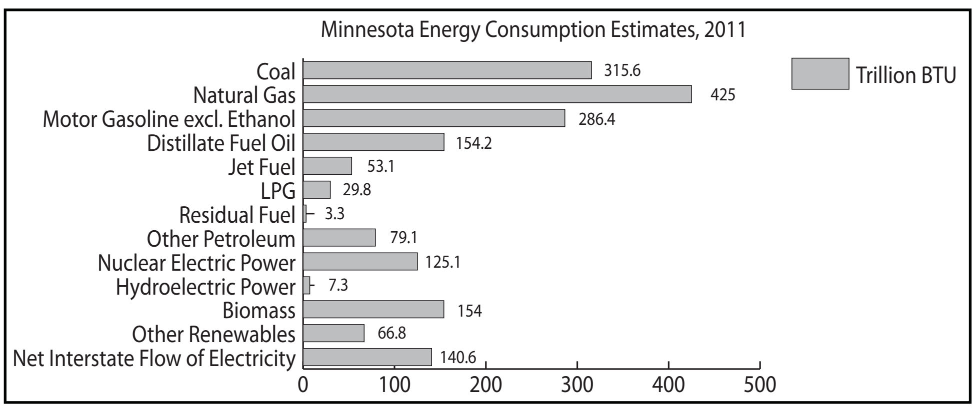
- Two nuclear power plants near Minneapolis-St. Paul, the Monticello reactor and the Prairie Island I and II reactors, account for 22% of Minnesota's net electricity generation.

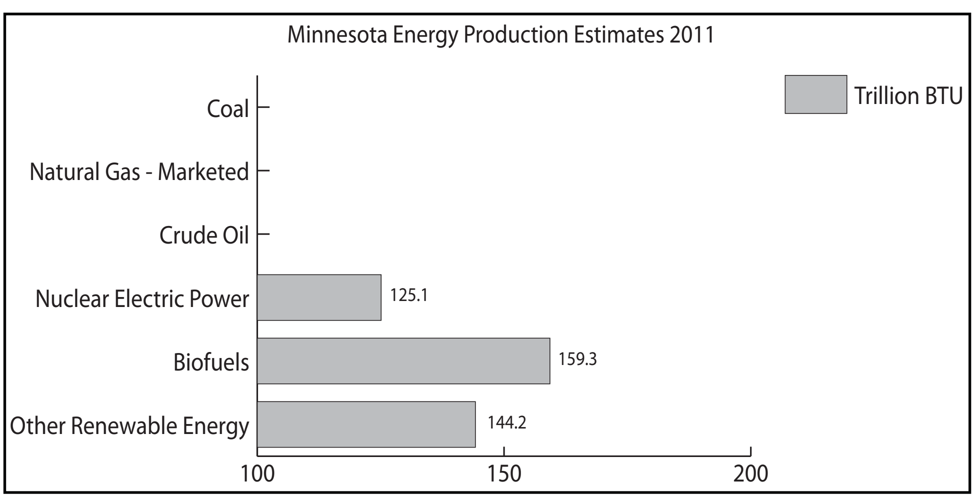
- Despite its extremely cold climate, Minnesota ranked 20th among all states for per capita energy use in 2010.

- Minnesota ranked fourth in the nation for ethanol production in 2011, and has approximately two dozen ethanol production plants.

- Fifty-three percent of the electricity generated in Minnesota came from coal-fired electric power plants in 2011; most of its coal supply was brought in by rail from Montana and Wyoming.

- Minnesota ranked fourth in the nation in net electricity generation from wind energy in 2011; its net generation was 6.8 million MWh in 2011, an increase of 42% from 2010.

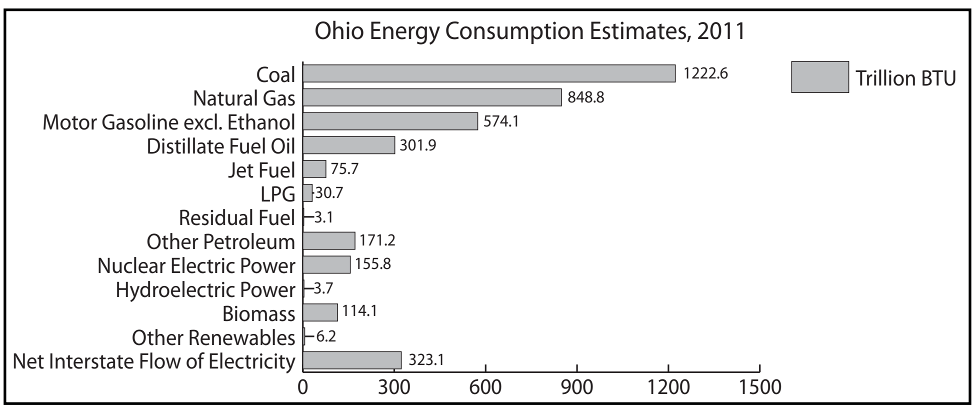


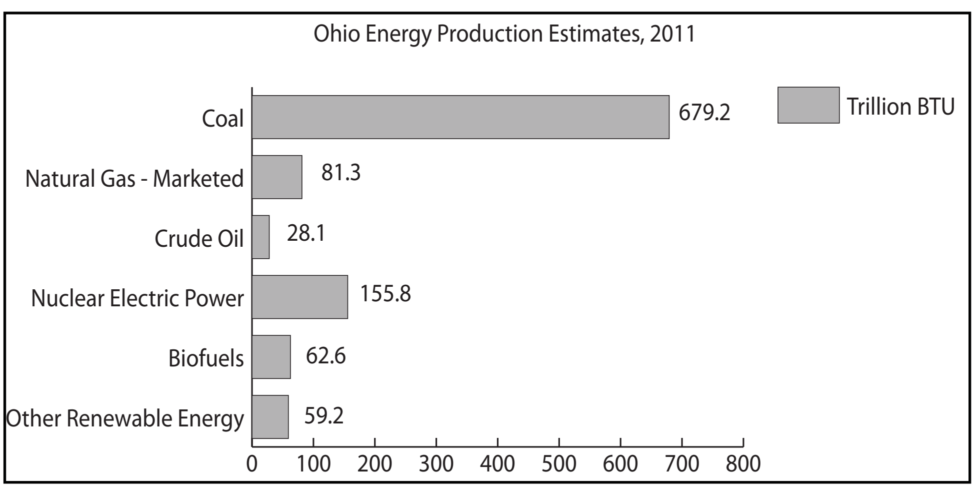


State Facts

Ohio

- Current interest in Ohio oil and gas exploration is focusing on two of its **shale** formations—the Marcellus Shale and the Utica Shale.
- In August 2003, a transmission failure in Ohio led to the largest blackout in North American history, affecting over 50 million people.
- Ohio had the eighth largest crude oil refining capacity in the nation in 2011.
- Coal fueled 78% of Ohio's net electricity generation in 2011, nuclear energy contributed 11%, and natural gas added another 8.9%.
- Ohio ranked fifth in the nation in 2010 in energy consumption by the industrial sector; in 2011, Ohio ranked third in manufacturing employment, with 5.4% of US manufacturing jobs.





7 Energy

State Facts

Wisconsin

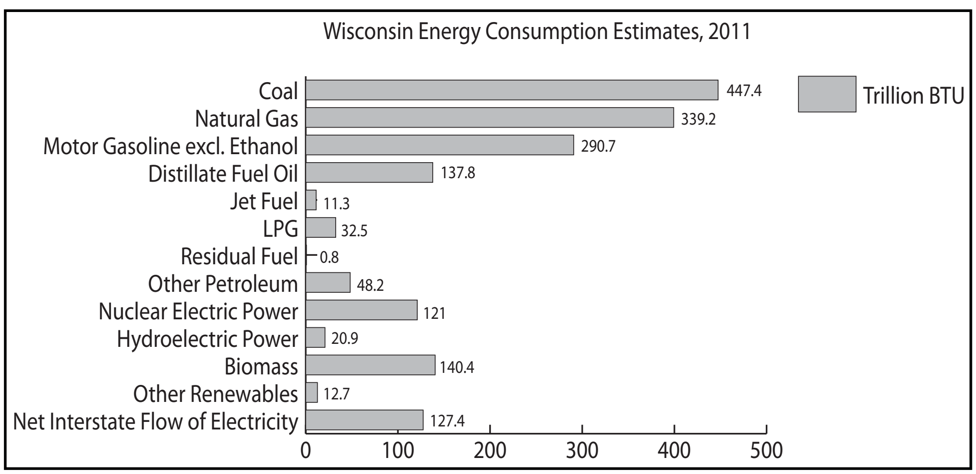
- Wisconsin's industrial sector, which includes energy-intensive industries such as food processing, chemical manufacturing, plastics, and forest products, was the highest energy-consuming sector in the state at 577 trillion Btu in 2010.

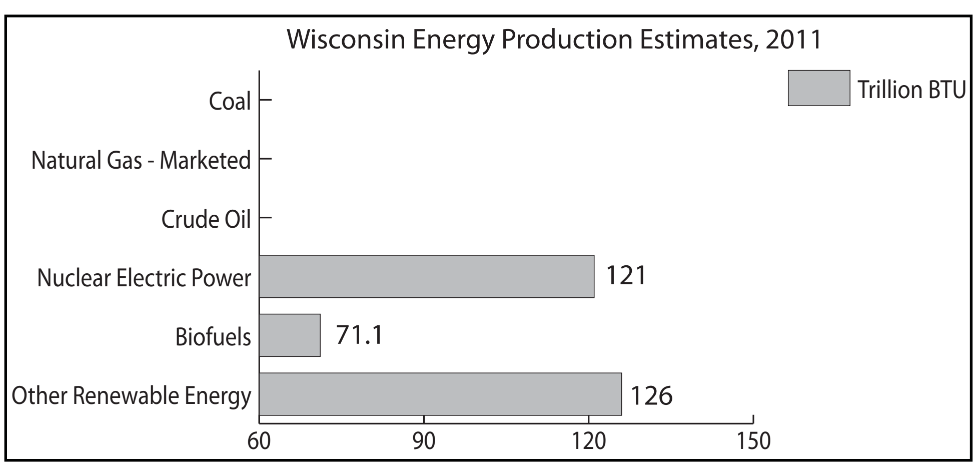
- In 2010, Wisconsin produced 438 million gallons of ethanol and ranked ninth among all states in ethanol production.

- Coal has dominated electricity generation in Wisconsin; in 2011, it provided 63% of the state's net electricity generation.

- Point Beach nuclear power plant's Unit 1 reactor, one of the oldest operating reactors in the United States, started commercial operations in 1970; in 2005, its operating license was extended 20 years (for a total of 60 years).

- In 2011, 8.4% of Wisconsin's net electricity generation came from renewable energy resources, split among conventional hydroelectric power, biomass, and wind.





Energy 7

Energy and Climate Change

The future of energy in the US

Americans have come to rely on a diverse and abundant energy system, one that provides a continuous supply of energy with few interruptions. However, **climate** change is projected to play a big part in changing the supply, production, and demand for energy. Increases in temperature will see an increase in energy used for cooling, while projected increases in the occurrence of hurricanes, floods, tornados, and other extreme **weather** events will continue to have a significant effect on the infrastructure of power grids and energy delivery systems. Drought and water shortages are already beginning to affect energy production and supply. In the Northeast, mild winter temperatures prior to the winter of 2013–2014 had decreased energy demands for heat, but they did not fully offset increased demands for cooling, and the regionally harsher winter of 2013–2014 saw increased demands for heating fuels. These disruptions affect us both locally and nationally, are diverse in nature, and will require equally diverse solutions.

Energy is a **commodity**, and supply and demand around the world will also affect the US energy system. As the global population grows and industrialization of the world continues, demand for energy will increase even further as resources are depleted. These factors could significantly affect US energy costs through competition for imported and exported energy products. Mediation of our energy production could have a huge positive impact on climate change. Unfortunately, there is no energy production system or source currently available that is truly **sustainable**. All forms of energy have negative impacts on the environment, as do many of the ways in which we use them.

Until we have a sustainable means of producing and delivering energy, we need to consider which means of energy production and transport make the least impact; we are faced with a sort of "energy triage." The answer to this problem will be multifaceted, depending in large part on what energy resources and delivery methods are available in each part of the US. The sources of energy that provide the least impact for the best price for those in the Midwest are probably not the same as for those in other areas.

Adaptation—changing our habits of energy use and delivery—can also make it easier for our existing energy infrastructure to adjust to the needs brought on by climate change. Investing in adaptation can pay off in the short term by reducing risks and vulnerabilities, thus minimizing future risks. Increasing sustainable energy practices, including harvesting and production, and improving infrastructure and delivery methods can go a long way toward not only decreasing the effects of climate change, but also our energy security.

Some of these changes are grounded in the development of new technologies for energy production and energy **efficiency**; others may be related to changes in behavior. These changes in technology and behavior may go hand in hand; two percent of electricity production now goes to data centers, for example, a

Climate Change

climate • *a description of the average temperature, range of temperature, humidity, precipitation, and other atmospheric/hydrospheric conditions a region experiences over a period of many years (usually more than 30).*

weather • *the measure of short-term conditions of the atmosphere such as temperature, wind speed, and humidity.*

commodity • *a good for which there is demand, but which is treated as equivalent across all markets, no matter who produces it.*

sustainable • *able to be maintained at a steady level without exhausting natural resources or causing severe ecological damage, as in a behavior or practice.*

efficiency • *the use of a relatively small amount of energy for a given task, purpose, or service; achieving a specific output with less energy input.*

use that did not exist in 1985. Additionally, the Internet is rapidly changing other ways we use energy, allowing us to telecommute and changing the way we shop.

In closing, some key points to keep in mind regarding the future of energy are:

1. Extreme weather events are affecting energy production and delivery facilities, causing supply disruptions of varying lengths and magnitudes and affecting other infrastructure that depends on energy supply. The frequency and intensity of extreme weather events are expected to increase.

2. Higher summer temperatures are likely to increase electricity use, causing higher summer peak loads, while warmer winters are likely to decrease energy demands for heating. Net energy use is projected to increase as rising demands for cooling outpace declining heating energy demands.

3. Both episodic and long-lasting changes in water availability will constrain different forms of energy production.

4. In the longer term, sea level rise will affect coastal facilities and infrastructure on which many energy systems, markets, and consumers depend.

5. As we invest in new energy technologies, future energy systems will differ from the present in uncertain ways. Depending on the way in which our energy system changes, climate change will introduce both new risks and new opportunities.

Resources

Books

Bird, K.J., 1989, North American fossil fuels, In: Bally, A.W. & Palmer, A.R. (eds.), *The Geology of North America – An overview*. The Geology of North America, vol. A, Geological Society of America, Boulder, CO, p . 555–574.

Duggan-Haas, D., R. M. Ross, and W. D. Allmon, 2013, *The Science Beneath the Surface: A Very Short Guide to the Marcellus Shale*. Paleontological Research Institution (Special Publication 43), Ithaca, NY, 252 p.

Hinrichs, R., & Kleinbach, M. H., 2012, *Energy: its use and the environment* (5th ed.). Thomson, Brooks/Cole: Belmont, CA, 640 pp.

Nye, D. E.,1998, Consuming power a social history of American energies. MIT Press: Cambridge, MA.

Richards, J., 2009, *Wind energy.* Macmillan Library: South Yarra, Victoria.

Smil, V., 2006, *Energy: a beginner's guide.* Oneworld: Oxford, UK.

Smil, V., 2010, *Energy myths and realities: bringing science to the energy policy debate.* AEI Press: Washington, DC.

Websites

Energy literacy: Essential principles and fundamental concepts for energy education at Energy.gov, http://www1.eere.energy.gov/education/energy_literacy.html.

History of Energy Use in the United States, by Hobart King at Geology.com. http://geology.com/articles/history-of-energy-use/.

US Energy Information Administration (EIA), http://www.eia.gov/.

US Energy Information Administration (EIA), by state, http://www.eia.gov/state/.

USGS Energy Resources Program, http://energy.usgs.gov/.

Chapter 8:
Soils of the Midwestern US

It's sometimes easy to take the soil beneath our feet for granted. Yet soil has always been with us—it is the foundation of our houses and roads, and from the soil comes our food, fiber, and paper. Soil provides a grassy surface for our parks and fodder for our gardens. Scientists look at soil as a record of the integration of the **climate** and life of an area. The scientist, the engineer, and the gardener may all look at the soil below them in different ways, but perhaps no one has a more integral relationship with soil than a farmer. The economic success of producing crops is intimately tied to the quality of the soil upon which those crops grow, and the most successful farmers are very well versed in the science of their soil.

Known for some of the richest soil in the US, the Midwest is home to some of the most productive agricultural soil in North America. According to the USDA, the US contains only about 5% of the world's population, but it provides more than 25% of the world's food supply. The Midwest is home to the Corn Belt, the largest corn producing area in the US, supporting over a hundred-billion-dollar-a-year industry that helps feed the world but also produces plastics, **biofuel**, livestock feed, and more. How did the soil in this area come to be so fruitful?

What is "Soil"?

Generally, **soil** refers to the top layer of earth—the loose surface of the Earth as distinguished from rock—where vegetation grows. The word is derived (through Old French) from the Latin *solum,* which means "floor" or "ground." It is the most basic resource upon which all terrestrial life depends, and soil is one of the most important resources we have. The Midwest has a wide variety of soils, and each type of soil has a story to tell of its origin.

Soils are composed of a mixture of two key ingredients. The first is plant litter, such as dead grasses, leaves, and fallen debris. Worms, bacteria, and fungi do the job of breaking these down into the nutritious organic matter that helps soil to be so nourishing to future plant growth. The second important component of soil is the sediment derived from the **weathering** of rock that is then transported by **wind**, water, or gravity. Both of these components can influence the texture and consistency of the soil, as well as the **minerals** available for consumption by plants.

All soils may seem alike, but there can be vast differences in soil properties even within small areas. A single acre may have several different soil types, each with its own assets and drawbacks. Some types of soil are clayey or prone to flooding, while others are stable enough to be used as a foundation for buildings. The most identifiable physical properties of soils are texture, structure, and **color**, which provide the basis for distinguishing soil **horizons**. Texture refers to the percentage of **sand**, **silt** and **clay** that makes up the soil. The textures have specific names, as indicated in *Figure 8.1*.

climate • *a description of the average temperature, range of temperature, humidity, precipitation, and other atmospheric/hydrospheric conditions a region experiences over a period of many years (usually more than 30).*

biofuel • *carbon-based fuel produced from renewable sources of biomass like plants and garbage.*

weathering • *the breakdown of rocks by physical or chemical means.*

horizon • *a layer in the soil, usually parallel to the surface, which has physical characteristcs (usually color and texture) that are different from the layers above and below it.*

sand • *rock material in the form of loose, rounded, or angular grains, and formed as a result of the weathering and decomposition of rocks.*

CHAPTER AUTHORS

William F. Kean
Carlyn S. Buckler

8 Soils

Review

loam • *a soil containing equal amounts of clay, silt, and sand.*

peds • *clumps of soil, identified by their shape, which may take the form of balls, blocks, columns, and plates.*

till • *unconsolidated sediment that is eroded from the bedrock, then carried and eventually depositied by glaciers as they recede.*

loess • *very fine grained, wind-blown sediment, usually rock flour left behind by the grinding action of flowing glaciers.*

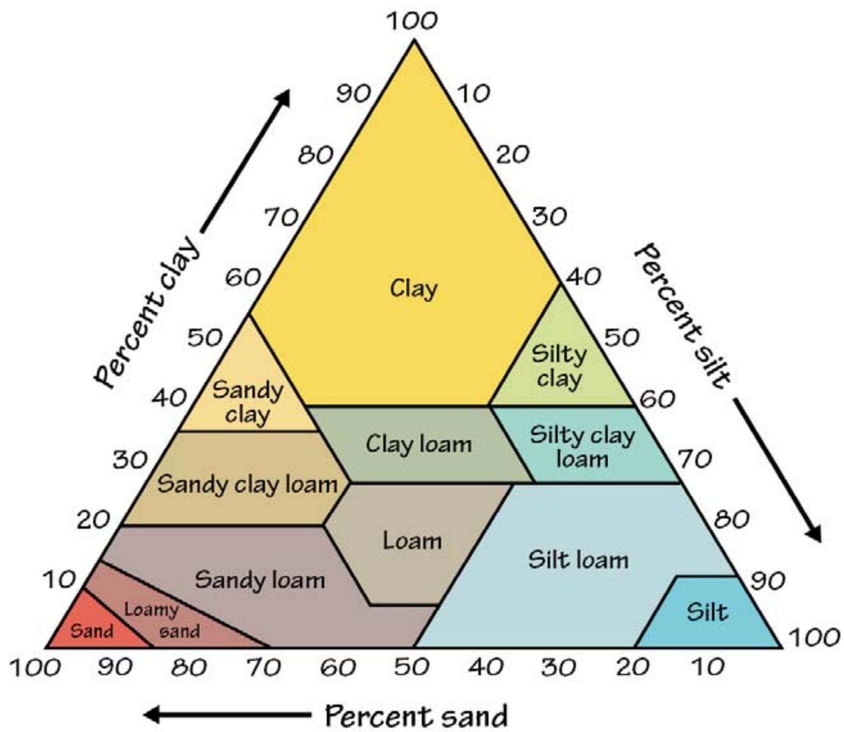


Figure 8.1: Soil texture triangle.

Generally, the best agricultural soils are those with about equal amounts of clay, silt, and sand. A soil of that type would be called a **loam**. Soils that are mostly sand do not hold water very well and dry quickly. Soils with too much clay may never dry out.

Soil structure refers to the way the soil forms clumps. These clumps are known as **peds**. The peds are identified by the shape of the soil clods, which take the form of balls, blocks, columns, and plates. These structures are easiest to see in recently plowed fields, where the soil is often granular and loose or lumpy. Soil color is its most obvious physical property. The color is influenced by mineral content, the amount of organic material, and the amount of water it routinely holds. The colors are identified by a standard soil color chart called the Munsell chart.

Ultimately there are five variables that affect the characteristics of soil worldwide.

1. *Parent material* is the original geologic material from which the soil formed. This can be bedrock, preexisting soils, or other materials such as **till** or **loess**.

2. *Climate* strongly determines the temperature regime, amount of moisture, and type of biota that interact with the parent material. This will affect the extent of chemical and physical weathering on the soil-forming material.

3. *Topography*, or landscape, of the area is related to the relative position of the soil on the landscape; this includes the presence or absence of hills and the slopes between high and low areas. Topography influences natural drainage. Gravity moves water down slopes to depressions or streams and pulls free water downward through the soil. Soils on hills tend to be dry, and soils in depressions and valleys are often wet or saturated.

4. *Biota* or living organisms that live on or in the material affect soil development through their influence on the amount and distribution of organic matter in the soil. For example, plants contribute significantly to the formation of humus, and animals alter a soil's characteristics by leaving behind decayed remains and wastes. Decomposers like bacteria and fungi help to free up the nutrients locked away in these remains and wastes, and these freed nutrients are then recycled and used by new life forms within the same soil. Additionally, animal burrows create spaces in the soil horizons that allow for deeper penetration of air and water, which, in turn, aid plant development. For its part, organic matter impacts the water-holding capacity of the soil, the soil's fertility, and root penetration.

5. *Time* is required for soils to develop while the four elements mentioned above interact. The effects of time can be seen when comparing soils on a glaciated region to either soils formed on recent flood plain deposits or soils in a non-glaciated area at the same latitude.

Soil Orders

Just as rocks are classified into different types based on how they formed (**igneous**, **metamorphic**, or **sedimentary**), their mineral composition, and other characteristics, soils also have their own classification scheme. Soils are divided into 12 dominant orders based on their composition, structures, and types and number of horizons. A typical soil profile is given below (*Figure 8.2*). It shows the transition from the parent material (horizons R and C) to the highly developed or changed horizons (O through B), although not every soil profile will have all the horizons present.

Soils can also be categorized by their location (northern vs. southern soils), the type of vegetation growing on them (forest soils vs. prairie soils), their topographic position (hilltop soils vs. valley soils), or other distinguishing features. The system used to classify soils based on their properties is called **soil taxonomy**. It was developed by the US Department of Agriculture, with the help of soil scientists throughout the country.

In soil taxonomy, all soils are arranged into one of 12 major units, or **soil orders**. These 12 orders are defined by diagnostic horizons, composition, soil structures, and other characteristics. Soil orders depend mainly on climate and the organisms within the soil. These orders are further broken down into 64 suborders based on properties that influence soil development and plant growth, with the most important property being how wet the soil is throughout

Review

igneous rocks • *rocks derived from the cooling of magma underground or molten lava on the Earth's surface.*

metamorphic rocks • *rocks formed by the recrystallization and realignment of minerals in pre-existing sedimentary, igneous, and metamorphic rocks when exposed to high enough temperature and/or pressure.*

sedimentary rocks • *formed through the accumulation and consolidation of grains of broken rock, crystals, skeletal fragments, and organic matter.*

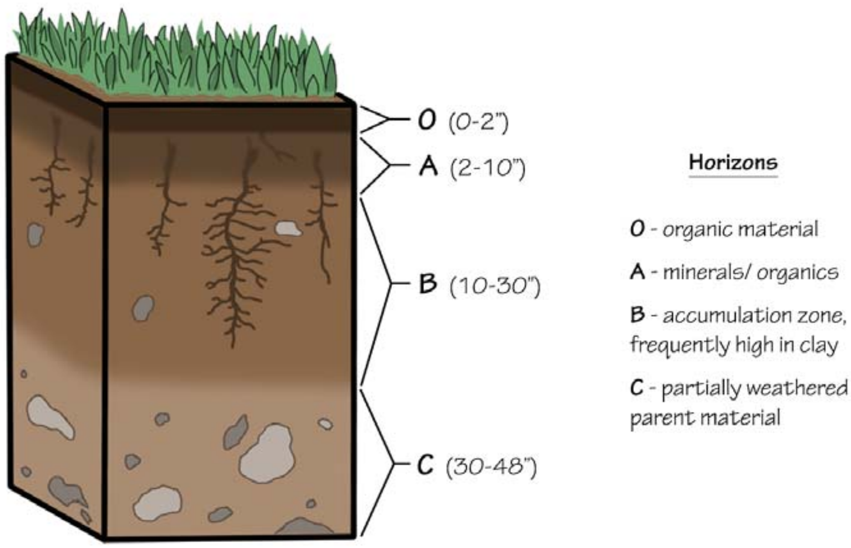


Figure 8.2: Typical soil profile.

the year. The suborders are, in turn, separated into great groups (300+) and subgroups (2400+). Similar soils within a subgroup are grouped into even more selective families (7500+), and the similar soils within families are grouped together into the most exclusive category of all: a series. There are more than 19,000 soil series described in the United States, with more being defined every year (*Figure 8.3*).

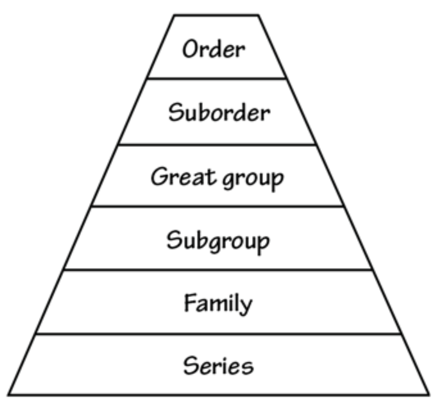


Figure 8.3: Soil taxonomy.

Soils 8

Review

The 12 soil orders

Name	Description	Controlling factors	Percentage of global ice-free land surface	Percentage of US ice-free land surface
Alfisols	Highly fertile and productive agricultural soils in which clays often accumulate below the surface. Found in humid and subhumid climates.	climate and organisms	~10%	~14%
Andisols	Often formed in volcanic materials, these highly productive soils possess very high water- and nutrient-holding capabilities. Commonly found in cool areas with moderate to high levels of precipitation.	parent material	~1%	~2%
Aridisols	Soils formed in very dry (arid) climates. The lack of moisture restricts weathering and leaching, resulting in both the accumulation of salts and limited subsurface development. Commonly found in deserts.	climate	~12%	~8%

The 12 soil orders (continued)

Entisols	Soils of relatively recent origin with little or no horizon development. Commonly found in areas where erosion or deposition rates outpace rates of soil development, such as floodplains, mountains, and badland areas.	time and topography	~16%	~12%
Gelisols	Weakly weathered soils formed in areas that contain permafrost within the soil profile.	climate	~9%	~9%
Histosols	Organic-rich soils found along lake coastal areas where poor drainage creates conditions of slow decomposition and peat (or muck) accumulates.	topography	~1%	~2%
Inceptisols	Soils that exhibit only moderate weathering and development. Often found on steep (relatively young) topography and overlying erosion-resistant bedrock.	time and climate	~17%	~10%
Mollisols	Agricultural soils made highly productive due to a very fertile, organic-rich surface layer.	climate and organisms	~7%	~22%

The 12 soil orders (continued)

Oxisols	Very old, extremely leached and weathered soils with a subsurface accumulation of iron and aluminum oxides. Commonly found in humid, tropical environments.	climate and time	~8%	~.02%
Spodosols	Acidic soils in which aluminum and iron oxides accumulate below the surface. They typically form under pine vegetation and sandy parent material.	parent material, climate, and organisms	~4%	~4%
Ultisols	Soils with subsurface clay accumulations that possess low native fertility and are often red hued (due to the presence of iron oxides). Found in humid tropical and subtropical climates.	climate, time, and organisms	~8%	~9%
Vertisols	Clayey soils with high shrink/swell capacity. During dry periods, these soils shrink and develop wide cracks; during wet periods, they swell with moisture.	parent material	~2%	~2%

8 Soils

Review

Great Lakes • *the largest group of freshwater lakes on Earth (by total surface area and volume), located on the US-Canadian border.*

glacier • *a body of dense ice on land that does not melt away annually and has sufficient mass to move under its own weight.*

Wisconsinian glaciation • *the most recent interval of glaciation, which occurred during the Pleistocene, 85,000 to 11,000 years ago.*

Illinoian • *a period of glaciation that occurred during the Pleistocene, 191 to 131 thousand years ago.*

Pre-Illinoian glaciation • *a grouping of the Midwestern glacial periods that occurred before the Wisconsinian and Illinoian glaciations.*

Dominant soils of the Midwestern US

The soil orders found in the Midwest are:

Alfisols (**al**-fuh-sawls): Alfisols are widely distributed throughout the Midwest but are less prominent in the western portion.

Entisols (**en**-ti-sawls): Entisols are most concentrated in the Central Sands of Wisconsin and the Loess Hills of western Iowa. They can also be found sprinkled about parts of Wisconsin, the western half of Michigan's Lower Peninsula, and northern Minnesota.

Histosols (**his**-tuh-sawls): As one would imagine, the Histosols are primarily clustered around the **Great Lakes** and can therefore be found in Michigan's Upper Peninsula, northern Wisconsin, and northern Michigan.

Inceptisols (in-**sep**-tuh-sawls): Inceptisols are not widespread throughout the Midwest, but they are highly concentrated in the northeast corner of Minnesota.

Mollisols (**mol**-uh-sawls): Mollisols dominate the western portion of the Midwest along with large parts of northern and central Illinois.

Spodosols (**spod**-uh-sawl): In the Midwest, Spodosols are exclusively concentrated in northern Wisconsin, Michigan's Upper Peninsula, and the northern portion of Michigan's Lower Peninsula.

National and Midwest Soils

Below are maps showing the locations of the predominant soils in the nation (*Figure 8.4*), and in the Midwest (*Figure 8.5*). The Midwest soil types tend to relate to topography and parent material, with some relation to climate.

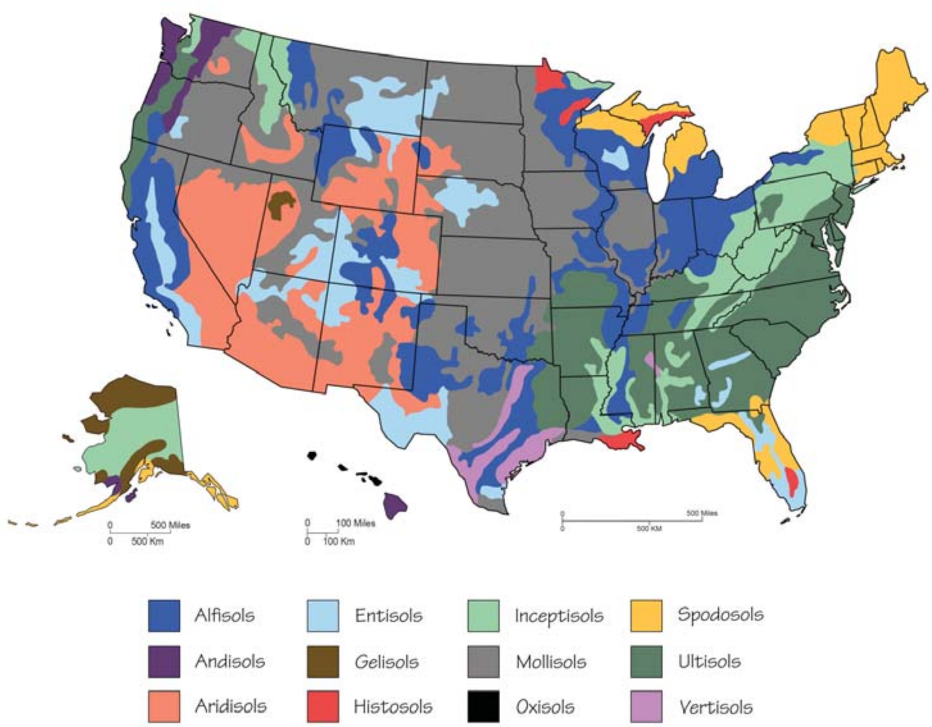


Figure 8.4: Soil map of the US.

Review

till • *unconsolidated sediment that is eroded from the bedrock, then carried and eventually deposited by glaciers as they recede.*

outwash plain • *large sandy flats created by sediment-laden water deposited when a glacier melts.*

kame • *an irregularly shaped mound made up of sediment that accumulated in a depression on a retreating glacier.*

esker • *a sinuous, elongated ridge of sand and gravel.*

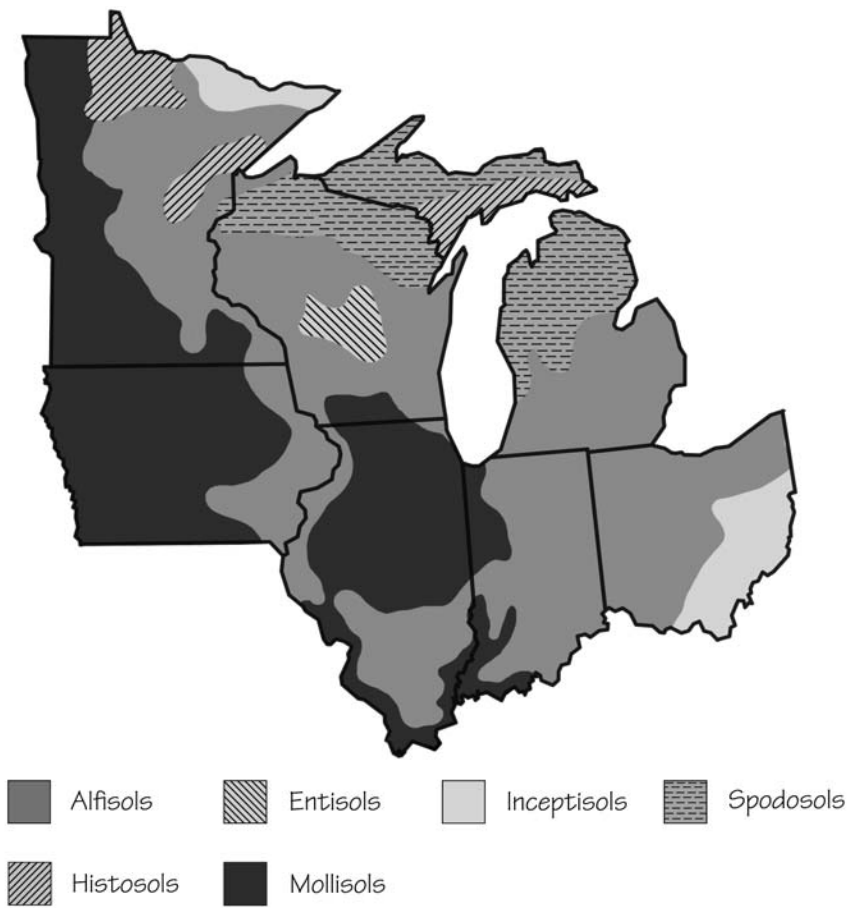


Figure 8.5: Soil map of the Midwest.

Geology of the Midwest: Parent Material

A quick look at the maps below (*Figures 8.6–8.8*) shows that the dominant parent material for Midwest soils is **glacial** deposits from the **Wisconsinan**, **Illinoian** and **Pre-Illinoian** advances. These covered the Midwest from about two million years ago to the final retreat of the Wisconsinan glaciation about 10,000 years ago. The material from the glaciers is primarily **till**, glacial fluvial deposits (as **outwash plains**), and loess deposits.

See Chapter 6: Glaciers for more information about these glaciations.

Till is the unsorted material—from boulders to fine clay silt—deposited by glaciers as they advance and recede. When a glacier retreats, a line of sediment from the flowing river remains behind and can be seen as a ridge of sand and/or gravel, such as that found in **kames** and **eskers**. Beyond the edges of the glacier, as melting of the glaciers continues, sediment-laden waters create large, sandy flats, known as outwash plain**s**. Fluvial (outwash) material is a very common parent material in the Central Lowlands region. Another aspect of glaciation in this region was the accumulation of loess (windblown silt) distributed across the landscape that was part of the outwash plains. The Mississippi and Missouri Rivers, as well as other rivers in the area, aided the distribution and deposition of loess to the Midwest, creating the rich agricultural area we have today.

A simplified map of the soils of the Midwest (*Figure 8.4*) shows that, when compared to *Figures 8.7* and *8.8*, the soil types are strongly correlated with the age of the glacial deposits. It is only the southern margins of the Midwest in Illinois, Indiana, and Ohio that escaped the advancing and retreating ice.

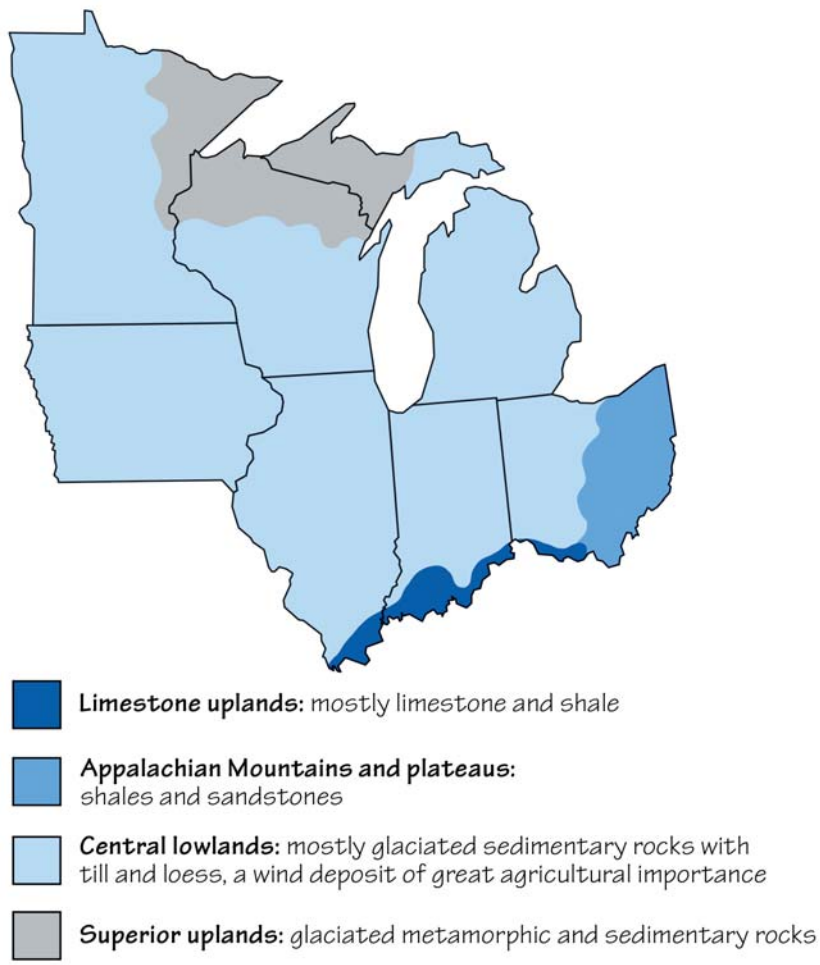


Figure 8.6: Physiographic and regolith map of the Midwest.

Review

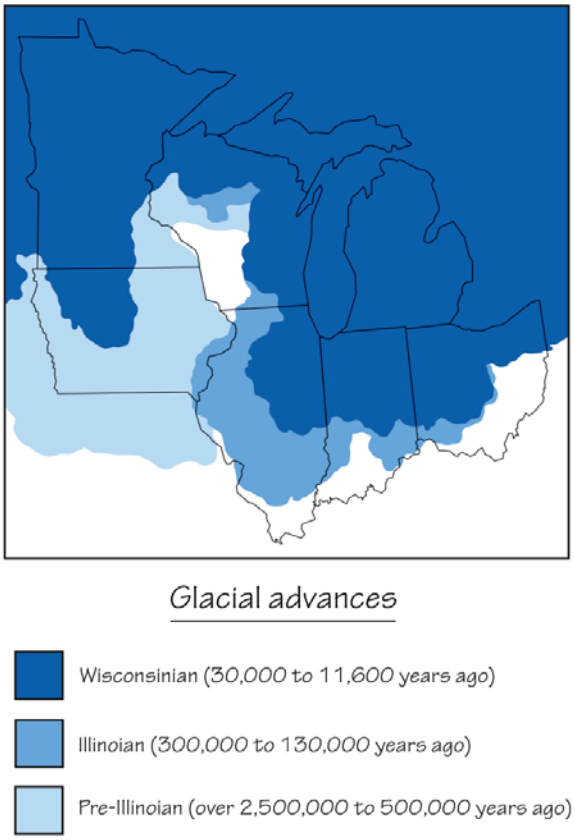


Figure 8.7: Extent of the glacial sheets in the Midwest.

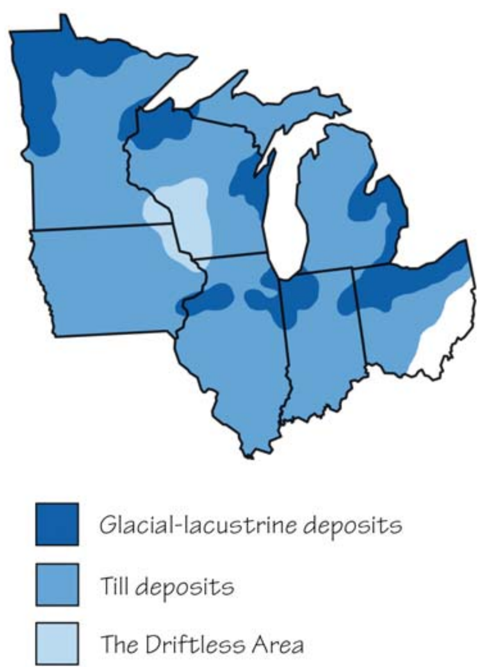


Figure 8.8 Generalized glacial deposits in the Midwest.

8 Soils

Region 1

volcanism • *the eruption of molten rock onto the surface of the crust.*

quartz • *the second most abundant mineral in the Earth's continental crust (after feldspar), made up of silicon and oxygen (SiO_2).*

iron • *a metallic chemical element (Fe).*

Laurentide Ice Sheet • *an ice sheet that covered most of Canada during the last major glaciation.*

ice age • *a period of global cooling of the Earth's surface and atmosphere, resulting in the presence or expansion of ice sheets and glaciers.*

Soils of the Superior Upland
Region 1

The Superior Upland region of the Midwest reveals a vibrant record of tropical seas, violent **volcanic** eruptions, and huge glaciers. Sand deposited over 400 million years ago provides some of the purest **quartz** deposits in the US, which are used in the glass and foundry industries today. Ten to twenty thousand years ago this area was covered by glaciers, and the deposits those glaciers brought with them—either directly or indirectly—make up most of the parent material of the soil today. Agriculture is big here, although not as prolific as in Region 2 due to the mountainous topography, near-surface bedrock, and cooler climate. However, the soil here does supports over 600,000 hectares (1.5 million acres) of mixed hardwood and coniferous forests in, among other places, the Chequamegon National Forest (Wisconsin), the Nicolet National Forest (Wisconsin), and the Porcupine Mountains (the Upper Peninsula of Michigan). This region is part of one of the oldest mountain ranges in the world, a range composed of resistant igneous and metamorphic rocks that includes the 3.6-billion-year-old **Morton Gneiss** of Minnesota, some of the oldest exposed rock in the world.

See Chapter 2: Rocks for more about the formation of the Morton Gneiss and other Midwestern rocks.

The climate, the hardwood and conifer forests, and the numerous wetlands provide the conditions for producing the dominant soil of the region, a Spodosol, or more specifically the Spodosol of suborder Orthods (*Figure 8.5*). This soil is typical of cold, wet climates and, frequently, sandy parent material. The spruce and fir forests and the bogs of the north are typical ecosystems for this soil.

Mineral mining is also big in this region. In northeastern Minnesota, the Minnesota Iron Range holds the largest deposit of **iron ore** in the nation, and it is composed of the Mesabi, Cuyuna, Vermilion, and Gunflint mountain ranges. The eastern end of the region is also home to many iron mines near Ishpeming and Negaunee in Michigan. These deposits color the local soils and sand deposits with a noticeable red hue due to the rusting iron.

About 13,000 years ago, the **Laurentide Ice Sheet**, which covered most of Canada at the time, began to melt at its southern border. In its prime, the Laurentide was more than 5 kilometers (3.1 miles) thick at its thickest point on what is now the Hudson Bay. This sheet of ice weighed so much that it depressed the **crust**, allowing for an expansive lake to form as the ice melted. This lake developed in an area that separates the Mississippi watershed from areas that drain northward. Lake Agassiz was born, and it is said to have been the largest lake ever to exist, the volume of which, today, could contain all the water in all the lakes on Earth. As glaciers continued to melt at the end of the last **ice age**, several modern river valleys were carved out by the waters spilling over from Lake Agassiz, including the Minnesota River and the Red River Valley, the latter of which was formed from silt deposited from the lake. Much of the water from Lake Agassiz was drained into what are now the Minnesota and the Mississippi Rivers and also into Lake Superior. These sediments provided the parent material for many of the soils in these northern river valleys and were also the source for some of the loess deposits common to the region.

Loess deposits are found throughout the Midwest, including the Superior Upland region, and although wind brought these materials to the area, water **erosion** is now the primary reason these soils are being washed away. Methods to combat the loss of the soil in this area include the use of "no till" farming and the planting of cover crops, which are crops planted after a main crop is harvested that help to decrease runoff, increase soil quality, and also provide habitat for animals during the winter.

Soils of the Central Lowland

Region 2

The Central Lowland is home to some of the richest agricultural land in the US. Although the soil here has been affected for a considerable amount of time by the climate, life, and **plate tectonics**, most of the topography and soil found here is the result of glacial activity during the **Pleistocene**. Multiple episodes of formation and melting of glaciers over the last 2.5 million years have shifted massive amounts of sediment and rock, carved gorges with their advance, and produced caves, lakes, river beds, and streams with their melt.

During this stretch of time, the glaciers advanced, receded, melted, and reformed repeatedly as the climate cooled during the ice age and then warmed somewhat during interval periods. The farther south one goes in the Midwest, the fewer the advances that were experienced. The glaciers brought with them rocks, sands, silts, and clays as they traversed the Canadian terrain. The more obvious glacier depositional features can be seen north of Illinois and Indiana, such as **drumlins**, kames, eskers, and **moraines** (*Figure 8.9*). The surfaces in the southern parts of the region are covered mostly by outwash and loess deposits that developed near the terminus of the ice sheets. These deposits are made up of predominantly silt and clay-sized material. While the parent material for much of the northern area is ground moraine, the sediment was plastered down by the advancing ice. Normally, the composition of the ground moraine is at least partly determined by the type of bedrock encountered by the advancing ice. Not surprisingly, much of central Wisconsin and Minnesota has sandy ground because the bedrock is **Cambrian sandstone**, whereas eastern Wisconsin has very clay-rich soils because the glaciers advanced over exposures of the Maquoketa Shale, a very soft and clay-rich **shale**. Prominent glacial features in Wisconsin are drumlins, elongated hills that form parallel to the flow of a glacier and are made of compacted glacial sediments, frequently till. They make for dramatic-looking farm fields, such as those seen in *Figure 8.10*.

plate tectonics • *the way by which the plates of the Earth's crust move and interact with one another at their boundaries.*

Pleistocene • *a subset of the Quaternary, lasting from 2.5 million to about 11,700 years ago.*

drumlin • *a teardrop-shaped hill of till that was trapped beneath a glacier and streamlined in the direction of the flow of the ice moving over it.*

moraine • *an accumulation of unconsolidated glacial debris (soil and rock) that can occur in currently glaciated and formerly glaciated regions.*

shale • *a dark, fine-grained, laminated sedimentary rock formed by the compression of successive layers of silt- and clay-rich sediment.*

8 Soils

Region 2

Driftless Area • *a region that did not experience glaciation, located in parts of southwestern Wisconsin, eastern Minnesota, and northeastern Illinois and Iowa.*

Quaternary • *a geologic time period that extends from 2.6 million years ago to the present.*

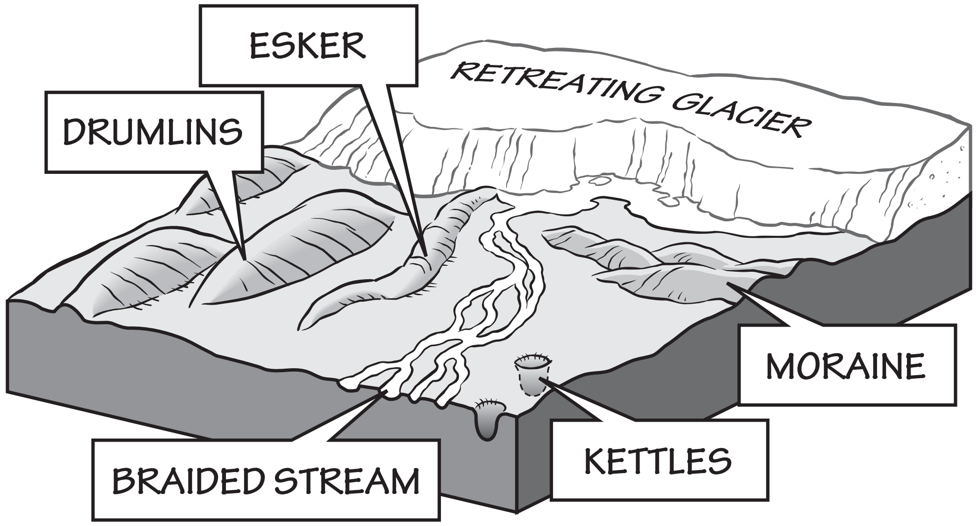


Figure 8.9: Glacial deposits.

Figure 8.10: Drumlins formed by glacial drifts near Cross Plains, Wisconsin.

The **Driftless Area**, found in parts of southwestern Wisconsin, eastern Minnesota, and northeastern Illinois and Iowa, did not experience glaciation. This locale is known as the Driftless Area since it lacks glacial deposits, which are collectively called drift. Glaciers are known to have reached all sides of the Driftless Area at various times throughout the **Quaternary** Ice Age, but are not known to have completely encompassed the area at any time.

See Chapter 6: Glaciers to learn more about the Driftless Area.

This resulted in an island of much older soils in a sea of younger soils. It also is one of the few areas of the Central Lowland with highly dissected river valleys, known locally as the Coulee Country.

Parts of Wisconsin also have remnants of drained glacial lakes. The most prominent example is Glacial Lake Wisconsin that drained rapidly as it broke through a terminal moraine of the Green Bay Lobe near the site of the Wisconsin Dells. The draining water carved the Wisconsin River Valley at the Dells and left behind a glacial lakebed near Tomah, Wisconsin where cranberries are grown today. Other noted glacial lakebeds that contributed to the agriculture of the state are Glacial Lake Oshkosh in the northeast part of the state, and Glacial Lake Yahara in the south central part of the state.

Western and northern Ohio along Lake Erie also have a distinct glacial history because much of the area is composed of glacial lakebed sediments generated when the ice retreated into the Lake Erie Basin, producing a marginal lake known as Glacial Lake Warren. This area is known for its vineyards, orchards, and fields of farm vegetables.

The dominant soil types for the Central Lowlands are Alfisols, of suborders Udalfs, and Aqualfs, with a small section in northwestern Minnesota of Boralfs. The first two are more common in warm humid regions, whereas the last is found in cold regions. They are not as weathered as some soils, so they are still rich in nutrients. The soils to the south of the region are thicker than those to the north.

The second most common soil types are Mollisols, which can be found in the Central Lowlands where loess deposits are dominant and the vegetation was originally grassland. These soils are prominent in western Minnesota, Iowa, and much of Illinois and are of the suborder Udolls.

There are small sections with Entisols (suborder Psamments) in central Wisconsin associated with Glacial Lake Wisconsin. Northern Minnesota has a section of Histosols, and northeast Michigan has a small area of Inceptisols.

Soils of the Inland Basin
Region 3

The Inland Basin is the only area not extensively influenced by the numerous glacial advances. The region is geologically referred to as a basin because of its bedrock type, but geographically it is a plateau formed during mountain building to the east. This plateau (the major portion of which is known as the Allegheny Plateau) occupies most of western Pennsylvania, part of eastern Ohio, more than half of West Virginia, the western tip of Maryland, the upland southern portion of New York, and a marginal portion of southern Indiana and Illinois. The Allegheny Plateau has been greatly eroded by swift rivers and streams that have cut deep valleys, leaving behind steep hills as remnants of the former surface. For the most part, elevations range from about 370 to 760

Region 3

bituminous coal • *a relatively soft coal containing a tarlike substance called bitumen, which is usually formed as a result of high pressure on lignite.*

petroleum • *a naturally occurring, flammable liquid found in geologic formations beneath the Earth's surface.*

natural gas • *a hydrocarbon gas mixture composed primarily of methane (CH4), but also small quantites of hydrocarbons such as ethane and propane.*

coal • *a combustible, compact black or dark-brown carbonaceous rock formed by the compaction of layers of partially decomposed vegetation.*

Mississippian • *a subperiod of the Carboniferous, spanning from 359 to 323 million years ago.*

meters (1200 to 2500 feet) above sea level. The valleys and gentler slopes of the Alleghenies are dotted with farms on which grain is grown and dairy and beef cattle are raised. The area is rich in **bituminous coal**, especially in Pennsylvania, West Virginia, and Ohio. There are deposits of **petroleum** and **natural gas**, and lumbering is also an important industry in this area. The plateau is divided into unglaciated and glaciated regions.

Unglaciated Allegheny Plateau

The Unglaciated Allegheny Plateau is located in an arc around southeastern Ohio that extends into western Pennsylvania and West Virginia. This area is a dissected plateau, characterized by sandstone, shale, and **coal** seams that are **Mississippian** through **Permian** in age. A good example of the dissected nature of this area, and a spectacular scenic location, is the Hocking Hills in southeast Ohio. This area is dominated by Inceptisols of suborder Ochrepeds (*Figure 8.5*). These soils have thin, light-colored surface horizons. The bedrock is mostly composed of shales, **limestones**, and sandstones that are **Devonian** through Permian in age but still have only thinly developed soils.

Glaciated Allegheny Plateau

The Glaciated Allegheny Plateau lies within the area covered by the **last glacial maximum**. As a result, this area of the Allegheny Plateau has lower relief and gentler slopes than does the relatively rugged Unglaciated Allegheny Plateau. In general, the glaciated portion lies to the north and west of the unglaciated portion, and it forms an arc from northeastern to southeastern Ohio. This area—only a few hundred square kilometers owing to the blockage that the steep relief of the mountains provides at the edge of the ice sheet—contains only old drift now buried by long periods of soil development. The dominant soil type of this area is an Alfisol of suborder Udalf.

State Soils

Just as many states have official state flowers, birds, and **fossils**, they also have official soils. State soils are most often determined by a vote of soil scientists in the state, and, absent any political wrangling, usually represent the most productive soils and those that most closely resemble everyone's favorite soil: loam. As mentioned earlier, loam soils are almost equal parts sand, silt, and clay.

Illinois

The Illinois state soil is the Drummer soil, an Alfisol. Drummer soils consist of very deep, poorly drained soils that formed in 1 to 1.5 meters (40 to 60 inches) of loess or other silty material in the underlying stratified, loamy, glacial drift. Drummer soils are the most extensive soils in Illinois and cover more than 600,000 hectares (1.5 million acres).

Soils 8

State Soils

Indiana

The state soil of Indiana is the Miamian series, formed in calcareous, loamy till on the Wisconsin Till Plains. This Alfisol covers 321,722 hectares (794,994 acres) of the state of Indiana and is nationally ranked for agricultural production because of its high productivity.

Iowa

The Tama series is the state soil of Iowa. This Mollisol is considered one of the most productive in the state and is not surprisingly used for agricultural purposes. It makes up about 333,000 hectares (825,000 acres) in east central and eastern Iowa. Tama soils formed in 1.2 meters or more (four feet or more) of silty loess, under tall prairie grasses.

Michigan

The Kalkaska soils are Michigan's state soil series. They are Spodosols that occur in both the Upper and Lower Peninsulas of Michigan. There are over 300,000 hectares (750,000 acres) of these soils throughout the state. Kalkaska soils formed in sandy deposits left behind by the retreating glaciers. These soils primarily support hardwood timber, namely sugar maple and yellow birch.

Minnesota

Lester soils, the state soil series of Minnesota, are found in the south central portion of the state. They are of moderate extent and total over 240,000 hectares (600,000 acres). These Mollisols formed in loamy, calcareous glacial till on ground moraines. The principal crops grown in these soils are corn and soybeans.

Ohio

The Miamian series is the state soil of Ohio. It consists of very deep, well-drained soils that formed in a thin layer of loess and in the underlying loamy till, which is also high in lime. They are the most extensive soils in Ohio and are found on more than 300,000 hectares (750,000 acres) throughout the state. Corn, soybeans, and winter wheat are the primary crops grown in this soil.

Wisconsin

Wisconsin's state soil is the Antigo Silt Loam, named after the city of Antigo, Wisconsin in the northern part of the state. Antigo soils, which are Alfisols, are well drained and formed in loess and loamy sediments over stratified sandy outwash that cover more than 120,000 hectares (300,000 acres).

Permian • *the geologic time period lasting from 299 to 252 million years ago.*

limestone • *a sedimentary rock composed of calcium carbonate ($CaCO_3$).*

Devonian • *a geologic time period spanning from 419 to 359 million years ago.*

last glacial maximum • *the most recent time the ice sheets reached their largest size and extended farthest towards the equator, about 26,000 to 19,000 years ago.*

fossil • *preserved evidence of ancient life.*

Resources

Books

Lindbo, D. L., & Mannes, J., 2008, *Soil!: Get the inside scoop*. Soil Science Society of America: Madison, WI.

Lindbo, D. L., 2012, *Know soil, know life*. Soil Science Society of America: Madison, WI.

Logan, W. B.,1995, *Dirt: the ecstatic skin of the Earth.* Riverhead Books: New York.

Soil Survey Staff, 2014, *Keys to Soil Taxonomy, 12th ed.* USDA-Natural Resources Conservation Service Conservation Service, Washington, DC. (Available at http://www.nrcs.usda.gov/wps/PA_NRCSConsumption/download?cid=stelprdb1252094&ext=pdf.)

Soil Survey Staff, 2014, Illustrated guide to soil taxonomy. US Department of Agriculture, Natural Resources Conservation Service, National Soil Survey Center, Lincoln, Nebraska (Available for download at http://www.nrcs.usda.gov/wps/PA_NRCSConsumption/download?cid=stelprdb1247203&ext=pdf.)

Websites

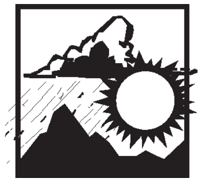
K-12 Soil Science Teacher Resources, Soil Science Society of America. http://www.soils4teachers.org/.

Soil Sustains Life, Soil Science Society of America, https://www.soils.org.

The Twelve Soil Orders Soil Taxonomy, University of Idaho College of Agricultural and Life Sciences, http://www.cals.uidaho.edu/soilorders/.

USDA Natural Resources Conservation Service—Soils. http://www.nrcs.usda.gov/wps/portal/nrcs/site/soils/home/.

Soil surveys by state, USDA Natural Resources Conservation Service http://www.nrcs.usda.gov/wps/portal/nrcs/soilsurvey/soils/survey/state/.



Chapter 9: Climate of the Midwestern US

Climate is a description of the average temperature, range of temperature, humidity, precipitation, and other atmospheric/hydrospheric conditions a region experiences over a period of many years. These factors interact with and are influenced by other parts of the Earth **system**, including geology, geography, insolation, currents, and living things.

Because it is founded on statistics, climate can be a difficult concept to grasp, yet concrete examples can be illuminating. Terms like "desert," "rain forest," and "tundra" describe climates, and we have gained a general understanding of their meaning. Climate can also encompass the cyclical variations a region experiences; a region with a small temperature variation between winter and summer—for example, San Francisco—has a different climate from one that has a large variation, such as Buffalo. Scientists have settled on 30 years as the shortest amount of time over which climate can be defined, but of course it can also refer to millions of years.

You cannot go outside and observe climate. **Weather**, on the other hand, can be observed instantly—it is 57 degrees and raining *right now*. Weather varies with the time of day, the season, multi-year cycles, etc., while climate encompasses those variations. Our choice of clothing in the morning is based on the weather, while the wardrobe in our closet is a reflection of climate. Residents of the Midwest are owners of a very diverse wardrobe. The entire area experiences the greatest seasonal variation of any place in the US, especially in the northern parts.

Past Climate of the Midwest

Climate, like other parts of the Earth system, is not static but changes over time, on human time scales and even on much longer time scales. Latitude, for example, has a very direct effect on climate, so as the continents shift over **geologic time**, the climates on them also shift. Furthermore, the conditions on the Earth as a whole have varied through time, altering what kinds of climates are possible. What is now the Midwest has gone from being ice-covered to tropical and back during its long history!

Ancient climates are reconstructed through many methods. Written records and tree rings go back hundreds of years, glacial ice cores hundreds of thousands of years, and **fossils** and rocks that indicate different climates go back hundreds of millions of years. These clues, coupled with modeling and a knowledge of physics and chemistry, help climatologists put together an increasingly detailed history of the Earth's climate, and that of the Midwest. Unfortunately, we do not have as clear an understanding of climate for the earliest part of Earth history

system • *a set of connected things or parts forming a complex whole.*

geologic time scale • *a standard timeline used to describe the age of rocks and fossils, and the events that formed them.*

fossil • *preserved evidence of ancient life.*

CHAPTER AUTHORS

Alex F. Wall
Judith T. Parrish

as we do for the later parts, because the oldest rocks are much more difficult to find. However, we can still say something about the climate of the ancient Earth, in large part due to our knowledge of atmospheric chemistry.

Ancient Atmosphere

Not long after the Earth first formed, more than 4.5 billion years ago, its atmosphere was composed mostly of hydrogen and helium. **Volcanic** activity and collisions with meteorites and comets added water vapor, carbon dioxide, and nitrogen. As the Earth cooled enough for liquid water to form, the vapor in the atmosphere formed clouds from which the rain poured forth in such a deluge as will never be repeated. These torrential rains were constant for *millions* of years, absorbing **salt** and other **minerals** from the earth as the rainwater coursed to the lowest areas, forming Earth's oceans and seas.

At this time, the sun produced significantly less **energy** than it does today, so one might expect that once the oceans formed, they would continue to cool and eventually freeze. Yet temperatures stabilized, perhaps because there was a greater concentration of potent **greenhouse gases** in the atmosphere and less land surface to reflect light, so temperatures remained high enough for liquid water to exist. Indirectly, the ocean was responsible for the final ingredient of the modern atmosphere because it was home to the first life on Earth. Photosynthetic bacteria appeared perhaps as early as 3.5 billion years ago, but the abundant **iron** and organic matter quickly absorbed the oxygen they produced. After hundreds of millions of years, these sinks were exhausted, and free oxygen could finally build up in the atmosphere. With this addition, the modern atmosphere was complete, though the relative amounts of the gases composing it would, and still continue to, shift. *The composition of the atmosphere and the huge volume of water on Earth are two of the most important factors affecting climate.*

Much of the light from the sun passes unimpeded through the atmosphere and hits the Earth. Approximately 70% of that light is absorbed and retransmitted from the surface as heat. The transmitted heat, which has a longer wavelength than light, is trapped by gases in the atmosphere including water vapor, carbon dioxide, and methane. The similarity between this process and that which warms a greenhouse earned these "greenhouse gases" their moniker.

While the atmosphere was forming above, the surface of the Earth was cooling to form a solid **crust** of rock about 3.7 billion years ago (although there are indications that this process may have started as early as 4.4 billion years ago). Regardless of precisely when this took place, it represented the beginning of tectonic processes that have continued ever since. Molten rock from the **mantle** constantly wells up from deep fissures and solidifies into relatively dense rock, while less-dense rock floats higher on the **magma** and is pushed

volcanism • *the eruption of molten rock onto the surface of the crust.*

salt • *a mineral composed primarily of sodium chloride (NaCl).*

mineral • *a naturally occurring solid with a specific chemical composition and crystalline structure.*

energy • *the power derived from the use of physical or chemical resources.*

greenhouse gases • *a gas in the atmosphere that absorbs and emits heat.*

iron • *a metallic chemical element (Fe).*

crust • *the uppermost, rigid outer layer of the Earth, composed of tectonic plates.*

mantle • *the layer of the Earth between the crust and core.*

around on the slow conveyor belts of mantle-formed rock (*Figure 9.1*). The denser rock forms oceanic **plates** that are lower and covered in water, and the lighter rock forms continental plates, though part or all of a continental plate may be submerged under a shallow sea. The motion of these plates, the rearranging of the continents, and the amount and types of minerals exposed to the atmosphere play a huge role in the climate. Not only do the continents and oceans move through different climate zones, but the continents also affect climate based on their size, and the **weathering** of rock on the continents plays a large role in the composition of the atmosphere. For example, rock that is enriched in organic matter will release abundant amounts of carbon dioxide as it weathers, while rock rich in **feldspar** and **mica** will take up carbon dioxide.

See Chapter 3: Fossils for information about banded iron formations as indicators of some of the earliest life on Earth.

Nearly one billion years ago, the Earth began fluctuating between warm and cool periods lasting roughly 150 million years each. During the cool periods, there is usually persistent ice at the poles; during the warm periods there is little or no glaciation anywhere on Earth. Today, we are still in a cool period. The world has been much hotter for much of its history, but it has also been a bit cooler. Through the shifting global climate and the movement of the tectonic plates, what is now the Midwest has at times been at the bottom of a shallow sea; a plain with swamps, rivers, and grasslands; and under very thick ice.

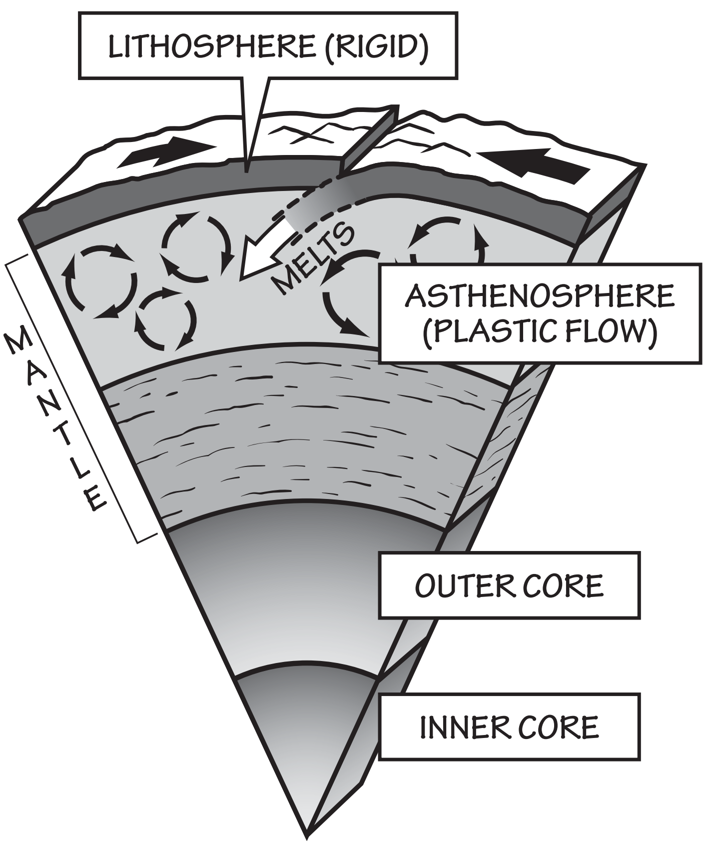


Figure 9.1: The layers of the Earth include the rigid crust of the lithosphere, which is constantly moving over the plastically flowing asthenosphere.

magma • *molten rock located below the surface of the Earth.*

plates • *large, rigid pieces of the Earth's crust and upper mantle, which move and interact with one another at their boundaries.*

weathering • *the breakdown of rocks by physical or chemical means.*

feldspar • *an extremely common, rock-forming mineral found in igneous, metamorphic and sedimentary rocks.*

mica • *a large group of sheetlike silicate minerals.*

9 Climate

Past

Snowball Earth

There is evidence suggesting that several times the entire surface of the planet was covered in ice, a hypothesis called Snowball Earth (*Figure 9.2*). Glacial deposits discovered near Lake Huron and elsewhere show that starting about 2.4 billion years ago the entire surface of the Earth may have been covered in ice for as long as 300 million years, an event known in North America as the **Huronian glaciation**. At that time the continental plates made up less than half as much of the Earth's surface as they do today and were unified as the continent Arctica. It may have been early life's production of oxygen that reacted with and lowered the amount of the greenhouse gas methane in the atmosphere, which tipped the Earth toward a series of cooling feedbacks, causing ice to spread from pole to pole.

An ice-covered planet would stay ice-covered because almost all of the sun's energy would be reflected back into space, but this did not happen on Earth because of tectonics: The Snowball Earth cycle was eventually disrupted by volcanic activity. While the Earth was covered in ice, volcanoes continued to erupt, dumping carbon dioxide and methane into the atmosphere. These gases are usually removed from the atmosphere by organisms and the weathering of rocks, but this was not possible through miles of ice! After millions of years, the concentrations of methane and carbon dioxide increased to the point that greenhouse warming began to melt the **ice sheets**. Once the melting started, more of the sun's energy was absorbed by the surface, and the warming feedbacks began. Because the oceans had been covered, nutrients from volcanic gases and chemical changes in the rocks accumulated in the waters. Once they were re-exposed to light, a population explosion of cyanobacteria produced more and more oxygen capable of combining with freshly thawed carbon sources to make more carbon dioxide, further enhancing the warming. Rocks in the Midwest do not contain direct evidence for this Snowball Earth, or for Earth history for several tens of millions of years afterward.

See Chapter 6: Glaciers for more information about glaciations.

For the next 1.5 billion years, the Midwest, free of ice, drifted around the surface of the Earth. A new supercontinent—**Rodinia**—formed, and the part that is now North America was stable, forming what is known as a craton, or continental interior relatively free of the folding and **faulting** that characterizes continental margins that are subjected to mountain building and other plate tectonic processes. The Midwest was under water for most of this time, and the simple lifeforms sustained on it produced the **stromatolites**, **banded iron formations**, and other evidence found in rocks of the Superior Upland Basin.

About 850 million years ago, during the **Cryogenian**, the Earth entered a 200-million-year **ice age**. The part of Rodinia that would eventually become North America was near the equator. There were two more Snowball Earth cycles during this time. The fact that North America was at such a low latitude yet

Huronian glaciation • *a glaciation beginning about 2.4 billion years ago, that covered the entire surface of the Earth in ice for as long as 300 million years.*

ice sheet • *a mass of glacial ice that covers part of a continent and has an area greater than 50,000 square kilometers (19,000 square miles).*

Rodinia • *a supercontinent that contained most or all of Earth's landmass, between 1.1 billion and 750 million years ago, during the Precambrian.*

fault • *a fracture in the Earth's crust in which the rock on one side of the fracture moves measurably in relation to the rock on the other side.*

stromatolite • *regularly banded accumulations of sediment created by the trapping and cementation of sediment grains in bacterial mats.*

banded iron formation • *rocks with regular, alternating thin layers of iron oxides and either shale or silicate minerals.*

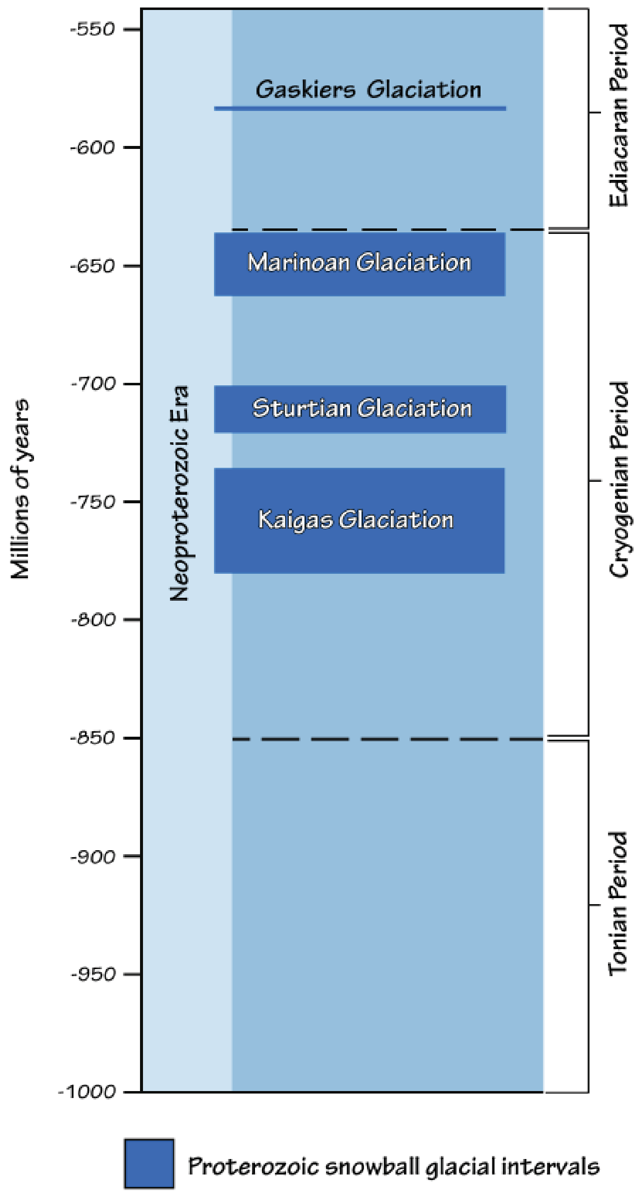


Figure 9.2: Snowball Earth periods during the Proterozoic.

contained **glaciers**, is strong evidence that the Earth really did freeze over completely. These events are not recorded in Midwestern rocks.

Life and Climate

By 635 million years ago, the Earth had warmed again, and the North American continent, of which the Midwest was the central part, moved towards the equator. During the **Ordovician**, much of the Midwest was covered by very pure, **quartz**-rich **sand**. This **sandstone**, now known as the **St. Peter Sandstone**, is an enduring enigma to geologists because it is not clear how all the non-quartz minerals could have been removed. Quartz is extremely resistant to weathering, and it is often the last mineral left when other minerals have weathered away. This suggests that the climate was intensely wet and warm and that the sand

***Cryogenian** • a geologic period lasting from 850 to 635 million years ago, during the Precambrian.*

***ice age** • a period of global cooling of the Earth's surface and atmosphere, resulting in the presence or expansion of ice sheets and glaciers.*

***glacier** • a body of dense ice on land that does not melt away annually and has sufficient mass to move under its own weight.*

***Ordovician** • a geologic time period spanning from 485 to 443 million years ago.*

***quartz** • the second most abundant mineral in the Earth's continental crust (after feldspar), made up of silicon and oxygen (SiO_2).*

***sand** • rock material in the form of loose, rounded, or angular grains, and formed as a result of the weathering and decomposition of rocks.*

***sandstone** • sedimentary rock formed by cementing together grains of sand.*

Past

__inland sea__ • a shallow sea covering the central area of a continent during periods of high sea level.

__limestone__ • a sedimentary rock composed of calcium carbonate ($CaCO_3$).

was washed or blown (or both!) back and forth for a long time before being buried. This weathering is all the more remarkable because land plants, which play a huge role in the weathering of rock on the continents today, were only just evolving. But they were similar to lichens, and even lichens can contribute to the weathering of rock.

After deposition of this sand, fossil evidence in Wisconsin and elsewhere in the Midwest shows that, with the warmer temperatures and higher sea level, at least some of the Midwest continued to be covered by a warm **inland sea**, this time with **limestone** that had formed from the innumerable remains of living creatures as the predominate sediment. This sea persisted in some form for several hundred million years, and, despite a global dip in temperature from 460 to 430 million years ago during yet another ice age, it was warm enough to maintain tropical reef ecosystems for much of that time (*Figure 9.3*). These reefs were among the largest the world had ever seen, and one of the largest was in the Midwest. It grew around the shallow edges of a wide basin centered on Michigan. Today, the reef deposits (as limestone) can be found in much of the Midwest, but they are thickest in Indiana and Illinois—as thick as 300 meters (1000 feet)! Although much of this limestone is under the surface, limestone quarries throughout the area have yielded building stones that show the richness of the fauna that constructed these impressive structures. Many buildings in the Midwest have facings or walls made of stone quarried from these ancient reefs (*Figure 9.4*).

See Chapter 2: Rocks to learn more about the formation of sedimentary rocks.

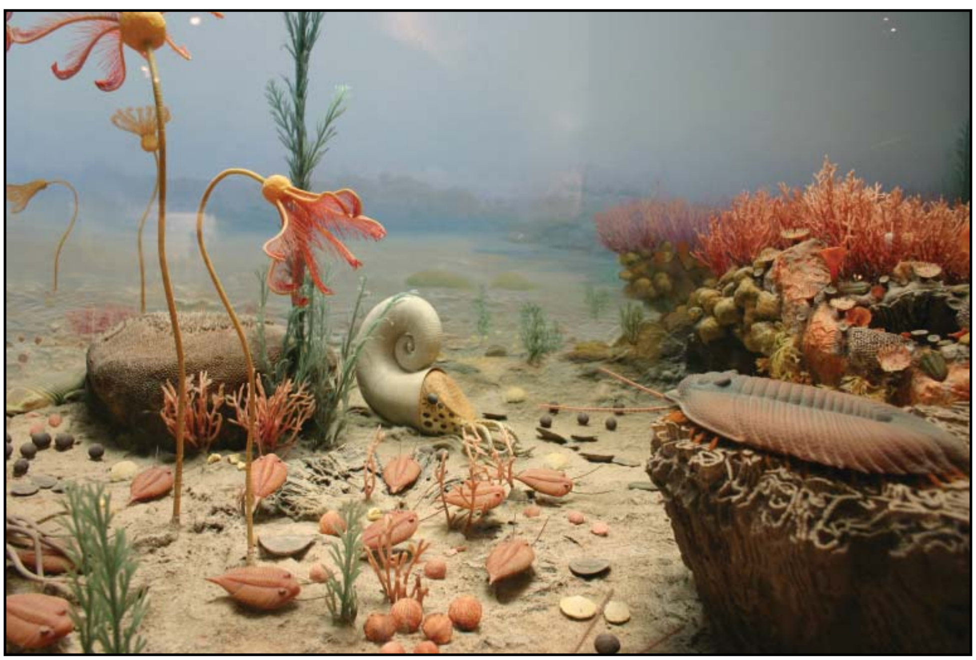


Figure 9.3: Life in the Silurian reefs.

Figure 9.4: A building in Indiana with a facing made of Bedford limestone.

Silurian deposits of salt centered on Michigan indicate that the North American climate experienced little precipitation during the warm period beginning 430 million years ago. Eventually, the salinity in the shallow seas of the ancient Midwest returned to normal in the **Devonian**, and a rich and diverse fauna occupied the sea floor, including reefs and other habitats. At the end of the Devonian, however, the fauna suffered a **mass extinction** that eliminated many of the more important groups of reef-builders and other animals that occupied the shallow seas. The causes of this mass extinction, which actually occurred in a series of steps, are still uncertain.

See Chapter 3: Fossils to learn about the fossils of the Midwestern inland seas.

As the continent continued across the Tropic of Capricorn and the equator, the cycle of warming and cooling repeated yet again, and, by 360 million years ago, glaciers formed near the South Pole. Although the Earth's temperature was falling during this time, the Midwest remained relatively warm, and the shallow, tropical seas continued to cover most of the Midwest until sea level dropped in the middle of the **Carboniferous**.

By this time, complex land plants had evolved and diversified, and they rapidly colonized the newly exposed landscape. Terrestrial fossils from this time show that the climate was humid and supported swampy forests. These swamps eventually became the **coal** deposits of the southern Midwest, especially in southern Illinois, Indiana, and Ohio. Farther north, the land was exposed and no record exists of this time, although it is likely that the area was traversed by rivers. The ice age that had started near the end of the Devonian around 360 million years ago intensified during the later part of the Carboniferous. Deposits in the southern part of the Midwest, in particular, show a cyclicity of rising and falling sea level that was caused by advance and retreat of the large ice cap

Silurian • *a geologic time period spanning from 443 to 419 million years ago.*

Devonian • *a geologic time period spanning from 419 to 359 million years ago.*

mass extinction • *the extinction of a large percentage of the Earth's species over a relatively short span of geologic time.*

Carboniferous • *a geologic time period that extends from 359 to 299 million years ago.*

coal • *a combustible, compact black or dark-brown carbonaceous rock formed by the compaction of layers of partially decomposed vegetation.*

Permian • *the geologic time period lasting from 299 to 252 million years ago.*

erosion • *the transport of weathered materials.*

Pangaea • *supercontinent, meaning "all Earth," which formed over 250 million years ago and lasted for almost 100 million years.*

in the Southern Hemisphere. This ice age lasted well into the **Permian** period, ending about 260 million years ago, when warm temperatures again became the norm.

Tectonic forces had by then pushed the Midwest above sea level, and **erosional** forces tended to dominate, so little direct evidence of the climate during this time is preserved, although adjacent areas have evidence that climate in the area was very warm and relatively arid. Worldwide temperatures, however, began to dip again around 150 million years ago, though perhaps not enough for ice sheets to form, and the tropics, presumably including the Midwest itself, became more humid. **Pangaea**, a supercontinent composed of nearly all the landmass on Earth, broke up into continents that would drift into increasingly familiar positions. By the Cretaceous, the world was heating up again, and a new body of water, the Western Interior Seaway (*Figure 9.5*), covered parts of North America, leaving fossils of tropical marine animals in Iowa and Minnesota.

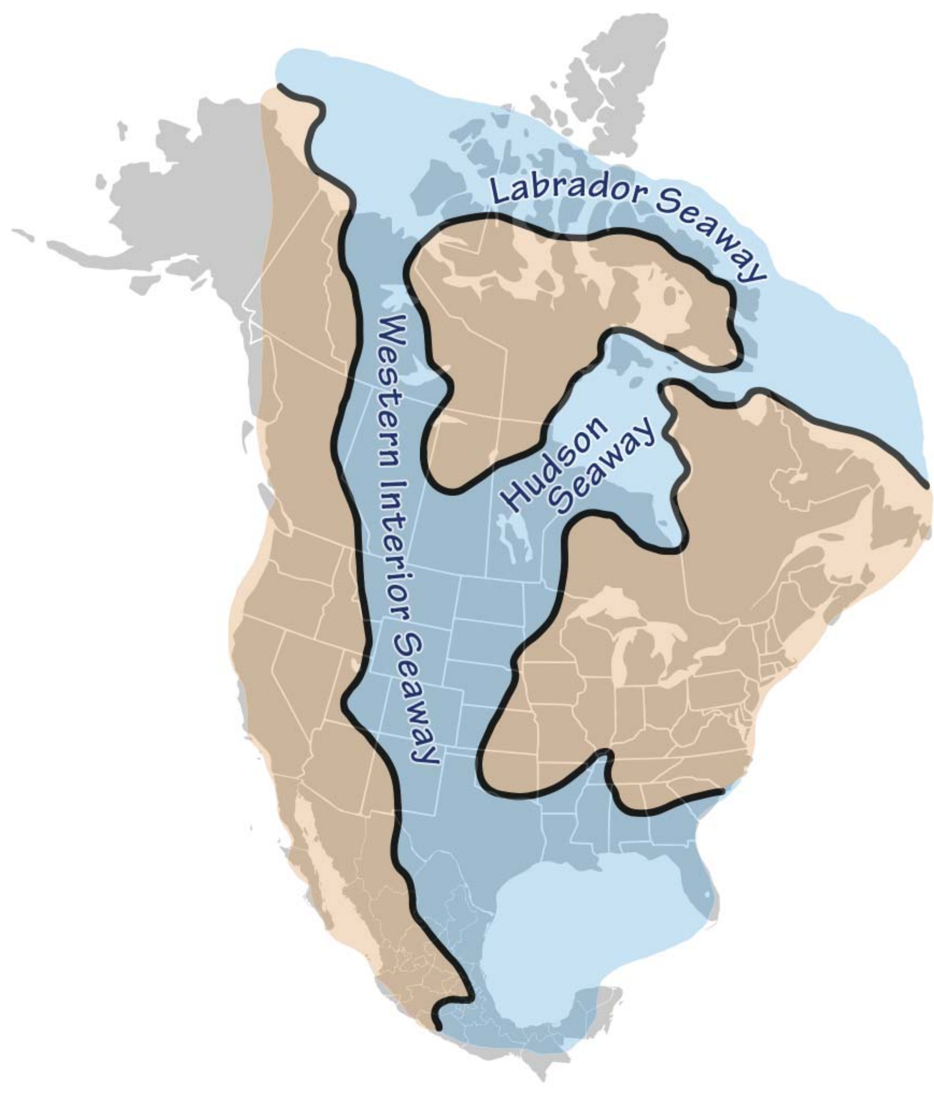


Figure 9.5: The Western Interior Seaway.

Past

extinction • *the end of species or other taxonomic groups, marked by death of the last living individual.*

Figure 9.6: Eskers are composed of sand and gravel deposited by streams that flowed under the ice, partially filling the sub-ice channel. When the ice melts, the sinuous deposit remains.

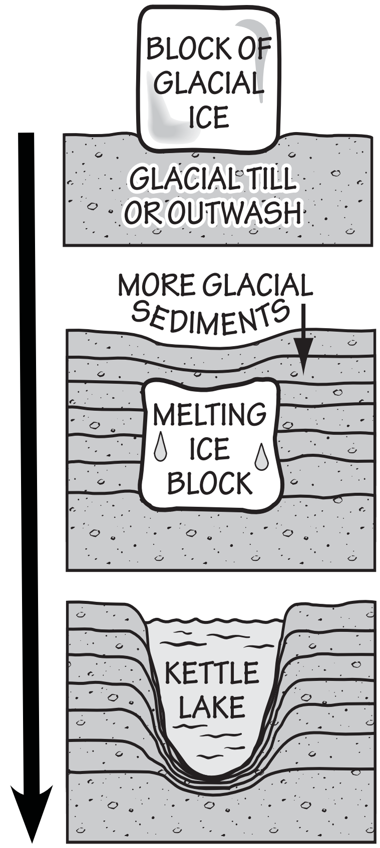


Figure 9.7: Kettle lakes formed where large, isolated blocks of ice became separated from the retreating ice sheet. The weight of the ice left a shallow depression in the landscape that persists as a small lake.

With the end of the Cretaceous and the **extinction** of the dinosaurs 65 million years ago, the world was cooling again. Antarctica moved south, and by 30 million years ago temperatures were low enough that glaciers were growing on its mountains. About 15 million years ago, ice covered much of that continent and had begun to form on Greenland. Eventually, by about 2 million years ago, a sheet of sea-ice formed over the Arctic, and other sheets spread over northern Asia, Europe, and North America and then pushed their way south. This is where the geologic record of climate in the Midwest picks up again.

Since just 800,000 years ago, a kind of equilibrium has been reached between warming and cooling, with the ice caps growing and retreating primarily due to the influence of astronomical forces. During the ice's maximum extent, it reached from the North Pole to where Chicago is now located, covering the northern half of the Midwest, while the southern half was far colder than it is today. The temperatures in areas not then covered in ice were moderated by its presence; the summers were much cooler, yet the winters were only a little cooler than they are today. The area was also somewhat wetter than it is

Great Lakes • *the largest group of freshwater lakes on Earth (by total surface area and volume), located on the US-Canadian border.*

esker • *a sinuous, elongated ridge of sand and gravel.*

kettle • *a lake formed where a large, isolated block of ice became separated from the retreating ice sheet.*

soil • *the collection of natural materials that collect on Earth's surface, above the bedrock.*

wind • *the movement of air from areas of high pressure to areas of low pressure.*

today, with wetlands and forests covering much of what would later become grassland. The glaciers last retreated from the area around 10,000 years ago, leaving behind the **Great Lakes** and many geologic features that define the landscape of the upper Midwest today, including **eskers** (*Figure 9.6*), **kettles** (*Figure 9.7*), and thick deposits of sand and gravel. The climate was warmer and slightly drier, much like that we experience today.

Present Climate of the Midwest

Nearly all of the Midwest has a humid continental climate, describing temperatures that vary greatly from summer to winter, and appreciable precipitation year-round. This is represented in the Köppen system with the prefix "D." Southernmost Illinois and Indiana are closer to a humid subtropical climate, or "C," the primary difference being warmer winters than are found in a D climate. While averages are important factors in describing climate, the Midwest has unusually extreme annual variation in temperature. At an average temperature of 10°C (50°F), it seems similar to that of England, which has an average of 8°C (47°F). But England's average high temperature of 21°C (70°F) and low of 2°C (35°F) is more indicative of how different their climate truly is. Average highs in the Midwestern states are around 29°C (85°F), with lows around -9°C (15°F), a variation fully twice as great as England's. Furthermore, each state has record high temperatures of more than 43°C (110°F) and lows of less than -34°C (-30°F)—a variation of a whopping 77°C (140°F)!

The Midwest is one of the most productive agricultural areas in the world, and the economies of its states depend on farmland. Its excellent **soil**, relatively flat geography, and bodies of water make it uniquely suited to cropland. Yet without a humid climate with warm summers, agriculture here would be completely different. It is one of the few places on Earth where huge amounts of corn and soybeans can be grown with little or no irrigation.

See Chapter 8: Soils for more on the soils and agriculture of the Midwest.

Weather

In part because of its climate's extreme temperature variation and humidity, the Midwest experiences nearly every variety of severe weather. Because the states are so far from the coasts, they rarely experience hurricanes, but heat and cold waves, droughts, floods, blizzards, and tornados are all fairly regular events.

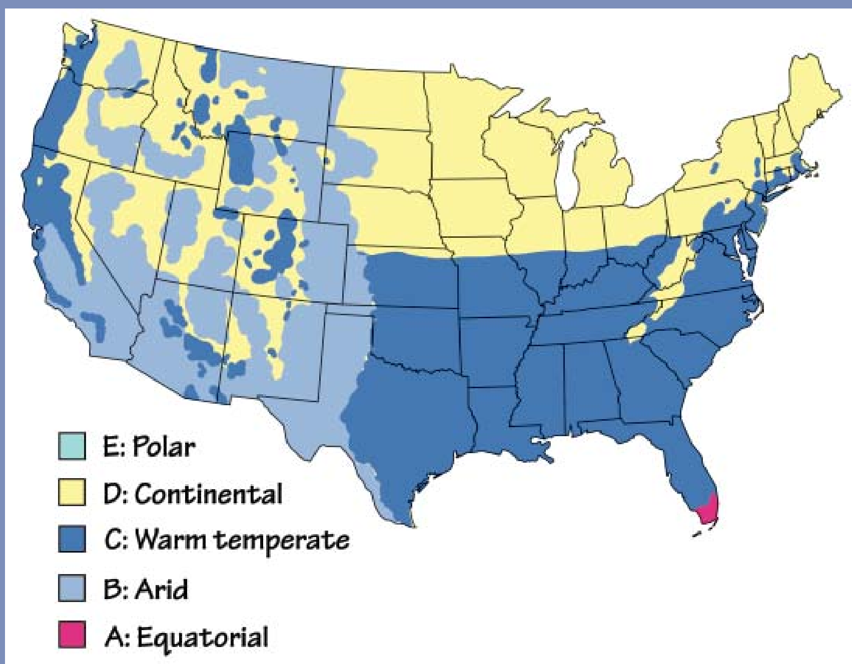
Thunderstorms

The geography and climate of the Midwest are nearly ideal for the formation of thunderstorms. Storms occur when there is strong convection in the atmosphere. Because warm air can hold more moisture than cool air can, convective mixing with cool air forces moisture to condense out of warm air, as vapor (clouds) and precipitation. It is hypothesized that the formation of precipitation causes the

Present

The Köppen Climate Map

Wladimir Köppen developed a commonly used system of climate categorization based on the kinds of vegetation areas sustain. He defined 12 climate types, many of which are familiar: rainforest, monsoon, tropical savanna, humid subtropical, humid continental, oceanic, Mediterranean, steppe, subarctic, tundra, polar ice cap, and desert. Updated by Rudolf Geiger, it has been refined to five groups, each with two to four subgroups.



(See TFG website for full-color version.)

electrical charging that produces lightning. Of course, air cannot mix without moving, and that movement is caused by the **wind**.

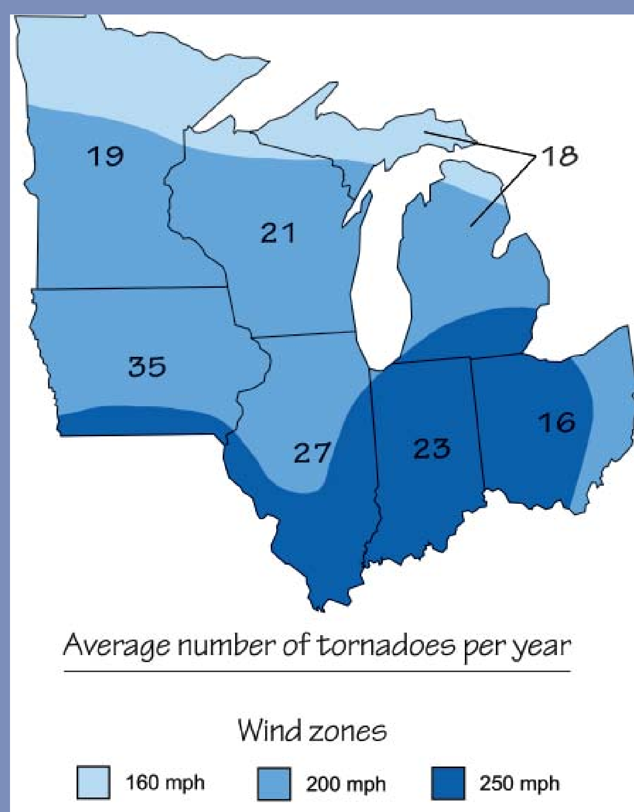
A strong temperature difference at different heights creates instability—the warmer the air near the surface is relative to the air above it, the more potential energy it has to move up. The Midwest frequently gets warm, moist air moving north from the Gulf of Mexico, and cold, dry air moving in from the Rocky Mountains or Canada. Where they meet, vigorous mixing causes storms. Typically, a storm blows itself out once the warm air has moved up and the cool air down—a vertical column turning over as a unit. But because the lower air from the Gulf is moving north while air higher up is moving west, more heat and moisture is constantly added to the system, allowing the storm to persist and strengthen. This movement in different directions is also the reason for the area's unusually high incidence of powerful tornados.

Tornados

Tornado Alley is a nickname for an area extending from Texas to Minnesota (including the western Midwest) that experiences a high number of exceptionally strong tornados. Correcting for size, Indiana and Iowa are the states with the third and fourth most tornados respectively. A few other places in the world see tornados more frequently per given area, but those in central North America tend to be much more powerful. The thunderstorms discussed above can sometimes produce dozens of violent tornados, called tornado outbreaks.

Midwestern Tornado Map

Number of average tornadoes per year in the Midwestern states.



Lake Effect
The Great Lakes create an interesting phenomenon primarily on their eastern shores, mainly affecting Michigan as well as parts of the Northeast, known as the lake effect. During the winter, the huge volume of water in the Great Lakes acts as a reservoir of heat, making the air above it relatively warm and humid. When cold air moves across the warmer lake, convection begins, and, as described above, a storm can form. The moisture from the lake begins to precipitate soon after the air cools. The Upper Peninsula of Michigan usually receives over five meters (200 inches) of snow per year, second only to Tug Hill Plateau in New York, which also gets lake effect snow.

All of the states of the Midwest experience winter storms to some extent, during which several inches of snow falls. While inconvenient and damaging to infrastructure, these storms do not frequently cause widespread disruption, as residents and governments are usually prepared to clear roads and repair damage. Additionally, schools have snow days calculated into their schedules. Ice storms can be more dangerous; as rain freezes to trees, power lines, and rooftops, they may collapse under the weight. If you are able to un-encase your car, the icy roads are even more dangerous to drive on than snowy ones.

Future Climate of the Midwest

While climate describes conditions over a long period of time, it does change, however slowly. In a previous section of this chapter, past changes were discussed. Using some of the techniques that help to reconstruct past climates, plus tracking trends in the present, we can predict how current climates might change. Overall, the world is warming, yet, because we are still in an ice age, eventually the current **interglacial** period will end, and glaciers will begin advancing towards the equator again, although likely not for about 100,000 years. Because the Earth is already getting warmer, the effects of **anthropogenic** sources of warming are amplified through feedback. Some scientists worry that, if not curbed, human activity could actually disrupt the cycle and knock the planet entirely out of the interglacial period, melting all the ice on Earth.

The Earth's orbit, tilt, and wobble alter its position with respect to the Sun, affecting the global climate. These changes in the Earth's movement are cyclical, and the changes in Earth's climate associated with them are known as *Milankovitch Cycles*.

Causes of Change
While astronomical and tectonic forces will continue to cause climates to change, their work is so slow that it will be overshadowed in the near term by human-induced effects. The burning of **fossil fuels**, removal of forests, and all manner of human activities are altering the composition of the atmosphere.

See Chapter 6: Glaciers for more about interglacial periods.

interglacial • *a period of geologic time between two successive glacial stages.*

anthropogenic • *caused or created by human activity.*

fossil fuels • *fuel for human use that is made from the remains of ancient biomass.*

permafrost • *a layer of soil below the surface that remains frozen all year round. Its thickness can range from tens of centimeters to a few meters.*

aerosol • *tiny solid or liquid particles in the air.*

biofuel • *carbon-based fuel produced from renewable sources of biomass like plants and garbage.*

natural gas • *a hydrocarbon gas mixture composed primarily of methane (CH4), but also small quantites of hydrocarbons such as ethane and propane.*

Most dramatically, we are adding huge amounts of carbon dioxide and other greenhouse gases, which trap heat radiated by the Earth. Since plants remove carbon dioxide from the atmosphere, deforestation compounds the issue.

There is a finite amount of carbon on the planet, and the ways in which it changes states and locations are almost innumerable. This makes it extremely difficult to predict the outcome of putting increasing amounts of carbon (as carbon dioxide) into the atmosphere, but there are several important reinforcing effects already being observed. The increasing heat is causing glaciers and sea ice around the globe to melt, and as the ground and ocean they covered is exposed, these darker surfaces absorb and re-radiate increasing amounts of heat.

As **permafrost** in high latitudes melts, the carbon in the soils will become free to enter the atmosphere and, worse, to be converted by bacteria into the even more potent greenhouse gas, methane. Less directly, higher temperatures lead to more frequent and severe droughts, which, in turn, lead to more wildfires that release carbon and **aerosols** into the atmosphere. Aerosols can have a cooling effect as they reflect away radiation from the sun, but they can also pose a public health hazard.

Water is extremely good at absorbing heat: water vapor is the most effective greenhouse gas. Higher temperatures allow more water to be held in the air, as well as increase evaporation. While water vapor feedback is the most significant reinforcer of climate warming, water tends to move out of the atmosphere in a matter of weeks—other greenhouse gases linger in the atmosphere for years.

The Midwest has a unique combination of contributors to climate change. The population of any industrialized, and particularly wealthy, country produces pollution. The more than 50 million residents of the Midwest use electricity, transportation, and products that come from carbon-rich fossil fuels. But it is also a major center for agriculture, manufacturing, and coal, gas, and **biofuel** production, each of which release greenhouse gases. The Midwestern states are also developing unique ways to curb their effect on the climate. Minnesota has some of the most aggressive energy objectives in the US and is on track to produce 25% of its energy from clean fuel sources by 2025. In fact, Minnesota and Iowa already produce more than 10% of their energy from wind and, along with Wisconsin, 50% from biofuel! A distinction should, however, be drawn between production and consumption—these states consume far more coal and **natural gas** than anything else.

Temperature, Precipitation, and Storms

The average temperature in the Midwest is predicted to continue to increase for the foreseeable future—likely 3°C (5°F) by 2100. Of course, this doesn't mean this will occur steadily or evenly. For example, since 1980, the average annual temperature for northern Illinois has increased from around 7°C (45°F) to 9°C (49°F), a change of 2°C (4°F), yet the average *winter* temperature has increased by 4°C (8°F)! Perhaps because of its distance from the moderating influence of the oceans, the Midwest appears to be affected by warming more quickly than are many other areas. Interestingly, higher temperatures and higher carbon dioxide levels are, up to a point, expected to extend the growing season and increase crop yields. The US Government's Global Change Research Program expects the plant hardiness zones for the Midwest to become warmer by up to one zone every 30 years, rapidly changing what kinds of plants and crops can survive. Translating this change to the Köppen climate classification, much of the Midwest will soon be redesignated as humid subtropical. Coupled with less precipitation overall, a garden you planted in Michigan as a child will look like one from Arkansas by the time you are an adult, and then like one from Texas after 30 more years!

We can also expect more incidences of extreme weather. The causes of specific weather events are incredibly complex, but strong correlations and consequences from climate change are already apparent, and they offer clues about what to predict. Because higher temperatures mean greater evaporation and the ability of the air to hold more water, precipitation will occur in greater amounts at a time, but less frequently. During the cooler spring this will lead to flooding, while in hot summers, droughts will become more frequent. Higher atmospheric moisture content has also been correlated with an increased incidence of tornados—a particular concern in the Midwest.

Resources

Books

Allmon, W.D., Smrecak, T.A., and Ross, R.M., 2010, *Climate Change - Past Present & Future: A Very Short Guide*, Paleontological Research Institution: Ithaca, New York, 200 p.

Melillo, J.M., Richmond, T.C., and Yohe, G.W. (eds.), 2014, Climate Change Impacts in the United States. The Third National Climate Assessment. US Global Change Research Program, 841 p.
Available online at http://www.globalchange.gov/nca3-downloads-materials.

Ruddiman, W.F., 2014, *Earth's Climate: Past and Future*, W.H. Freeman and Company: New York, NY

Committee on the Importance of Deep-Time Geologic Records for Understanding Climate Change Impacts, 2011, Understanding Earth's deep past lessons for our climate future. 2011, Washington, D.C.: National Academies Press.
Available online at http://www.nap.edu/download.php?record_id=13111.

Websites

Climate Impacts in the Midwest, EPA, 2013.
http://www.epa.gov/climatechange/impacts-adaptation/midwest.html.

Climate Literacy & Energy Awareness Network (CLEAN). (A rich collection of resources for educators.)
http://www.cleanet.org.

Envisioning Climate Change Using a Global Climate Model, by Youngman, B., Chandler, M., Sohl, L., Hafen, M., Ledley, T., Ackerman, S., and Kluge, S., SERC Earth Exploration Toolkit, http://serc.carleton.edu/eet/envisioningclimatechange/index.html.

Global Climate Change: Vital Signs of the Planet, NASA. (Climate data particularly from satellite-based remote sensing)
http://climate.nasa.gov.

Global Warming and Hurricanes, Geophysical Fluid Dynamics Laboratory, 2013.
http://www.gfdl.noaa.gov/global-warming-and-hurricanes.

Intergovernmental Panel on Climate Change, Fifth Assessment Report (AR5).
http://www.ipcc.ch/.

National Climate Assessment. (Reports summarizing impacts of climate change)
http://nca2014.globalchange.gov.

National Hurricane Data Center, NOAA. (News on current hurricane forecasts.)
http://www.nhc.noaa.gov.

National Weather Service, NOAA, http://www.weather.gov.

Regional Climate Trends and Scenarios for the US National Climate Assessment, NOAA.
http://www.nesdis.noaa.gov/technical_reports/142_Climate_Scenarios.html.

Weather Base. (Weather and climate data by country, state, and city.)
http://www.weatherbase.com.

Weatherunderground maps. (Variety of types of weather maps, including surface, temperature, moisture, wind, cloud cover, precipitation.)
http://www.wunderground.com/maps.

Why Does the U.S. Midwest Get So Many Severe Thunderstorms?, Cliff Mass Weather Blog Monday, 23 May 2011.
http://cliffmass.blogspot.com/2011/05/why-does-midwest-us-get-so-many-severe.html.

Chapter 10: Earth Hazards of the Midwestern US

Natural hazards are events that result from natural processes and that have significant impacts on human beings. Extreme **weather** conditions or geologic activity can cause substantial short-term or long-term changes to our environment. These changes can influence crops, homes, infrastructure, and the **atmosphere**. The 4.6-billion-year-old Earth has experienced many of these natural changes, and it has always adjusted accordingly.

Most of the natural hazards in the Midwest are related to weather, geology, or some combination of the two. Examples of weather-related hazards include **tornados** (which cause a narrow path of extreme destruction) and long periods of unseasonably high temperature (which are a threat to crops and human health). Geologic hazards include events such as **earthquakes**, which can cause damage to housing, bridges, and roads. There is often little that can be done to prevent these natural events from occurring, but advanced planning can minimize their impact.

Weather Hazards

Weather is the measure of short-term conditions of the atmosphere such as temperature, **wind** speed, and humidity. The average weather of a region over decades is its **climate**. Although weather can vary day-to-day or year-to-year, the climate of a region is relatively stable because it represents the average weather over a long period of time. Extra-warm summers and extra-cold winters, when combined with typical seasonal change, result in a moderate average temperature over long periods of decades or centuries. Proximity to a large body of water can also decrease the temperature range of a geographic region. While the Midwest is far from an ocean, it is in close proximity to the **Great Lakes**; nevertheless, states in this area experience a considerable range of temperatures over the course of a year. The greatest temperature ranges are found during the winter: The average winter temperature of northern Minnesota is -13°C (8°F) while that of areas around the Ohio River is 2°C (35°F). Weather hazards can occur fairly frequently, such as several times a year, or relatively infrequently, such as once every century.

Extreme Temperature

Extreme temperatures can create dangerous conditions for people and may lead to property damage. **Heat waves** are periods of excessively hot weather that may also accompany high humidity. Temperatures of just 3°C (6°F) to 6°C (11°F) above normal are enough to reclassify a warm period as a heat wave. Under these conditions, the mechanism of sweating does little to cool people

weather • *the measure of short-term conditions of the atmosphere such as temperature, wind speed, and humidity.*

atmosphere • *a layer of gases surrounding a planet.*

wind • *the movement of air from areas of high pressure to areas of low pressure.*

climate • *a description of the average temperature, range of temperature, humidity, precipitation, and other atmospheric/hydrospheric conditions a region experiences over a period of many years (usually more than 30).*

Great Lakes • *the largest group of freshwater lakes on Earth (by total surface area and volume), located on the US-Canadian border.*

CHAPTER AUTHOR

Nicole D. LaDue

> ***heat island effect*** • *a phenomenon in which cities experience higher temperatures than do surrounding rural communities.*

> ***polar vortex*** • *a regularly occurring area of low pressure that circulates in the highest levels of the upper atmosphere.*

> ***cold front*** • *the boundary between the warm air and the cold air moving into a region.*

> ***hurricane*** • *a rapidly rotating storm system with heavy winds, a low-pressure center, and a spiral arrangement of thunderstorms.*

down because the humidity prevents sweat from evaporating and cooling off the skin. Heat waves have different impacts on rural and urban settings. In rural settings, agriculture and livestock can be greatly affected. Heat stress recommendations are issued to help farmers protect their animals, particularly pigs and poultry, which, unlike cattle, do not have sweat glands.

The impacts of heat waves on urban settings include a combination of the natural conditions of excessive heat and the social conditions of living in a densely populated space. Cities contain a considerable amount of pavement, which absorbs and gives off more heat than vegetation-covered land does. Air conditioning units that cool down the inside of buildings produce heat that is released outside. Pollution from cars and industrial manufacturing also elevate the outdoor temperatures in cities. This phenomenon, in which cities experience higher temperatures than surrounding rural communities do, is known as the **heat island effect**. Other social conditions can cause an increase in the hazards associated with heat waves in urban areas. People who are in poor health, live in apartment buildings with no air conditioning, or are unable to leave their houses are at greatest risk of death during heat waves. In 1995, a heat wave impacted the Midwest, leading to nearly 740 heat-related deaths in Chicago alone. In addition to causing widespread illness from dehydration and exposure to extreme heat, the high temperatures buckled road pavement and warped train rails.

Recently, a different extreme temperature phenomenon has made the news: the **polar vortex**. As the name implies, a polar vortex is a regularly occurring area of low pressure that circulates in the highest levels of the upper atmosphere. Typically, the polar vortex hovers above Canada. However, a pocket of the counter-clockwise rotating low-pressure center can break off and shift southward at a lower altitude, covering the Midwest with frigid air. The jet stream then shifts to a more southward flow than usual, chilling the Midwest and even the southern states. A polar vortex can lock the jet stream in this new pattern for several days to more than a week. Extreme low temperatures can endanger livestock, and precautions should be taken regarding travel on roadways. Although the cold temperatures of a polar vortex can be uncomfortable and make traveling dangerous in the winter, the Midwest has not yet experienced any major economic or health-related impacts from this extreme weather event.

Seasonal Severe Storms

Several types of severe storms present challenges to people living in the Midwest. Summer brings severe thunderstorms associated with **cold fronts**. Fall and spring can bring ice storms, and winter brings the challenge of snow and, in some cases, blizzard conditions. Although rare, **hurricanes** moving north from the Gulf of Mexico can impact the weather in the Midwest as well.

Severe thunderstorms are a common occurrence for people living in the Midwest because the conditions over the Great Plains are perfect for the development of severe weather. The flat, open fields are warmed by the summer sun, which sits high in the sky during this time of year. This results in large temperature differences when cold air masses move across the country. The boundary between the warm air and the cold air moving into a region creates a cold front.

At this boundary, denser, colder air moves in, making the less dense, warm air rise. This displaced warm air cools as it rises because air pressure decreases with increasing height in the atmosphere. As the air cools, it becomes saturated with water vapor, and condensation (the shift from a vapor [gas] state to a liquid state) begins to occur. This phase shift takes place because the cooler air contains less thermal energy than warmer air does, and this reduction in energy allows the water molecules to "link" together faster than they are torn apart. At frontal boundaries, warm air quickly rises and condenses, and clouds form. Because liquid water droplets in the clouds must be very small to remain suspended in the air, when there is a significant amount of condensation, the small water droplets come together, eventually becoming too large to remain suspended. This process leads to dramatic rainstorms.

Air pressure plays a key role in the formation and severity of these storms. Warm air has a lower pressure relative to cold air, and the movement of air from areas of high pressure to areas of low pressure generates wind. Therefore, when a cold front moves into an area that is very warm, the significant difference in air pressure will generate strong winds. The greater the temperature difference, the greater the air pressure difference and, consequently, the greater the speed at which the air will move. Wind is very common in the Midwest, and the **topography** of the area plays an important role in wind formation, allowing for warm air to heat up over large expanses of flat cropland without hills or mountains to influence the direction of air movement. Therefore, the Midwest has the perfect ingredients for severe weather: flat topography and large temperature differences on a day-to-day basis.

While severe thunderstorms are often a weekly occurrence in much of the Midwest, two less common storm hazards have the potential to cause serious property damage and endanger lives: **derechos** and tornados. Both storm events are associated with **wind shear**, which occurs when the wind speed or direction changes with increasing height in the atmosphere. Wind shear can happen when a cold front moves rapidly into an area with very warm air. There, the condensing water droplets mix with the cooler, drier air in the upper atmosphere to cause a downdraft.

When these downdrafts are very powerful, they can cause a derecho, or a set of powerful straight-line winds that exceed 94 kilometers per hour (kph) (58 miles per hour [mph]) and can often approach 160 kph (100 mph). These powerful windstorms can travel over 400 kilometers (250 miles) and cause substantial wind damage, knocking down trees and causing widespread power outages. The lightning associated with these intense storms can cause both forest fires and house fires. Approximately one derecho every year or two will occur in much of the Midwest (*Figure 10.1*). They are less frequent in the upper Midwest states, which remain cooler throughout the summers.

The differences between tornadoes and derechos are indicated in their names: the word *derecho* is the Spanish word for straight ahead, while the word tornado has its roots in the Spanish word *tonar*, which means to turn. Both types of storm events can be associated with the same major cold front boundary because they require similar ingredients to get started. However, tornado formation is

Weather

topography • *the landscape of an area, including the presence or absence of hills and the slopes between high and low areas.*

derecho • *a set of powerful straight-line winds that exceed 94 kph (58 mph) and can often approach 160 kph (100 mph).*

wind shear • *when wind speed and/or direction changes with increasing height in the atmosphere.*

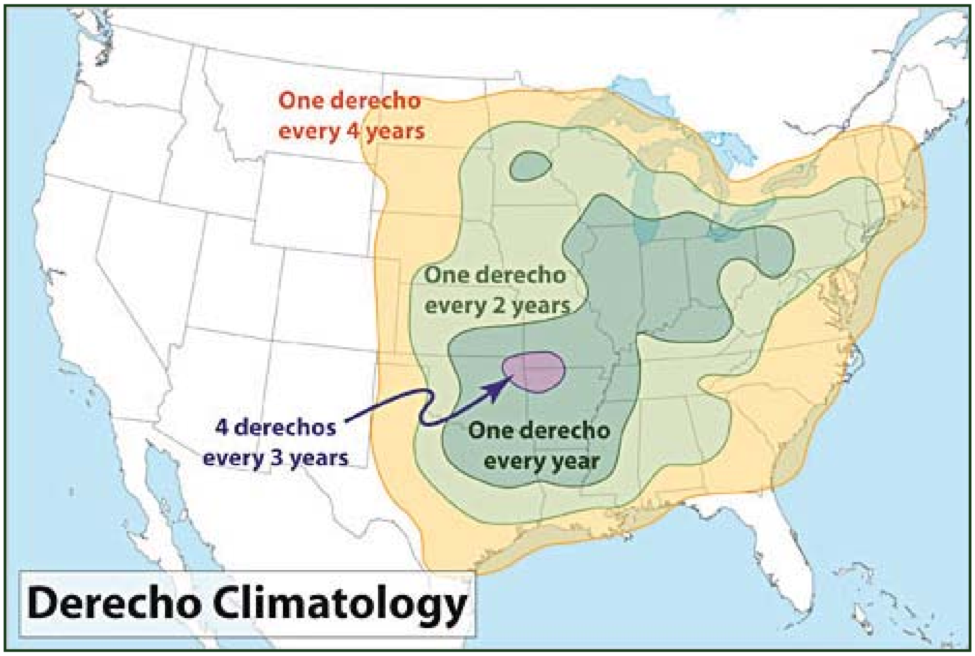


Figure 10.1: Derecho frequency in the continental US.

a more complicated process. At the frontal boundary, warm, moist air rapidly rises as cooler, dry air descends. In the meantime, the pressure differences between the warm and cold air masses cause strong winds. As conditions in the atmosphere develop to cause a tornado, clouds with a visible horizontal rotation can appear. The clouds seem to roll like waves crashing on the shore of a beach. This horizontal motion can tilt, lifting the rotating cloud vertically, and the rolling cloud will form a tornado. Most tornados will last a few seconds to several minutes. During that time, many tornado-prone areas will use tornado sirens to alert residents of the danger. A smaller tornado might generate flying debris that can cause injury or damage to buildings, while larger tornados can cause buildings and houses to be completely broken apart. Tornados are classified by their ranking on the Enhanced Fujita scale, or EF scale. The classifications are estimates of the wind speeds based on the type of damage that is observed following the storm.

Although specific tornado paths are not predictable, the conditions that produce them are used to alert people so that they will seek shelter. The National Weather Service issues a *watch,* if the conditions are right for a type of storm event, or a *warning,* if the conditions are occurring or imminent for the storm event. The National Weather Service is part of the National Oceanographic and Atmospheric Administration, which maintains a US map of all current watches and warnings. Since the atmospheric conditions can change very quickly, an important factor in preventing loss of human life is getting the public to act upon the severe weather alerts. One way in which severe weather expert Dr. Greg Forbes has sought to improve public response to warnings is through a tornado alert index that helps people evaluate the risk of a local tornado. The Tor:Con index used by the Weather Channel provides a number from 1 to 10 that represents the probability of a tornado occurring. Meteorologists evaluate the atmospheric conditions associated with a storm and assign a score. For example, a 4 on the Tor:Con index would indicate a 40%, or moderate, chance of a tornado forming in a particular area. The hope is that by representing risk as a number from 1 to 10, people will be more likely to heed warnings and seek shelter.

Other severe weather events are more loosely associated with seasonal weather. Hurricanes occur when a warm and moist tropical low-pressure air mass forms over portions of the Atlantic Ocean south and east of Florida. These storms gather strength because the warm summer ocean water evaporates, causing very humid, low-pressure air. The air rises and condenses into water droplets that form clouds and release latent heat. The latent heat provides energy for even greater evaporation of warm ocean water, and thus the cycle continues until the low-pressure center moves over land. These storms are considered **tropical depressions** when wind speeds are below 63 kph (39 mph). As the storm develops a more organized structure, however, with more concentrated rising warm air in the center and bands of rain, it will officially become a tropical storm when its wind speeds reach the 63 to 117 kph (39 to 73 mph) range. Once winds have reached 119 kph (74 mph), the storm is classified as a hurricane.

__tropical depression__ • an organized, rotating system of clouds and thunderstorms.

Hurricanes are not common in the Midwest. However, if a hurricane is particularly strong, it can move far enough northward and inland to cause a significant rain event for areas in the Midwest. The impact on the Midwest is usually less serious than the property damage experienced along the southern and eastern seaboards of the United States. Natural hazards experienced during a hurricane are similar to those experienced during a severe thunderstorm that is accompanied by flooding.

Climate Change

With the earlier definitions of weather and climate in mind, it is important to understand that most of the extreme climate change in Earth's history occurred before humans existed. That being said, the rapid release of carbon dioxide into the atmosphere from human activity is causing a **global warming** event. The seemingly slight increase in the average annual temperatures in the Midwest has been accompanied by more frequent heat waves and shorter winters. In addition to the previously mentioned risks associated with heat waves, increasing temperatures allow for certain bugs, such as ticks and mosquitoes, to live longer, thereby increasing the risk of contracting the diseases they carry. Heat waves can also be associated with droughts that hurt crop production. In contrast, scientists are predicting more severe rainfall events in the Midwest in the coming years. This has recently resulted in an increase in severe flooding, damage to infrastructure, and even death. While the coexistence of these two types of events may seem contradictory, it is indicative of an increase in extreme events overall. Ultimately, the Midwest,

__global warming__ • the current increase in the average temperature worldwide, caused by the buildup of greenhouse gases in the atmosphere.

See Chapter 9: Climate for more about the impacts of climate change.

unlike the coastal US states, should be able to more easily endure the effects of climate change because of its considerable distance from an ocean that would be subjected to rising sea levels.

Humans have designed and built air conditioning and heating *systems* for protection from extreme weather. The crops, fish, and livestock, upon which humans depend for food, however, live without these climate control systems, and will therefore experience the impacts of environmental changes more directly. Increasing temperatures and changes in rainfall patterns will alter the type of crops that can be successfully grown and harvested across the Midwest (*Figure 10.2*). Models have predicted that the climate of Midwestern states, such as Michigan and Illinois, will be more similar to the current climate of Texas by the end of the 21st century (*Figure 10.3*).

Another concern regarding hazards exacerbated by climate change in the Midwest is whether or not there has been or will be an increase in the number or the severity of storms, such as hurricanes and tornadoes. According to NASA, the present data is inconclusive in terms of whether the Atlantic Ocean

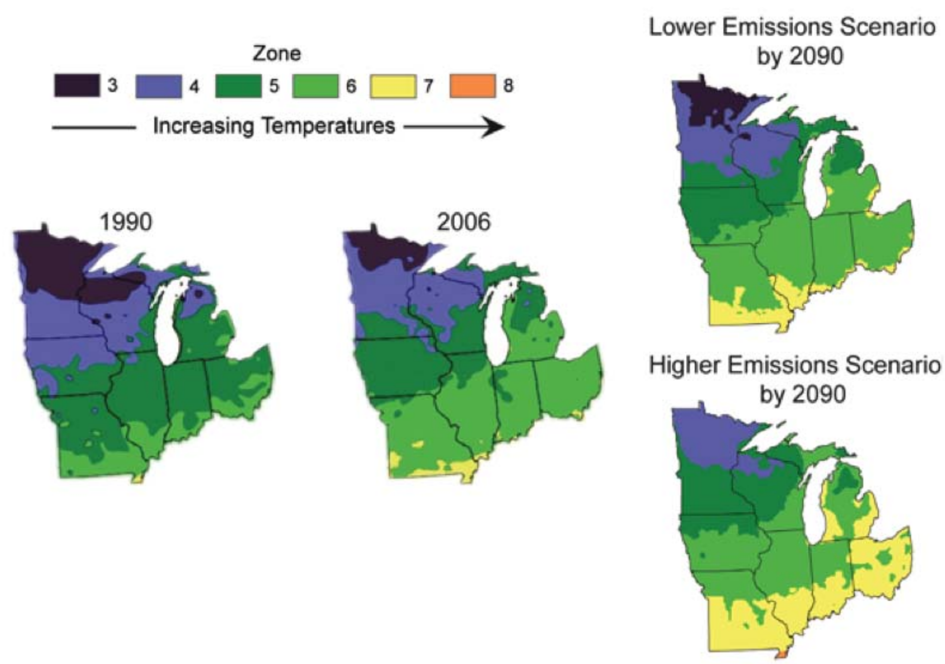


Figure 10.2: Shifts in USDA Hardiness Zones as a result of climate change.

hurricanes are already more severe, but there is a greater than 66% chance that global warming will cause more intense hurricanes in the 21st century. Since tornados are hard to predict, involve a complex mix of atmospheric conditions, and occur on a much smaller geographic scale than hurricanes do, it is difficult to determine if global warming is currently influencing the frequency or severity of tornado activity. Since climate is weather averaged over decades, it might take many years to determine that a change has occurred with respect to these

Climate Change

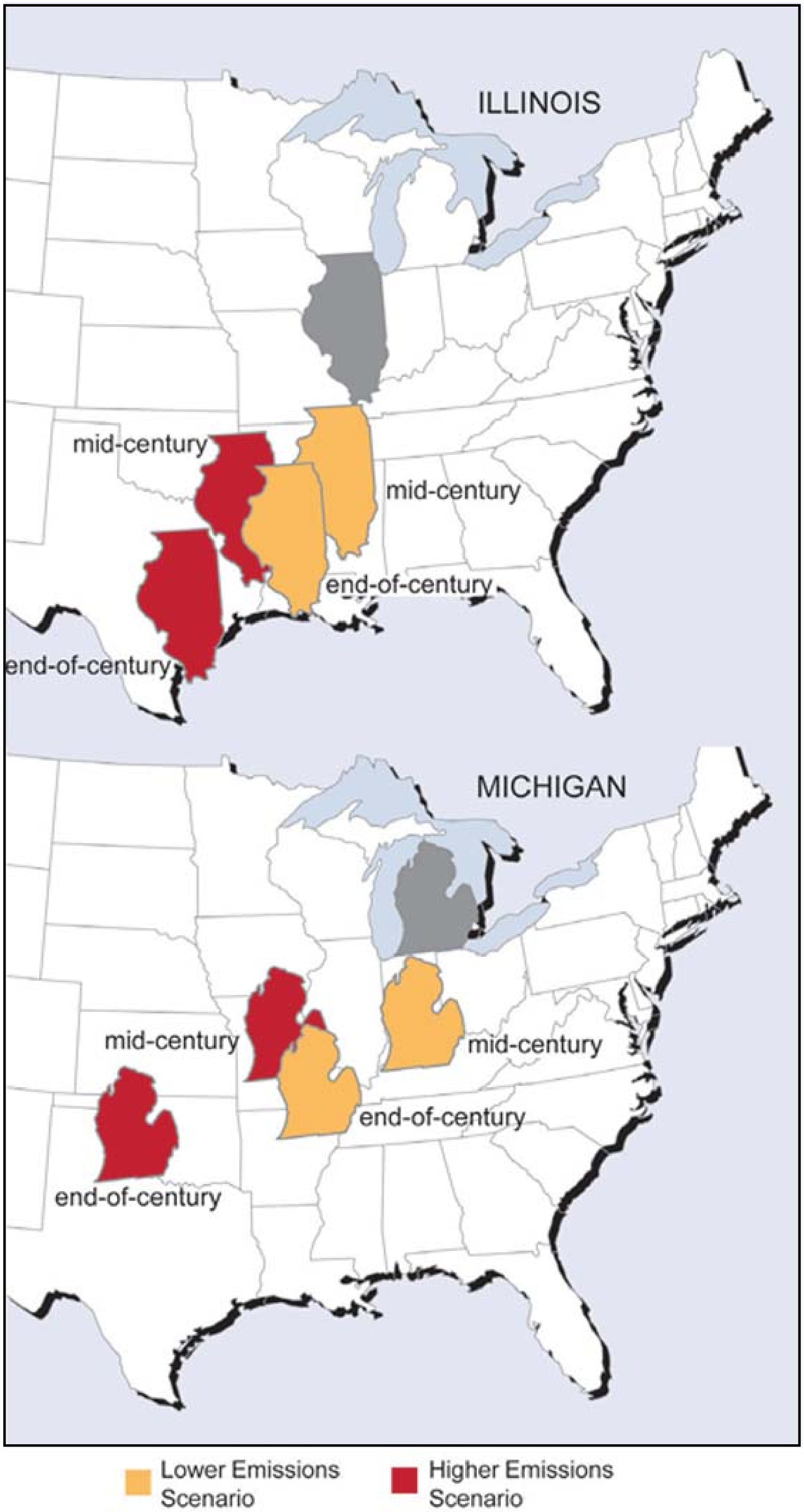


Figure 10.3: Prediction of the relative climates for Illinois and Michigan's Lower Peninsula due to climate change.

radon • a naturally occurring radioactive, colorless, odorless gas.

plates • large, rigid pieces of the Earth's crust and upper mantle, which move and interact with one another at their boundaries.

fault • a fracture in the Earth's crust in which the rock on one side of the fracture moves measurably in relation to the rock on the other side.

limestone • a sedimentary rock composed of calcium carbonate ($CaCO_3$).

dolostone • a rock primarily composed of dolomite, a carbonate mineral.

radioactive • when an unstable atom loses energy by emitting radiation.

seismic zone • a regional zone that encompasses areas prone to seismic hazards, such as earthquakes or landslides.

two types of storms. Scientists are certain that the conditions necessary to form such storms are becoming more favorable due to global warming.

The Union of Concerned Scientists has created an infographic that demonstrates the relative strength of the evidence that various hazards are increasing as a result of climate change (*Figure 10.4*).

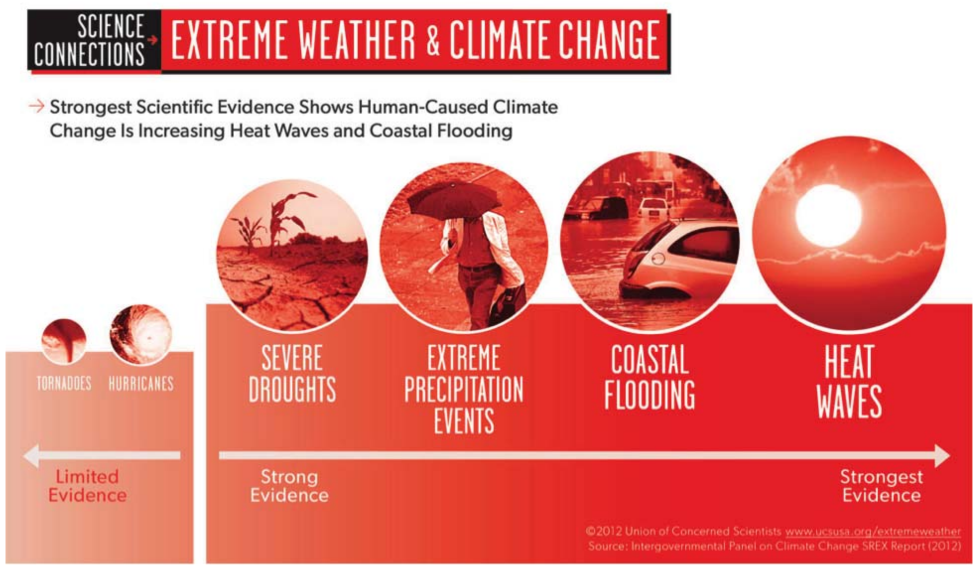


Figure 10.4: The strength of evidence supporting an increase in different types of extreme weather events caused by climate change.

Geologic Hazards

Several natural hazards are the result of the geologic conditions beneath the surface of the Midwest. Three hazards that are common in the Midwest are earthquakes, sinkholes, and **radon**. Although the Midwest does not lie on a **plate** boundary, the New Madrid **fault** is currently active and capable of generating earthquakes. Sinkholes are caused by the dissolving of **limestone** and **dolostone** rocks beneath the surface of some regions in the Midwest. Radon is a gas that is released from the natural breakdown of **radioactive** elements found in bedrock. Although these three hazards are not unique to the Midwest, they do pose some challenges for people living in this area.

Earthquakes

While earthquakes usually bring California to mind, the New Madrid and Wabash **seismic zones** are responsible for earthquakes throughout the southern Midwest (*Figure 10.5*). The New Madrid seismic zone is in the Mississippi Valley, at the boundaries of Arkansas, Tennessee, Kentucky, Illinois, and Missouri. The Wabash Valley seismic zone extends northward along the boundary between Illinois and Indiana. These seismic zones are poorly understood because, unlike other seismic zones, there is nothing on the surface to help scientists understand the faults responsible for the seismic activity. For example, there is a thick layer of river-deposited sediments (called **alluvium**) that covers what is thought to be a strike slip fault. Microseismic earthquakes that are too small to be felt by humans happen every other day, but larger earthquakes are fairly rare. The bedrock that makes up most of the central US is colder, drier, and less fractured than rocks on the East or West Coast. As a result, the earthquakes here can release the same amount of energy as other earthquakes, but the shaking affects a much larger area because the **seismic waves** travel through denser, more solid bedrock.

seismic wave • *a regional zone that encompasses areas prone to seismic hazards, such as earthquakes or landslides.*

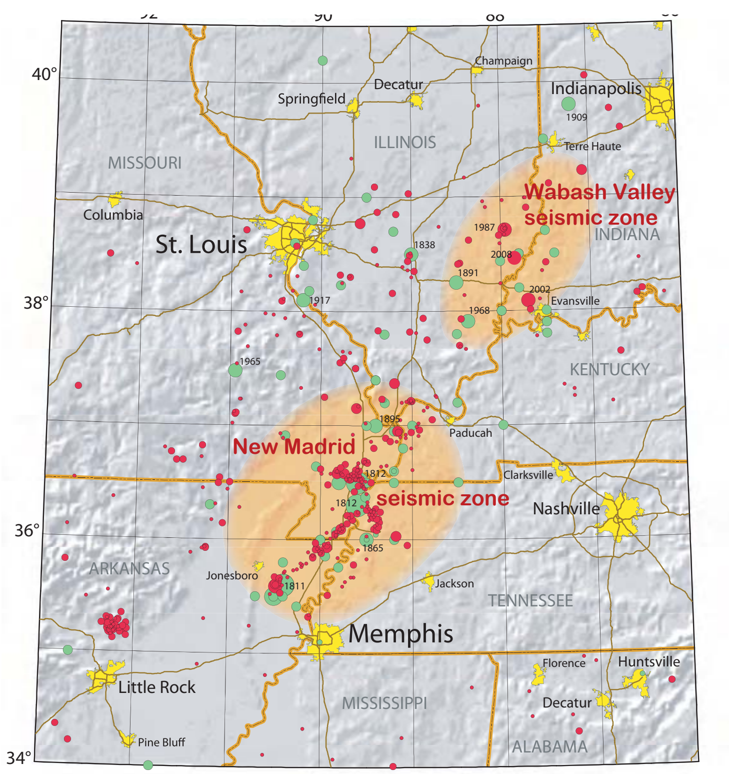


Figure 10.5: Earthquake events in the New Madrid and Wabash Valley seismic zones.

Earthquake prediction is very difficult because most of the mechanisms that cause earthquakes are beneath the Earth's surface. Scientists typically make use of historical records as well as limited surface monitoring to understand the probability of a seismic event occurring. Historical reports of earthquakes from 1811 to 1812 indicate a two-month period that included several major earthquakes thought to be greater than 7.0 in magnitude. Based on these historical reports, and the absence of a large magnitude earthquake in the past century, scientists expect that the New Madrid seismic zone is overdue for a large magnitude earthquake.

10 Earth Hazards

Geologic

karst topography • *a kind of landscape defined by bedrock that has been weathered by dissolution in water, forming features like sinkholes, caves, and cliffs.*

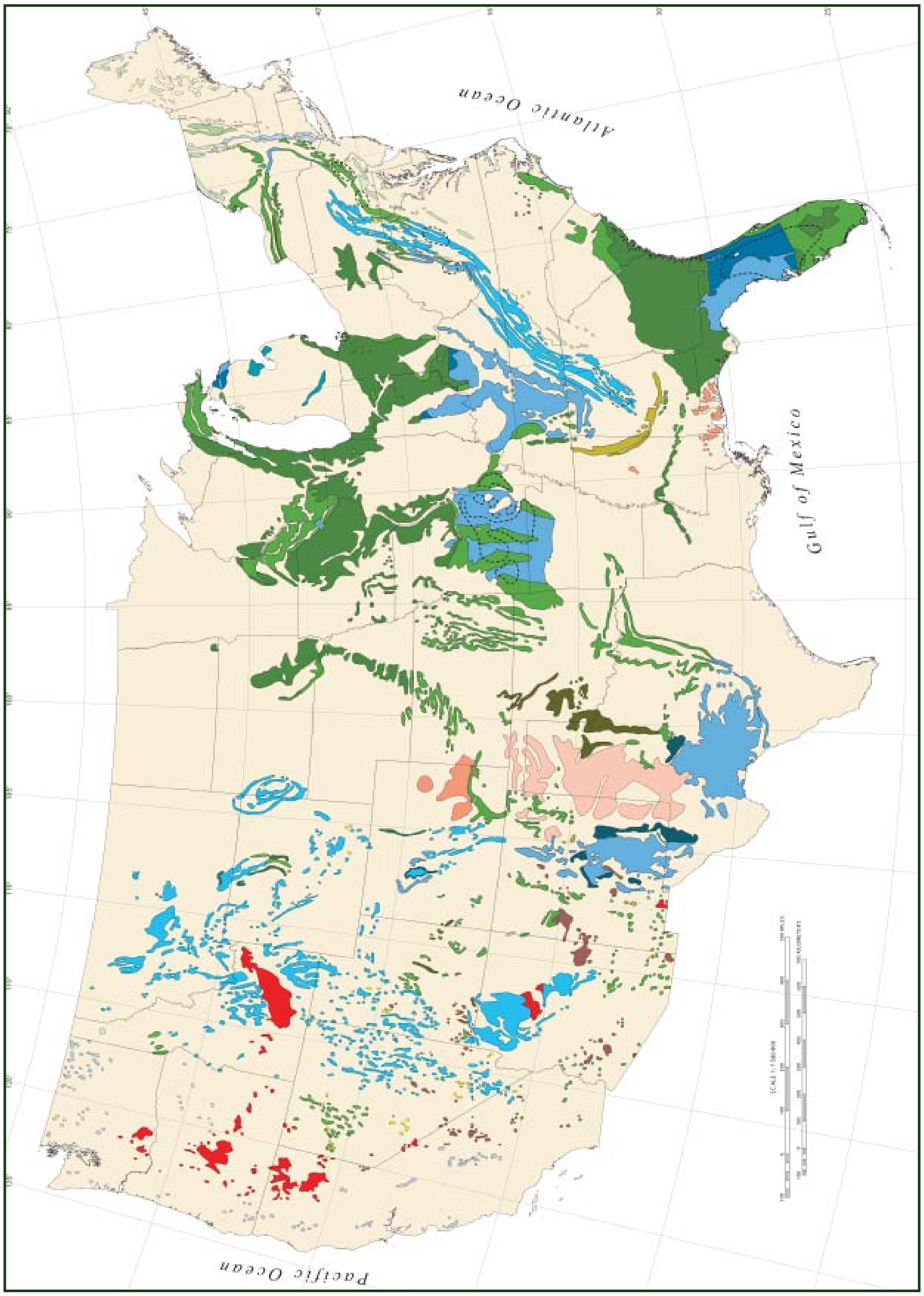


Figure 10.6: Karst topography in the continental US. See Key on facing page.

FISSURES, TUBES, AND CAVES OVER 1,000 FT (300 M) LONG; 50 FT (15 M) TO OVER 250 FT (75 M) VERTICAL EXTENT

- In metamorphosed limestone, dolostone, and marble
- In moderately to steeply dipping beds of carbonate rock
- In gently dipping to flat-lying beds of carbonate rock
- In gently dipping to flat-lying beds of carbonate rock beneath an overburden of noncarbonate material 10 ft (3 m) to 200 ft (60 m) thick
- In moderately to steeply dipping beds of gypsum
- In gently dipping to flat-lying beds of gypsum

FISSURES, TUBES, AND CAVES GENERALLY LESS THAN 1,000 FT (300 M) LONG; 50 FT (15 M) OR LESS VERTICAL EXTENT

- In metamorphosed limestone, dolostone, and marble
- In crystalline, highly siliceous intensely folded cabonate rock
- In moderately to steeply dipping carbonate rock
- In gently dipping to flat-lying carbonate rock
- In gently dipping to flat-lying beds of carbonate rock beneath an overburden of noncarbonate material 10 ft (3 m) to 200 ft (60 m) thick
- In moderately to steeply dipping beds of gypsum
- In gently dipping to flat-lying beds of gypsum
- In gently dipping to flat-lying beds of gypsum beneath and overburden of nongypsiferous material 10 ft (3 m) to 200 ft (60 m) thick
- In carbonate zones in highly calcic granite (Alaska only)
- In moderately to steeply dipping beds of carbonate rock with a thin cover of glacial till and frost-derived residual soil (Alaska only)

FISSURES, TUBES, AND CAVES GENERALLY ABSENT; WHERE PRESENT IN SMALL ISOLATED AREAS, LESS THAN 50 FT (15 M) LONG; LESS THAN 10 FT (3 M) VERTICAL EXTENT

- In crystalline, highly siliceous intensely folded carbonate rock
- In moderately to steeply dipping beds of carbonate rock
- In gently dipping to flat-lying beds of carbonate rock

FEATURES ANALOGOUS TO KARST

- Fissures and voids present to a depth of 250 ft (75 m) or more in areas of subsidence from piping in thick unconsolidated material
- Fissures and voids present to a depth of 50 ft (15 m) in a of subsidence from piping in thick, unconsolidated mate
- Fissures, tubes, and tunnels present to a depth of 250 ft (75 m) or more in lava
- Fissures, tubes, and tunnels present to a depth of 50 ft (15 m) in lava
- Areas in which extensive historical susidence has occurred

10 Earth Hazards

A new research study is likely to better explain the seismic activity of the Midwest. EarthScope is a large-scale project funded by the National Science Foundation to gather data about the lithosphere beneath the Earth's surface. There are three large investigations of the seismic activity of this area. A network of 400 temporary **seismometers** has been installed, with a distance of approximately 70 kilometers (40 miles) between each seismometer. The volume of data collected by these seismometers will help geophysicists create three-dimensional models of the lithosphere. With these models, we will have a virtual picture of the seismic zones, and, hopefully, we will come to better understand the seismic hazards of the Midwest.

Sinkholes

Sinkholes are usually caused by a geologic feature known as **karst topography**. Karst can form where the underlying bedrock is composed of material that can be slowly dissolved by water. Much of the Midwest has **carbonate** bedrock consisting of limestone, dolostone, and **marble**. These particular types of **sedimentary rock** contain significant amounts of carbonate (carbon atoms combined with multiple oxygen atoms). Water that mixes with carbon dioxide in the air and **soil** reacts to produce carbonic acid (H_2CO_3). This acid and the carbonate react, dissolving the rock. Although this takes a long time to occur, much of the bedrock in the Midwest is **Paleozoic** in age (between 541 million years and 252 million years old) (*Figure 10.6*). Eventually, caves and caverns form in the rock, and sinkholes form when caves near the surface collapse. The karst topography is noticeable in areas that contain many sinkholes and where the land surface is scattered with large, round depressions.

There are a few conditions that increase the hazards associated with sinkholes. The previously mentioned underground caves are often filled with groundwater. In regions where there is a rapidly growing population, a greater amount of water is extracted from the ground. Likewise, during periods of drought, the **water table** can drop considerably, leaving these caves filled with air instead of the water that would normally help to support the weight of the ground above. Without the support of the ground water, the surface can collapse. In some cases, increasing the weight on the surface by rapidly building large structures can also lead to sinkhole collapse. There are a few steps that can be taken to mitigate these issues. Geologists and environmental engineers can use ground-penetrating radar to identify the location of sinkholes. In some areas where sinkholes are very prevalent, engineers can fill the sinkholes with gravel, which will allow for water drainage while still supporting the surface.

Radon

Radon is a naturally occurring radioactive, colorless, odorless gas. It is the leading cause of lung cancer in non-smokers and the second leading cause of lung cancer overall. It can collect in homes, buildings, and even in the water supply. The bedrock geology and glacial history of the Midwest provides ideal conditions for radon hazards.

Radon is one of the products of decay from the breakdown of radioactive elements in soil, rock, and water. Uranium-238 undergoes radioactive decay, producing energy and several radioactive products, such as Radon-222 and

Geologic

seismometer • *an instrument that measures seismic waves (movements) within the ground.*

carbonate rocks • *rocks formed by accumulation of calcium carbonate, often made of the skeletons of aquatic organisms.*

marble • *a metamorphic rock composed of recrystallized carbonate minerals, most commonly calcite or dolomite.*

sedimentary rock • *formed through the accumulation and consolidation of grains of broken rock, crystals, skeletal fragments, and organic matter.*

Paleozoic • *a geologic time period that extends from 541 to 252 million years ago.*

water table • *the upper surface of groundwater.*

granite • *a common and widely occurring type of igneous rock.*

sandstone • *sedimentary rock formed by cementing together grains of sand.*

Thorium-232, the latter of which decays to emit energy and Radon-220. Uranium and Thorium are naturally occurring radioactive elements found in bedrock such as **granite**, **shale**, and limestone. Most of the Midwest has bedrock consisting of shale, **sandstone**, limestone, and dolostone, all of which can contain radon (*Figure 10.7*). Most of the northern Midwest has been substantially **eroded** from the **glaciers** of the **Pleistocene**. These glaciers left behind large deposits of gravel, **sand**, and **clay** as they receded and melted. The gravel, sand, and clay are often the eroded remnants of radon-containing bedrock, and the moist temperate climate of the Midwest provides an excellent environment for **weathering** of both the bedrock and the glacial sediments. As they weather, more rock is exposed, which, in turn, allows more radon to be released.

Radon gas finds its way through cracks in the basement foundation, sump pump wells, dirt floor crawlspaces in the basement, and basement floor drains. Radon can be found in water from wells and municipal water. Since radon is more easily released from warm water than from cold water, one of the greatest forms of exposure likely occurs while showering in water with high radon levels. Fortunately, with proper monitoring and mitigation (reduction) techniques, radon gas can be easily reduced to low levels. One technique that is often used in homes involves sealing cracks in the basement floor, covering drains,

glacier • *a body of dense ice on land that does not melt away annually and has sufficient mass to move under its own weight.*

Pleistocene • *a subset of the Quaternary, lasting from 2.5 million to about 11,700 years ago.*

erosion • *the transport of weathered materials.*

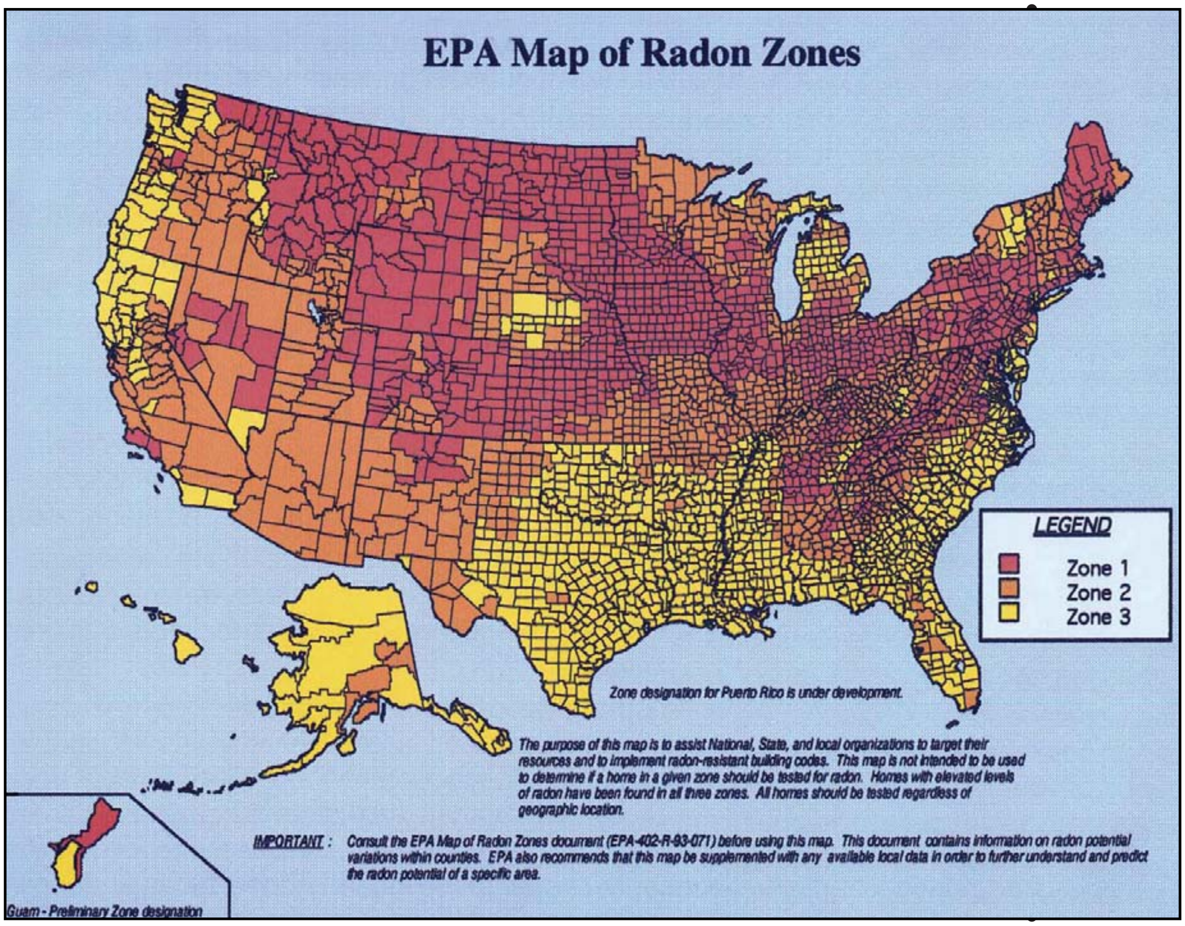


Figure 10.7: Radon zone map of the US. (Note: Zone 1 contains the highest radon levels.)

and installing ventilation systems. A well ventilated space will prevent the radon from accumulating and will reduce the risk of exposure. Most states have licensed radon mitigation specialists who are trained in the proper testing and mitigation of radon levels in buildings. The EPA has published a homebuyer's guide designed to help citizens make informed decisions about radon gas. For radon in water, filtration systems can be installed to mitigate exposure in the home.

Hazards Where Geology and Weather Interact

Flooding is a natural hazard resulting from the combination of geology and weather. The flat-lying bedrock of the Midwest and the large storm events create an ideal setting for flooding. Much of the southern and western boundaries of Midwestern states border the Mississippi and Ohio Rivers. Additionally, most of the waterways of the Midwestern states drain through the Upper Mississippi and Ohio River Basins (*Figure 10.8*). Areas near rivers, tributaries, creeks, and streams are likely to experience flooding during periods of heavy rainfall. The **floodplain** of a river is the land around the river that is prone to flooding. This area can be grassy, but the sediments under the surface are usually deposits from previous floods. For those living near a river, it is important to know both the location of the floodplain boundaries and the likelihood and extent of flooding in that area.

Scientist assess the hazard risk of flooding based on historical data, and they then establish a probability of an extreme flood event taking place over a particular time interval. **Recurrence interval** is the time between major flood events. The physical extent of the flooding during that interval is the floodplain itself. For example, a 100-year flood would be the most extreme flood event to happen over 100 years and would identify a zone of land in the 100-year floodplain with a 1% chance of recurrence each year. Since this value represents only the probability of flooding, it is possible for multiple 100-year floods to occur within a few years. Most people who live within the 100-year floodplain must carry flood insurance on homes, businesses, and personal property. It is not a matter of if a flood will occur in these floodplains, but rather when.

Flooding has some direct impacts that can themselves be hazards. For example, the increased volume of water flowing through a river channel travels at an increased velocity. This allows for the transport of large amounts of sediment, which can erode supports for roadways, bridges, and buildings. Water traveling at high velocity can also carry large objects like cars and buildings. The water itself can enter buildings (causing permanent damage to homes and businesses) and flood farmland (damaging crops and killing livestock). There are also secondary impacts of major flooding events: Floods can cause transportation problems, loss of electricity for long periods of time, and contaminated drinking water supplies. This can cause long-term economic strain on the towns and industries impacted by flooding.

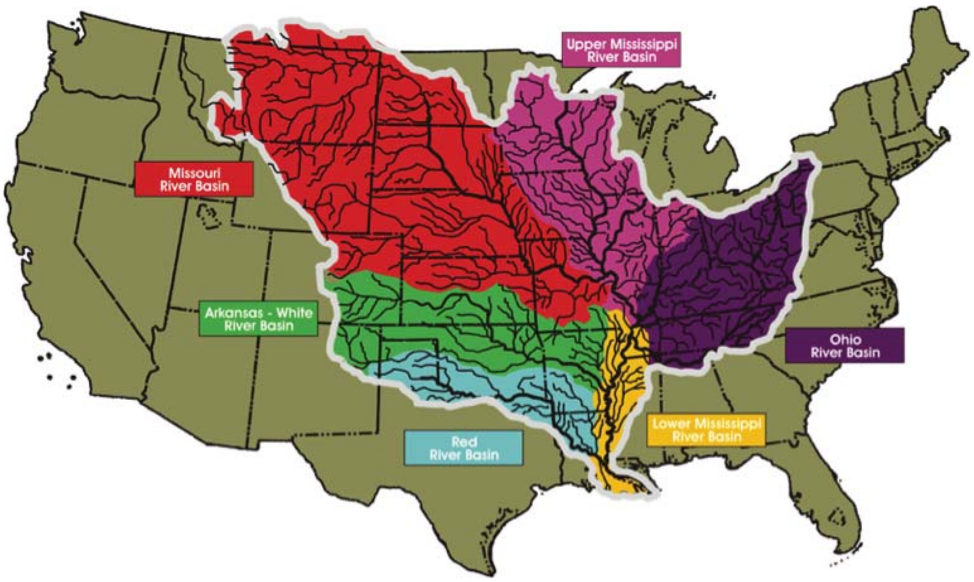


Figure 10.8: Major river basins of the continental US.

In addition to the direct hazards associated with large flooding events, human land use can greatly impact the type and severity of the natural hazards associated with flooding. Because water cannot infiltrate impermeable pavement, there is much more concentrated runoff during rainstorms as the water flows off roads into drains and directly into rivers. To accommodate this, humans have built extensive storm drain systems to prevent the flooding of roads. Unfortunately, these storm drains empty into already swelling rivers. Although these efforts are helpful in preventing flooding in one area, they amplify the flooding event in the river. Heavily developed areas with extensive buildings and bridges can also put increased weight on the ground surface, causing compaction of underlying sediments. This can decrease infiltration rates and the storage capacity of the ground.

While there is no way to completely avoid these human impacts on the natural system, good community planning and informed decision-making can greatly reduce the safety concerns and economic impacts of these events. The Federal Emergency Management Agency (FEMA) provides guidelines for communities that are planning mitigation strategies designed to minimize the impacts of natural hazards such as flooding.

Resources

Books

Macdougall, J. D., 2011, *Why geology matters decoding the past, anticipating the future.* University of California Press: Berkeley, CA

Websites: Storms

(See also resources on climate change in Chapter 9: Climate)

What is a tropical disturbance, a tropical depression, or a tropical storm?, NOAA Hurricane Research Division Frequently Asked Questions, 2011. http://www.aoml.noaa.gov/hrd/tcfaq/A5.html.

Thunderstorms and Flying. National Weather Association, 2003. http://www.nwas.org/committees/avnwxcourse.teachl1.htm.

TWC's Exclusive Tor:Con Index [tornado forecast] by Forbes, G., Weatherunderground, 2014. http://www.wunderground.com/news/tornado-torcon-index.

About Derechos, by Corfidi, S.F., Evans, J.S., and Johns, R.H., NOAA-NWS-NCEP Storm Prediction Center. http://www.spc.noaa.gov/misc/AbtDerechos/derechofacts.htm.

The Derecho of June 29, 2012, by Zubrick, S. National Weather Service, 2012. http://www.erh.noaa.gov/lwx/events/svrwx_20120629/.

Hazards Associated with Flooding, by Nelson, S., 2012. http://www.tulane.edu/~sanelson/Natural_Disasters/floodhaz.htm.

Floods: Recurrence Intervals and 100-year Floods, US Geological Survey, 2014. http://water.usgs.gov/edu/100yearflood.html.

Effects of Urban Development on Floods, USGS Fact Sheet FS-076-03, 2012. http://pubs.usgs.gov/fs/fs07603/.

What is the Polar Vortex?, NASA Ozone Watch, 2013. http://ozonewatch.gsfc.nasa.gov/facts/vortex_NH.html.

What's a Polar Vortex? The Science Behind Artic Outbreaks, by Erdman, J., 2014. http://www.wunderground.com/news/polar-vortex-plunge-science-behind-arctic-cold-outbreaks-20140106.

Websites: Earthquakes

USGS National Earthquake Information Center, USGS. http://earthquake.usgs.gov/regional/neic/.

US Earthquake monitor, USGS, http://earthquake.usgs.gov/earthquakes/map/.

Incorporated Research Institutions for Seismology (IRIS) education and public outreach. http://www.iris.edu/hq/programs/epo.

IRIS Seismic monitor, IRIS, http://www.iris.edu/seismon/.

Facts about the New Madrid Fault Zone, Missouri Department of Natural Resources. http://www.dnr.mo/gov/geology/geosrv/geores/techbulletin1.htm.

Websites: Radon

Radon: Health Risks, EPA, 2013, http://www.epa.gov/radon/healthrisks.html.

Radon Fact Sheet, Air Check, Inc., 2009, http://www.radon.com/radon/radon_facts.html.

Radon information, EPA, http://www.epa.gov/radon/index.html.

Radon Potential of the Upper Midwest, USGS, 1995. http://energy.cr.usgs.gov/radon/miswest4.html.

Websites: Sinkholes

The Science of Sinkholes, US Geological Survey, 2013.
http://www.usgs.gov/blogs/features/usgs_top_story/the-science-of-sinkholes.
Sinkholes in Missouri, Missouri Department of Natural Resources.
http://www.dnr.mo.gov/geology/geosrv/envgeo/sinkholes.htm.

Websites: Teaching Resources

Impact of Natural Disasters on the Earth by J. Radke, Hamline University Graduate School of Education MnSTEP Teaching Activity Collection.
http://serc.carleton.edu/sp/mnstep/activities/19789.html.
Investigating Speed and Acceleration Using Tornado Tubes, Hamline University Graduate School of Education MnSTEP Teaching Activity Collection.
http://serc.carleton.edu/sp/mnstep/activities/27202.html.
Karst Formation, City of Austin Youth Education resources.
http://austintexas.gov/sites/default/files/files/Watershed/youth_education/karst_lesson_high_school.pdf.
Natural Hazards and Risks: Hurricanes by Gilbert, L., Galster, J., and Ramage, J., SERC module on hurricane hazards.
http://serc.carleton.edu/integrate/teaching_materials/hasards/index.html.
Landslide Hazards Program, USGS, http://landslides.usgs.gov/.
Radon activities from the Alabama Radon Program, Alabama and Auburn Universities Extension.
http://www.aces.edu/fcs/hndh/radon/alradon.php.
Teaching Quantitative Concepts in Floods and Flooding, SERC Resources for Undergraduate Students and Faculty.
http://serc.carleton.edu/quantskills/methods/quantlit/floods.html.

Websites: State Resources on Earth Hazards

Illinois Emergency Management Agency, http://www.iema.illinois.gov/planning/HazardInfo.asp.
Illinois Natural Hazard Mitigation Plan 2013.
http://www.iema.illinois.gov/planning/documents/Plan_IllMitigationPlan.pdf.
Indiana State Environmental Health, Indiana State Department of Health.
http://www.in.gov/isdh/20389.htm.
Current Disasters in Iowa, Iowa Department of Natural Resources.
http://www.iowadnr.gov/InsideDNR/SocialMediaPressRoom/DisasterAssistance.aspx.
Iowa Disaster History, Iowa Homeland Security & Emergency Management.
http://homelandsecurity.iowa.gov/disasters//iowa_disaster_history.html.
Ohio Department of Public Safety.
http://ohiosharpp.ema.state.oh.us/OhioSHARPP/Hazards.aspx#overview.
Michigan Hazard Analysis, Michigan Emergency Management and Homeland Security Division, Michigan Department of State Police.
http://www.michigan.gov/documents/msp/Doc1_39416_7.pdf.
Minnesota Climate Hazards, Minnesota Department of Natural Resources.
http://www.dnr.state.mn.us/climate/index.html.
Minnesota Natural Disasters and Severe Weather, Minnesota Department of Health.
http://www.health.state.mn.us/divs/eh/emergency/natural/.
Wisconsin Emergency Management.
http://readywisconsin.wi.gov/Informed/Informed.asp?maintab=0.

Chapter 11: Real and Virtual Fieldwork:

“Why Does This Place Look the Way it Does?”

All the major topics in *The Teacher-Friendly Guides*™ were built upon observations of the natural world, and these observations are the clues that scientists use to reconstruct the history of the Earth. Shelly fossils along the Himalayas tell of ancient sea floors that have been uplifted into mountains. Ripple marks that have since turned to stone tell of ancient shorelines. And scratches along the bedrock in Central Park tell of massive glaciers that—some 20,000 years ago—created a skyline much different than the one of steel and glass found in New York today. A number of forces and processes have made seas, forests, deserts, and the life those ecosystems hosted appear and disappear from the landscape over the course of geologic time. Many of these changes left behind hints that we can interpret today when we tell the story of a place. That massive glaciers once advanced as far south as New York is not a conclusion derived from mathematical modeling in a lab; it is instead evidenced by not only those scratches, but also by a host of observed glacial deposits that litter not only New York, but much of northern North America.

> *The story of a place is written in its landscape, rocks, fossils, and biota; fieldwork investigations help scientists—and students and teachers—tell that story.*

Introducing students to the practice of fieldwork can be a tremendous experience. Its central role in the education of geoscientists makes fieldwork a “signature pedagogy” in the preparation of professionals within the field, and fieldwork warrants a larger place in the K-12 curriculum. For these reasons, real and virtual fieldwork practices are well suited for addressing both *The Next Generation Science Standards* and *The Common Core Learning Standards.* Fieldwork as a topic is also fundamentally different from the other chapter topics in this guide. Therefore, this chapter is somewhat different in structure and is significantly longer than the other chapters in the Guide. The chapter begins by laying out some of the rationale for engaging in real and virtual fieldwork, and it then addresses some of the nuts-and-bolts issues for planning, carrying out, and documenting fieldwork with your students.

Exploring local natural history through inquiry-based approaches emphasizes critical thinking. And by conducting such investigations, students have taken a tremendous leap: they are not merely learning about science; they are doing science! But getting students into the field can be difficult. An alternative is for the educator to visit the field on his or her own time, returning to the classroom with a series of images and specimens that permit a Virtual Field Experience

CHAPTER AUTHORS

Don Duggan-Haas
Richard A. Kissel

(VFE). Virtual fieldwork offers the opportunity to explore an area without leaving the classroom, and it allows multiple "visits" to a site. VFEs can also enhance and extend the experience when actual fieldwork is possible. The Earth is a system, after all, and any one site—virtual or real—can display a host of natural phenomena, from simple erosion and deposition to the principles of superposition and faunal succession to the formation of ripple marks or mud cracks. By adding to a VFE year after year, you can also document changes within the environment, such as changes to a stream's course, the succession of an ecosystem, or the nature of human disturbance. Ideally, virtual fieldwork in the classroom captures the active experience of a scientist examining an area: It provides opportunities to actively explore, discover, ask questions, and make observations that help to answer those questions, ultimately allowing students to develop educated responses to the question *"Why does this place look the way it does?"*

Commonalities of Virtual and Actual Fieldwork

This chapter addresses both actual and virtual fieldwork and the many connections between them. The process of making VFEs, at least in the ways we lay out here, involves doing actual fieldwork. Much of the work of making a VFE involves simply following good fieldwork practices in combination with a heightened attention to sharing the experience with students or other learners. While VFEs can be used in place of actual fieldwork, they can also be used to both prepare for and reflect upon actual fieldwork. Engaging students as partners in the creation of VFEs is an opportunity for teaching through inquiry while also building a resource that is useful to people outside of the school, as well as to future students. What follows addresses all of these possibilities.

NASA scientists routinely conduct actual fieldwork remotely.

We also draw attention to the distinction between field*work* and field *trips*. We strive to engage learners in *figuring things out*, while field trips—whether actual or virtual—are too often characterized by trip leaders *pointing things out*. Building in the opportunity for genuine discovery is challenging but promises to yield longer-term engagement and understanding.

Just Go (and Don't Stop)

The minimum requirement for conducting fieldwork is your own sweet self. This chapter discusses a wide range of tools and approaches, but doing fieldwork of any (safe) sort that doesn't damage the site is a key objective. The tools and approaches discussed in this chapter will extend your senses and help you to capture the experience in ways that will make it easier to share with students. Work within your comfort zone (but perhaps at its edge) and at a pace appropriate to what life allows, and gradually build your virtual representation of the local environment over the course of years, increasing student participation in the process as time goes by. Use the local landscape to nurture skills within your students that will allow them to read any type of landscape. Through this process, your students can teach members of your community about the story of your site while also creating and extending resources that can teach other learners around the country about where you live. Building a deep understanding of place through VFE development and then comparing your local environment with VFEs created by other teachers and students is an excellent way to use the local environment to understand the global environment.

Whether the fieldwork is real or virtual, it can either involve a single visit or be extended over many, many visits. Scientists may reach points where they have figured out particular pieces of the puzzle when understanding the nature of a site, but they never fully understand all aspects of a place's story. Fieldwork, therefore, is something that is never "finished." Whether it is the second or seven-hundredth visit to a site, there is always more to discover. This is part of what makes science fascinating! It connects to the idea that while fieldwork may focus primarily upon a single topic, researchers (whether K-12 students, educators, or professional scientists) who develop a deep understanding of the story of a place must understand the roles of geology, ecology, climatology, anthropology, and more. Of course, this type of understanding will not come from a single class period of fieldwork, or even a single course infused with fieldwork, but the appreciation of this systems idea can be planted and nurtured.

Start local

In choosing a field site, whether it is local or distant or for actual or virtual fieldwork, it should be interesting from an Earth systems science perspective. Fortunately, if you know how to look, *every* site is interesting from an Earth system science perspective. Over the grand course of Earth history, the story of any location is a fascinating one that involves myriad changes. The work of telling the story of any environment is a form of rich inquiry. While it would also be fascinating to find a place that hasn't changed, no such place exists on the surface of Planet Earth!

While VFEs provide the opportunity to study distant or otherwise difficult to access locations, we suggest starting close to home or school, at a location that students are already familiar with or have access to. What is outside your classroom door has more immediate relevance to the lives of your students than anywhere else on Earth. Nearly every unit in an Earth or environmental science course, and most of the units in a biology course, play out in some meaningful way in the local environment, and the local environment can extend the boundaries of the classroom tremendously with little or no cost. Things are only understood in comparison to something else, so comparing sites to one another can deepen one's understanding of both or even of all sites—but it is still best to start with the local.

Students can use real or virtual field sites to study how all the major topics in their Earth or environmental science curriculum are manifest in the "real world." In an ideal situation, the classroom is immediately adjacent to a safe, accessible field site, and there is flexibility within the school schedule that allows for in-depth study of the site in ways that cut across disciplinary boundaries. Unfortunately, it's not always practical to repeatedly visit an actual field site with 30 students throughout the year or semester. Through virtual fieldwork, students can come to see how the rock types and flora and fauna outside their classroom tell part of the story of that place.

In order to create VFEs, authors must closely study their field sites with an eye toward doing fieldwork with students. VFEs are a stepping-stone to bringing students into the field, even if the field is “only” the schoolyard. VFEs can be used to prepare students for the field and/or to process the fieldwork after visiting the actual site. Ideally, students will participate in the creation and extension of VFEs, but we recognize that getting to this point may take years.

Connecting to Earth Science Bigger Ideas, the Next Generation Science Standards, and the Common Core

Fieldwork investigations have the potential to be extended indefinitely in time and can involve the integration of a wide range of science and non-science disciplines. *“Why does this place look the way it does?”* is a bottomless question, meaning that it can be productively investigated for a very, very long time. Field scientists, be they professionals or fifth graders, will never fully answer this driving question absolutely or at every scale.

The act of VFE creation is a valuable type of professional development (PD) that creates useful evidence of having done the PD. Through the creation and continued use of virtual fieldwork, a teacher can become a true expert on his or her local environment—perhaps the preeminent expert. The process of VFE creation and use can also create evidence of inquiry teaching aligned to relevant standards. The VFE you create or augment can serve as a key piece of a professional portfolio.

The ultimate goal of our instruction is to build understanding of the Earth system and the ways in which science is used to build that understanding. We bring focus through the use of a small set of bigger ideas and overarching questions. These are discussed in detail in the Big Ideas Chapter and are also summarized below.

Overarching questions:

- How do we know what we know?
- How does what we know inform our decision making?

Earth system science bigger ideas:

- The Earth is a system of systems.
- The flow of energy drives the cycling of matter.

- Life, including human life, influences and is influenced by the environment.
- Physical and chemical principles are unchanging and drive both gradual and rapid changes in the Earth system.
- To understand (deep) time and the scale of space, models and maps are necessary.

Fieldwork should provide the opportunity to explore, describe, and build understanding of these questions and ideas. These ideas and questions map onto the *Next Generation Science Standards'* Disciplinary Core Ideas, Crosscutting Concepts, and Science and Engineering Practices. The Crosscutting Concepts and Scientific and Engineering Practices are shown in *Table 11.1*. As you read through the rest of this chapter, and as you and your students carry out fieldwork, revisit these lists of concepts and practices frequently in order to draw attention to how they connect to the work of reading the landscape.

Table 11.1: NGSS's Scientific and Engineering Practices and Crosscutting Concepts. As you and your students engage in fieldwork, consider how the practices and concepts are being used to make sense of the environment. See the Big Ideas Chapter for a more in-depth discussion.

Scientific and Engineering Practices	Crosscutting Concepts
1. Asking questions and defining problems	1. Patterns
2. Developing and using models	2. Cause and effect
3. Planning and carrying out observations	3. Scale, proportion, and quantity
4. Analyzing and interpreting data	4. Systems and system models
5. Using mathematics and computational thinking	5. Energy and matter
6. Constructing explanations and designing solutions	6. Structure and function
7. Engaging in argument from evidence	7. Stability and change
8. Obtaining, evaluating, and communicating information	8. Interdependence of science, engineering, and technology
	9. Influence of engineering, technology, and science on society and the natural world

Fieldwork Challenges and Benefits

Of course, VFEs also allow for some kind of "fieldwork" experience when actual fieldwork is difficult or impossible to carry out. The reasons that actual fieldwork is difficult are fairly obvious:

- **Fieldwork is logistically challenging.** It's hard to fit into a typical class period, or even a double lab period. To go off site requires permission slips, busing, and figuring out how to deal with behavior outside the normal classroom setting.

Challenges

- **It costs money.** Field trip budgets have been slashed, and weren't even very common at the secondary level before budget cuts.

- **Many teachers have only limited experience doing field science themselves.** Earth science has more teachers teaching out of field than any other science discipline, and fieldwork is not a component of many Earth, biology, or environmental science teacher certification programs. It is intimidating to lead fieldwork if you haven't been through it yourself.

- **Fieldwork poses safety and behavior concerns different from those in the classroom.** Falling off a cliff has different consequences than falling off a chair.

- **Teaching in the field employs a different set of skills than teaching in the classroom.** The logistics of moving groups of students from place to place and focusing their attention on the goals of the fieldwork takes careful planning, especially if multiple classes are involved.

These issues shouldn't preclude fieldwork, but they undeniably complicate it. These challenges are not insignificant, but the rewards of doing fieldwork are worth the trouble. Field trips are among the most memorable and most valued school experiences.

Fieldwork 101: Gathering Information and Creating Your Own VFE

What follows are recommendations. These recommendations are intended to help prepare you for fieldwork, but they are just guidelines, not steadfast rules. Bringing the field to the classroom at any scale is better than not bringing the field to the classroom at all. The careful attention to detail described here will prove extremely helpful, but avoid being discouraged if your first trip to the field isn't as productive as you had initially imagined. Scientists of all disciplines continually refine their methods and procedures, leading to more productive and "better" results over time. With time and more fieldwork, your confidence will grow. Get into the field, be safe, and do your best to capture the experience in a way that allows you to best reproduce it for your students!

Fieldwork 11

Fieldwork 101

Before visiting the site: understand the natural history of the region

In order to make sense of a local site, it's helpful to understand the geologic history of the larger region before your visit. Did inland seas once flood the area? Have mountain-building events shaped the landscape and its rocks? Was it glaciated? Since the reasons that a place looks the way it does are dependent upon more than the geology, you want to pay attention to this concept as well. That being said, since the geology is the base upon which the landscape is built, starting there makes good sense. *The Teacher-Friendly Guides*™ are an excellent source for discovering the history of a region, as well as that history's effect on the rocks, fossils, and other features of the area.

Questions to Keep in Mind

When visiting or examining any area, the ultimate question to answer is: *Why does this place look the way it does?* But to help understand such an overarching concern, it is important to have certain other questions in mind. These questions will guide exploration, and they will help ensure that important information is recorded during your visit:

- What kind(s) of rock(s) are found in the area? How do you know?

- In what environment did these rocks probably form?

- What is the arrangement of the rocks?

- Are fossils preserved in the rocks? If so, what can they tell you about past environments?

- What has happened to this area to make it look the way it does today? (That is, what has happened to the area since the rocks formed?) Why do you think so? (What is the evidence for your claim?)

We have put together a set of questions that build upon the fundamentals listed above and that can be asked of any site. This is a key idea—that there are questions that can be asked productively about any environment. Recognizing that idea is a key step toward being able to take the lessons of one field trip and applying them to the "reading" of any landscape. These questions are included in the graphic organizer in *Figure 11.1*, and as a checklist in the section entitled Back in the Classroom.

11 Fieldwork

Fieldwork 101

Figure 11.1: This pair of graphic organizers shows various paths of inquiry that stem from the question: Why does this place look the way it does? *The top graphic focuses upon the geosciences, and the bottom focuses upon the environmental sciences. The questions within the diagrams are also included as printable checklists in the section "Back in the Classroom."*

Safety and Logistics in the Field

At the Site

Considerations are different for an adult or a group of adults in the field than they are for taking students into the field, but certain measures related to safety are universal. At any field site, safety is the first priority. No photograph, measurement, or fossil is worth the risk of personal injury or death. To ensure safe and productive fieldwork, keep the following thoughts in mind:

- Always carry a small, standard first-aid kit.
- Wearing the proper clothing is very important. Long pants are recommended, as are sturdy boots, which will help prevent twisted ankles as you scurry over uneven or loose surfaces.
- While walking through a valley or next to any outcrop, always be on the lookout for rock falls. Remember, slopes with no vegetation tend to produce more falls.
- If more than one individual is climbing an outcrop, do not climb single file. Rocks dislodged from one climber can quickly tumble down the outcrop and hit the next climber.
- When using your rock hammer, protective eyewear should always be worn. If your hammer possesses a sharp pick opposite the flat surface, always use the flat surface when striking. And if you are working with others, notify all in the vicinity before striking any surface with your hammer.
- Never use one hammer to strike another. Metal chips can be broken off and thrown at high speeds.

Sunscreen, insect repellent, flashlights, food, and water should be considered in relation to environmental conditions and length of the field excursion. Please note that this chapter is written with shorter excursions in mind where substantial supplies will not generally be required. The next section offers more detail on the materials to take with you into the field.

Give appropriate consideration to group management. We suggest taking individual classes into the field for short trips before attempting either longer fieldwork excursions or trips with multiple classes. Managing larger groups or longer trips requires attention to logistics that will not be addressed in depth here. Whether the group is large or small, consider the benefits of a buddy system and measures to keep track of where everyone is—both children and adults. If groups are spread out on the trail, the lead group should stop at trail crossings to make sure everyone follows the intended trail. Younger students should not be left unsupervised for *any* length of time. Schedules and rendezvous points are important for longer trips and larger groups. All teachers and chaperones should have one another's cell phone numbers.

Things You Might Use in the Field

The Essentials and Near Essentials

As noted above, the essential materials for going in the field (besides yourselves) are clothing (especially footwear) that is suited to the weather and trail conditions and a first-aid kit appropriate to the situation. You will likely also want tools or devices to extend your senses, to preserve your observations, to collect materials (where safe and legal), to take photographs, and to store data, all of which will allow for continued observation and analysis after you return from the field. If your fieldwork is on the school grounds, or adjacent to it, you perhaps won't need anything different than what is needed on a typical class day, at least for the initial visit.

To extend your senses, start with simple things like magnifying loupes and rulers and potentially move on to include more sophisticated tools like probeware (to measure pH, temperature, and dissolved oxygen) or field microscopes. Since tools are used for both extending your senses and for capturing and preserving your observations, the most obvious tools for preserving one's observations are notebooks, pencils, cameras, GPS units, smartphones, and tablets.

As varied as field science is, a few items should be in every scientist's gear whether you are investigating rocks, observing streams, or documenting ecology. Even though processes and concepts are universal, each place is also unique, a product of its position on the Earth, its geological and ecological history, and the local human impacts. Making sense of why a place looks the way it does must take that context into account. Further, good science depends upon repeatability of observations: if another scientist (or your next class!) wants to analyze or build upon your observations, he or she must be able to know precisely where your study took place and how you made your observations. It is thus critical to locate the position of your studies on a map as precisely as possible. With modern GPS technology, it has never been easier to record a location to within a few meters, though you can certainly follow good science practices even if you don't have this capability. *Table 11.2* lists equipment and materials that are useful in the field.

Maps and Notebooks

Large-scale maps provide a way to see your field site in the context of other features in the area. At a closer scale they also provide a way to show the position of several sites relative to each other. At still higher resolution, maps provide the medium to store and display spatial information from one site. You will therefore probably want maps at all of these scales.

Large- and medium-scale maps for providing context can be found online. Google Maps and Google Earth are two of the best known interactive sources. If students need help understanding maps and scale, a helpful exercise is to create a "Powers of Ten" map of your schoolyard, starting with an overhead shot of the school yard that students recognize, then zooming out—making each of the new images increase in dimension by ten times—until one can see the site from the perspective of the whole Earth. A video tutorial, inspired

Table 11.2: Materials to take in the field. (Items in bold are highly recommended.)

For Safety and Comfort	For Extending the Senses	For Preserving and Extending Observations
☐ **Yourself** ☐ **Appropriate footwear** ☐ **First aid supplies** ☐ Water ☐ Sunscreen ☐ Insect repellent ☐ Food ☐ Safety goggles ☐ Flashlight	☐ **Ruler or scale card** ☐ Measuring tape or meter stick ☐ Magnifying loupe or hand lens (about 10× magnification) ☐ Water test kit ☐ Compass ☐ Clinometer ☐ Field microscope ☐ Field guides	☐ **Notebook** ☐ **Pencil** ☐ **Materials for collecting** o Baggies o Specimen labels o Sharpies ☐ Rock hammer ☐ Camera
***Common sense** should be your guide when determining what is needed for a particular visit to the field. Trips that last a class period and are adjacent to the school may require nothing beyond materials for a typical class—a notebook and a pencil.*	**For Both Extending the Senses and Preserving Observations**	
	☐ **Maps** ☐ **Camera** (possibly with video) ☐ Probeware and interface (like the Vernier LabQuest) ☐ Digital field microscope ☐ GPS unit, smartphone, or tablet ☐ Apps used in the field might include: o GPS o Google Earth or other virtual globe o Skitch (or other image-annotating app) for adding notes to photos. Skitch also includes a map annotation function. o Photosynth or other panorama app o Video (the YouTube Capture app allows for basic video editing on your smartphone or tablet) o Other specialized photography apps o Audio recorder o Notes o Photo management software, such as Web Albums	

by the classic film, is available at http://www.virtualfieldwork.org. It is simple to add your field site to the same Google Earth file containing the Powers of Ten centered on your school. This can help students better understand the location of the field site in relation to the school.

Field scientists typically show information about their field site: the location of observations (such as photographs and specimen collection) and also the scientific data (such as rock type, position of faults, areas of bedrock exposure, water quality information, and much more). For these purposes you may want to have a paper copy of a map you can bring into the field upon which you can make notes. Commonly topographic maps are used as base maps, in part because the contours can help you locate yourself on the map (if it's not completely flat) and partly because the topography itself is often relevant to Earth and the environmental data being collected. If your field area is larger than about 100 meters (330 feet) on a side, you can create a topographic map tailored to your needs using online software (http://www.gpsvisualizer.com). USGS topographic maps of the entire US are available as free downloads at http://www.usgs.gov/pubprod/. You may wish to download the local map and take an excerpt of the area surrounding your site.

Needs

Positions of samples, photographs, and observations can be located using GPS. In this case, you can make notes about your GPS locations, and plot the locations on a computer later, or make use of an app like Skitch that allows you to annotate digital maps in the field. Photos taken with smartphones, tablets, and GPS-enabled cameras will include location data with pictures. Those familiar with Geographic Information Systems (GIS) can make elaborate maps using your own sets of coordinates and data. While GPS and GIS technology are now standard in most types of fieldwork, they are not essential for doing good fieldwork. Standard, intuitive tools for measuring are, however, quite helpful. A compass (either traditional or digital) can be helpful in orienting your field site in space, and a ruler and protractor can be helpful when drawing the field site in correct proportions (e.g., the position of samples along a transect or the angle of bedding or faults). Bring a clipboard so that you have a flat surface to write upon in the field—pencils and a good eraser are the best writing implements for drawing and annotating your map.

It is possible in principle to capture all your data electronically, but most field scientists still use a notebook even if they have access to the latest technology. Certain information can be captured very simply in the field with a pencil and paper while it may prove challenging with digital technology, such as when making annotated sketches of the field site and taking written notes. Normally pencil is used, in part because it doesn't smear if it gets wet, but also because it's erasable; while not essential, field scientists who know they may have to work in wet conditions will purchase notebooks with waterproof paper (Rite-in-the-Rain notebooks). An audio recorder (smartphone or standalone digital recorder) is handy when writing a lot of text is impractical, though it does create transcription work at the end of the day. Remember that it is considered a form of "best practice" to make sure that each entry includes the date, time, and locality.

Documentation and Specimen Collection

Photographs

Once at a field site it is easy to immediately begin taking photographs without recording notes to accompany them—a problem experienced by professional and amateur scientists alike. But the lack of proper documentation is perhaps the most common mistake made in the field, especially with digital photography, where it is easy to take tens or even hundreds of photographs at a single site. Also, before you begin photographing it is advisable to first explore the entire location and develop a plan for how you will communicate the site to your students back in the classroom. This plan will guide your photography, and the recorded notes will ensure that every image makes sense long after you've visited the site. Proper documentation includes the following steps:

- Note the location and orientation of the photographs you take. Recording this information on a map is very helpful.

- In each photograph, it is important to have a sense of scale. For smaller structures (like ripple marks or fossils) or close-ups of an outcrop or rock, it is important to show scale by using a common object, such as a penny, rock hammer, an unsharpened pencil, or (ideally) a clearly marked ruler. For larger structures, a really great scale is a person, so feel free to step into the picture! The importance of a scale cannot be overstated, as the proper identification of geologic features in photographs often depends on knowing the feature's size.

- In addition to showing scale within photographs, be sure to pay attention to different scales across the set of photographs you take. That is, include photographs across a wide range of scales, from the smallest fossil or mineral crystal to panoramic shots of the landscape. Maps and virtual globe software, such as Google Earth, can extend scales from the local landscape to a global perspective.

Drawings

Although photographs are key, simple sketches or drawings are also useful for documenting a field site. In fact, subtle changes in rock layers, for example, may not be visible in photographs, so to capture such features, drawing may be required. Drawing also forces you (or your students) to observe closely. It will be helpful to use either a Rite in the Rain notebook or a large, clear plastic bag to hold your notebook in case of rain. When drawing, keep in mind that you should document the same type of information that is documented in photographs (location, orientation, and scale). Drawing also requires close study in a way snapping a photograph does not. Louis Agassiz once said that "…a pencil is one of the best of eyes." While drawing, you have to think about the relationship of the elements you are representing, their scale, and their arrangement.

Annotating Photographs

The use of smartphones and tablets in the field allows for a hybrid of photographs and drawings. Many apps allow for captioning photos in the field, and some allow you to draw and write text on photos as you take them. Skitch is one such app, and it also allows for the taking of notes on the maps themselves. Photos taken on smartphones and tablets are also (typically) geo-referenced. This means that they can easily and quickly be included in a Google Earth or other GIS program in the precise location where the image was taken. If you are unable to annotate photographs in the field, or you wish to add more detail than is practical on your electronic device while you are at the field site, the "old fashioned" technique is to take a picture, then make a simple notebook sketch containing labels of key features. Later you can annotate a digital or printed version of the photograph using your field notes. If the conditions are poor for note taking either digitally or manually, it may be more practical to record audio notes that you can later match to your picture.

Using Field Guides

Select field guides appropriate to the focus of your work and consider whether or not you wish to bring others. The appropriate field guide might be something as simple as a single sheet with line drawings of the fossils common at your field site, a few pages containing a dichotomous key of common rock types, or a collection of field guides on fossils, birds, mammals, butterflies, rocks, flowering plants, and more. While scientists will come to know by sight the kinds of specimens commonly found at their site, they do not typically set out to memorize them, and uncommon things are sometimes found that send even experts back to their field guides.

Collecting Specimens

Rocks and fossils often provide significant clues for interpreting past environments. Layers of basalt indicate past volcanism, for example, whereas shales bearing trilobite and other fossils indicate deposition in a shallow sea. Collecting specimens from a site provides a wonderful opportunity to take a piece of the field into the classroom, allowing you to engage students in hands-on learning. Collecting specimens also permits further study away from a site where time and field conditions can impose certain limitations. You can and are encouraged to identify rocks, minerals, fossil types, and flora and fauna in the field. So, what do you need to know about collecting specimens?

- **You first need to confirm that collecting specimens at the site you are visiting is legal**. Typically, collecting is not allowed in parks, so be sure to check.

- Just as you made decisions about photography based on how you plan to communicate the site to students, collect specimens that will help tell the story of the site back in the classroom. If rock types change from area to area, either vertically or horizontally, then specimens of each type are ideal.

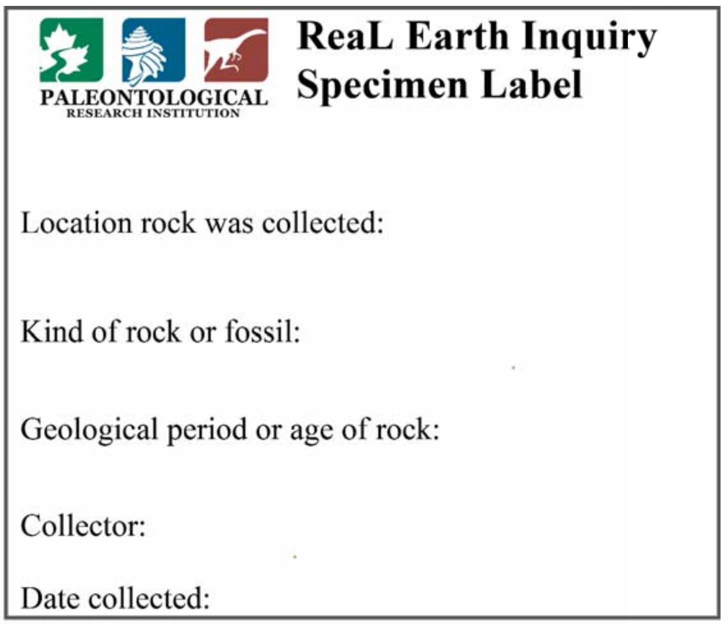
- Before collecting a specimen, take a photograph of it in situ, both close up as well as from a distance. Don't forget to include an object for scale in the photograph!

- Document the location from which the specimen is collected, preferably on a map of the area. Labeling the specimen with a number that corresponds to a number on your map is an effective technique.

- Specimens should be broken directly from the outcrop so the exact source is known. Eroded rocks scattered about on the floor of the site may have originated from multiple locations.

- The weathered surface of rocks often carries a different appearance than a "fresh" break. Ideally, collected specimens possess one weathered surface but are otherwise not weathered. Rocks broken directly from outcrops will ensure fresh surfaces.

- As specimens are collected, place each in a separate resealable bag, noting on the bag with permanent marker each specimen's location as indicated on your map. Include a specimen label within the bag, including the information shown in *Figure 11.2*.


PALEONTOLOGICAL RESEARCH INSTITUTION

ReaL Earth Inquiry Specimen Label

Location rock was collected:

Kind of rock or fossil:

Geological period or age of rock:

Collector:

Date collected:

Figure 11.2: This specimen label, printed six to a page, is available for download at http://virtualfieldwork.org/Assessments_and_Student_Materials.html.

Back in the Classroom: Virtual Field Experiences (VFEs)

Following your trip to a field site, perhaps the most critical step after returning to your lab or classroom is to examine all of your photographs, illustrations, specimens, and notes associated with each. Sometimes even the most diligent geologist forgets to record notes that, in hindsight, are critical. It is therefore recommended that one makes sure that his or her notes are legible and complete. Recopy your notes. Such an activity will not only ensure legibility for the future, but it will help indicate any gaps in your note taking. If gaps exist, then it is easiest to fill them in when your memory of the site is fresh.

Once your materials from the site visit are in order, it is time to develop an activity that will allow your students to experience the site much like you did—but in the classroom. VFEs allow you to compile this information in a way that is easy to share with others who wish to learn about the site. Ideally, VFEs provide opportunities for open-ended exploration, just as actual fieldwork does. Scientists in the field are not limited to a single possible way to operate, nor do they have a guide explaining what they see at every turn. In the field, one might pick up a rock and take a closer look, or pull out a magnifying glass and look at a cliff face. Exploration drives inquiry in the field, and inquiry and exploration are key goals of VFEs.

The concept of VFEs can take on multiple forms. For example, kits containing maps, printed photographs, and specimens (with notes on the map indicating where the specimens were collected or where the photographs were taken) can be produced. Or, your digital photographs can be embedded within a PowerPoint or Prezi presentation, a website, or a Google Earth tour with placemarks containing photos, video, or other data in the exact locations where the specimens were collected. Maps can also be overlain. Historic maps can be included, and Google Earth has historical imagery included for much of the world. Many VFEs incorporate more than one technological platform.

Keep in mind that these electronic presentations may take on a very linear, directed feel. In that respect, be careful that your VFE does not turn into a Virtual Field Trip. Virtual Field Trips have become increasingly common at many levels of education, but these experiences are typically guided tours rather than opportunities for inquiry. An online search will yield many examples of these tours, as will a search of the Digital Library of Earth System Education (DLESE). Such resources clearly have value, but they are passive experiences for students. VFEs, in contrast, should stress the importance of inquiry; learning for understanding involves students figuring things out. The act of making new, or extending existing, VFEs may be the simplest way to bring inquiry to the use of VFEs.

In considering VFEs as a recurring practice, initial experiences are perhaps more guided than the later experiences; allow a gradual transfer of responsibility from teacher to student. But VFEs ideally offer the same opportunities for exploration as those provided at an actual field site, with occasional moments of discovery that lead to new questions about the site. By asking such questions and then seeking answers, students are doing science. And it is perfectly reasonable to virtually visit a site several times for further data collection, or even to study different concepts at the same site. Scientists, of course, do exactly the same thing.

Prezi and PowerPoint VFE Templates

This section discusses templates intended to simplify VFE production in addition to providing general information on VFE development and use. There are templates in both Prezi and PowerPoint formats, each with a version of the graphic organizer shown in *Figure 10.1* as its centerpiece. Questions in the graphic organizers and in the rest of the templates are written generically, so they may be applied to any site. The templates serve as starting tools that are useful for creating an “entry level” VFE. They are available at http://virtualfieldwork.org/Template.html. The template includes graphic organizers for both Earth and environmental science, with the environmental science organizer embedded within the geoscience organizer.

How are teachers using virtual fieldwork?

VFEs might be used as a single, in-class exercise, or they can be explored across an entire year. We hope that teachers who use and develop VFEs will eventually use them across the entire curriculum, but it makes sense to start smaller. There is no single correct approach to using VFEs in the classroom. Here are some examples of ways teachers are using virtual fieldwork:

- Students in a rural community are using Google Earth to create Powers of Ten tours centered on their homes (based on the Eames' classic film). This helps students to internalize the abstraction that is central to making maps and to build deeper understandings of scale.
- Students are making geologic maps of the local bedrock.
- Students are creating an interpretive guide for a county forest.
- Students are exploring lakes, dams, streams, outcrops, quarries, waterfalls, and more.

For more VFEs, see our growing database at http://virtualfieldwork.org/.

What do I need to consider as I begin to build my VFE?

Considerations fall into four categories:

- **Logistical:** What do I have the attitude, time, resources, and skills to do? (Attitude is listed first as it is the most important factor.)
- **Pedagogical:** How do I bring the scientific content together with technologies in a way that best builds enduring understandings of bigger ideas and overarching questions, as well as of the smaller scale ideas and questions I deem important?
- **Technological:** What hardware and software do I need to assemble the materials for the VFE and to make it accessible to my students? This may include traditional scientific tools, like a rock hammer or a compass, as well as the computer technologies discussed in this chapter and on our website.
- **Content:** What scientific knowledge, ideas, processes, and practices do I want my students to understand and be able to do at the end of the experience?

Of course, these categories overlap and interplay substantially—teachers of Earth science use Google Earth in different ways than other Google Earth users do.

11 Fieldwork

VFEs

Most of the remainder of this chapter is a set of checklists to help you address these different considerations when outlining your VFE design. Take it with you into the field as you collect pictures and other kinds of data for your VFE; use it to identify issues you think are most important for the development of your VFE. Most of the items in the checklists are there to start you thinking about how to address a particular issue. Content is listed last for the sake of readability, as the checklists for the content section are longer than they are for the other categories.

The framework for understanding how to effectively blend <u>t</u>echnology, <u>p</u>edagogy, <u>a</u>nd <u>c</u>ontent <u>k</u>nowledge is known by its acronym TPACK.

Table 11.3: A checklist of cross category issues. Many of the questions in the checklist relate to more than one of the categories identified above. Because of this overlap, only the cross-category issues and content sections are of significant length.

Have I considered this?	Question:	Logistical	Pedagogical	Technical	Content
	Do I have appropriate safety and first aid equipment and materials?	√		√	
	What content do I want to address?	√	√	√	√
	Do I have connections in mind to at least a couple of the bigger ideas and overarching questions? • The Earth is a system of systems. • The flow of energy drives the cycling of matter. • Life, including human life, influences and is influenced by the environment. • Physical and chemical principles are unchanging and drive both gradual and rapid changes in the Earth system. • To understand (deep) time and the scale of space, models and maps are necessary. • How do we know what we know? • How does what we know inform our decision-making?		√		√
	How much time do I realistically have to spend on VFE creation?	√			
	How much class time do I want to dedicate to VFEs?	√	√	√	√
	Am I okay with the trade-off between some expected frustration and the pedagogical payback?	√	√	√	√
	Can I productively engage students in VFE development? *Or is that something to aspire to for next year?*	√	√	√	√
	How does the technology I have serve the goals I wish to meet?	√		√	
	Do I have enough batteries for my powered equipment?	√		√	
	Is the site accessible to me? *This includes legal, safety and proximity considerations.*	√	√		
	Are my students familiar with the site? If not, is it accessible to *all* of my students? *If the answer to both questions is no, select another site.*	√	√		
	Are the required pedagogical, technological, and content skills and knowledge needed to create the VFE within my reach? *Ideally, select challenges that are just within (or just beyond) your reach so that you grow professionally.*	√	√	√	√
	Do I have the hardware (including field equipment) and software needed for VFE creation? *The bare essentials are an Internet-connected computer, a digital camera, and either PowerPoint or Google Earth.*	√	√	√	

Logistical

We hope that VFE development is used to expand teachers' skills and knowledge. Performing fieldwork for the first time can be overwhelming, but remember that science is a process, and not even professional scientists capture all that they need in one visit. With practice, and the proper attitude, you will become more and more comfortable when visiting the field.

Pedagogical

While most pedagogical questions also address other categories as noted above, there are issues that deserve explicit attention here.

- Does the data you are collecting go toward answering why this place looks the way it does? *Or is there a good reason to introduce distracting information?*

- If the site is especially striking or unusual, have you considered how to get yourself and your students beyond the "novelty space" of the location? Crudely summarized, novelty space is the idea that you can't figure out what's going on at a field site if you're either awed by its beauty or freaked out by its perceived dangers. This is one of several reasons for choosing a site that is already familiar to the students.

Technological

Most technological issues are also logistical; these are addressed in the table above.

Content

Why does this place look the way it does? The driving question of our work can serve as an entry into any major topic in Earth or environmental science curricula. It also brings relevance to the science since we want to start with sites near the school that are already somewhat familiar to the students. We want students to look at the familiar with new eyes, and to become skilled at reading their local landscape. Ultimately, we want the skills built by reading the local landscape (being able to tell the story of why a place looks the way it does) to be transferable to *any* landscape.

What scientific content do you want your students to better understand through their work in the VFE? How does this fit into the larger goals of the course? Can you draw, and help your students to draw, connections to bigger ideas and overarching questions? What topics in Earth science can be addressed by doing fieldwork?

Understandings will be made much deeper in schools where teachers in more than one subject or grade level engage their students in studying the local environment.

Below are questions taken from the geoscience and environmental science graphic organizers. Most teachers will likely use one sheet or the other, but not both. Your VFE likely won't address all of the questions (on either sheet), but you should be able to strategically select what you minimally wish to address.

11 Fieldwork

VFEs

For the Geosciences:

For all of the following questions:

- How do you know? (What evidence is there?)
- What does it tell you about past environments?
- What does it imply about the future?

☐ **Describe the shape of the land.**

- Are there mountains, valleys, or hills?
- What are the valley shapes?
- What can cause valleys to form?
- What can cause mountains or hills to form?
- Are the mountains or hills young or old?
- What roles does tectonics play in shaping the site?

☐ **What effects has water had on the landscape?**

- Is water depositing material, eroding material, or both?
- Is the action of water primarily chemical, primarily physical, or both chemical and physical?

☐ **What effect has the climate had on the landscape?**

- Was the past climate different?
- What factors may have been affected or caused by climate?
- How has fire played a role in shaping the environment?

☐ **Describe the ecosystem.**

- See the ecosystem graphic organizer and checklist.

☐ **What does the arrangement of the rocks and soils indicate about past conditions?**

- Do the rocks seem to form a sequence?
- Where would you find the oldest rocks? The youngest rocks?
- Does the rock record include evidence of ancient disturbances? If yes, describe.
- Are there different kinds of rocks at different outcrops?

☐ **What types of rock and soils are there and what do they indicate about past conditions?**

Sediments and Sedimentary Rocks

- Is the sample clastic or organic /chemical?
- If clastic, what is the grain size?
- If organic, what minerals is it made out of?
- Are there fossils?

Metamorphic

- Is the rock foliated or non-foliated?
- What was the parent rock?

Igneous

- Did the rock form above or below ground?
- Is it felsic or mafic?

☐ **What effects has life, including human life, had on the landscape?**

- How have plants shaped the landscape?
- How have animals generally, and humans in particular, changed the landscape?
- On what scale?

For the Environmental Sciences:

For all of the following questions:

- How do you know? (What evidence is there?)
- What does it tell you about past environments?
- What does it imply about the future?

☐ **Describe how life shapes the land.**

- What are the pioneer plants?
- How do pioneer plants impact soil formation?
- How are animals shaping the land?
- Are there invasive species? If yes, what are they, and how are they changing the ecosystem?
- Have disturbances played a role in the introduction of invasives? If yes, describe.
- How are new invasives likely to change the ecosystem over the next century?

☐ **Describe the role of water in the ecosystem.**

- In what ways does water serve or disturb habitats?
- How does life move, use, and store water?

☐ **How has climate shaped the ecosystem?**

- How is the climate reflected by living things at the site?
- Describe any microclimates and how they affect life.
- Describe how sun and shadow affect life.
- What roles do fire, hurricanes, or other climate-related disturbances play in shaping this landscape?

☐ **Describe the role rocks and soil play in the ecosystem.**

- How does life change the rocks and soil at the site?
- How is life dependent upon the rocks and soil at the site?
- Does the rock record include evidence of ancient disturbances? If yes, describe.
- See also the geoscience questions.

☐ **Describe the types and arrangements of plants and animals and what they indicate about present and past environments.**

- Why do living things in the environment look the way they do?
- What life forms were the earliest to arrive?
- Describe how different life forms are distributed throughout the field site.
- What is the impact of invasive species and other disturbances?
- See also the **Describe how life shapes the land** section.

Plants

- How have plants shaped the landscape?
- How has the landscape affected the plants?

Animals

- How do animals contribute to plant distribution?
- How has the landscape affected the animals?

Other biota

☐ **What effects have humans had on the landscape?**

- What resources do humans use from here?
- How have humans changed the landscape?
- On what scale?

Closing

Closing Thoughts

This chapter was written to help get you started in the creation of VFEs and, in a broader sense, to help you learn more about fieldwork. But how do you know when to stop? It may be more productive to think of VFEs or activities involving actual fieldwork as undertakings that are becoming ready for use rather than as finished products. Here is a nice quote from Wendell Berry's essay "Faustian Economics" that relates to this concept:

> *It is the artists, not the scientists, who have dealt unremittingly with the problem of limits. A painting, however large, must finally be bounded by a frame or a wall. A composer or playwright must reckon, at a minimum, with the capacity of an audience to sit still and pay attention. A story, once begun, must end somewhere within the limits of the writer's and the reader's memory. And of course the arts characteristically impose limits that are artificial: the five acts of a play, or the fourteen lines of a sonnet. Within these limits artists achieve elaborations of pattern, of sustaining relationships of parts with one another and with the whole, that may be astonishingly complex. And probably most of us can name a painting, a piece of music, a poem or play or story that still grows in meaning and remains fresh after many years of familiarity.*

Resources

Field Geology Teaching Practices

Greene, J. P., Kisida, B., & Bowen, D. H., 2014, The Educational Value of Field Trips. *Education Next*, *14*(1), 78–86.

Issigonis , M., 2006, Field Trips as an Aid to Teaching Earth Science Courses. *The Earth Scientist*, 22(3): 14–16.

Johnson, J.K., and Reynolds, S.J., 2005, Concept sketches – Using student- and instructor-generated annotated sketches for learning, teaching, and assessment in geology courses. *Journal of Geoscience Education*, 53: 85–95.

Orion, N., and Hofstein, A. (1994). Factors that influence learning during a scientific field trip in a natural environment. *Journal of Research in Science Teaching,* 31: 1097–1119.

Russell, H.R., 1998, *Ten-Minute Field Trips* (3rd ed.), National Science Teachers Association: Alexandria, VA. (Focused on elementary and junior high; chapter on Earth science p.113–137.)

Shulman, L. S., 2005, Signature pedagogies in the professions. *Daedalus*, 134(3): 52–59.

Whitmeyer, S.J., Pyle, E.J., Mogk, D.W. (eds.), 2009, *Field Geology Education: Historical Perspectives and Modern Approaches*, GSA Special Papers volume 461. (29 articles, focused on undergraduate education.)
Available at http://specialpapers.gsapubs.org/content/461.toc.

Extraordinary Science Field Trips, NSTA Reports, Summer 2013, 25(1): 1–2.
Available at http://www.nsta.org/docs/NSTAReports201307.pdf.

My Geologic Address: Locating Oneself in Geologic Time and Process, by Ault, K., SERC InTeGrate workshop “Teaching the Methods of Geoscience” activities.
http://serc.carleton.edu/integrate/workshops/methods2012/activities/ault.html.

Teaching in the Field, National Association of Geoscience Teachers. (Set of resources for teaching field geology.)
http://nagt.org/nagt/teaching_resources/field/index.html.

Guides to Fieldwork

(Mostly focused on post secondary education, but useful as references)

Coe, Angela; Argles, Thomas; Rothery, David and Spicer, Robert, 2010, *Geological Field Techniques*. Wiley Blackwell: Chichester. (This is a current standard.)

Compton, Robert R., 1962, *Manual of Field Geology*, John Wiley & Sons, Inc.: New York.(an old classic)

Compton, R., 1985, *Geology in the field*. Wiley: New York. (an updated version)

Lambert, David, 2006, *The field guide to geology*. The Diagram Group.

Lisle, R., Brabham, P. & Barnes, J., 2011, *Basic geological mapping.* Chichester, West Sussex Hoboken, NJ: Wiley-Blackwell.

Maley, Terry S., 2005, Field Geology Illustrated, Second Edition, Mineral Land Publications: Boise, Idaho.

Mathur, S.M., 2004, *Guide to Field Geology*. New Delhi: Prentice Hall of India, 220 pp.

Spencer, E., 2006, *Geologic maps : a practical guide to the preparation and interpretation of geologic maps*. Long Grove, Ill: Waveland Press.

Walker, J. & Cohen, H., 2009, *The geoscience handbook AGI data sheets.* Alexandria, Va: American Geological Institute, 316 pp.

Walker, J. Douglas, and Harvey A. Cohen, 2007, *The Geoscience Handbook: AGI Data Sheets*, 4th edition, American Geological Institute.

How to read a geologic map, Wisconsin Geological and Natural History Survey.
http://wgnhs.uwex.edu/wisconsin-geology/bedrock-geology/read-geologic map/.

Appendix: The Teacher-Friendly Guides™, Virtual Fieldwork, and the NGSS's Three-Dimensional Science

The Next Generation Science Standards contain a set of learning goals that define and describe the ideas and practices that we need in order to think scientifically. The NGSS are not a curriculum. They tell teachers not how to teach, but rather, are tools to show what to teach. They also help families know what children are expected to learn, and help schools and teachers know what to assess. So, how do you teach in ways that align with NGSS, if NGSS itself doesn't tell you? The strategies, tools and resources associated with the ReaL Earth Inquiry project, like this *Teacher-Friendly Guide™*, are intended to offer a partial answer to that question.

"ReaL Earth Inquiry" is the project name of the NSF grant (0733303) to the Paleontological Research Institution to develop teacher resources such as Teacher-Friendly Guides™ to regional Earth science and Virtual Fieldwork Experiences. "ReaL" refers to Regional and Local.

Acronyms frequently used in *The Next Generation Science Standards* (NGSS):

PE: Performance Expectation
DCI: Disciplinary Core Idea
CC: Crosscutting Concept
SEP: Scientific and Engineering Practice
PS: Physical Sciences
LS: Life Sciences
ESS: Earth & Space Sciences
ETS: Engineering, Technology, and the Applications of Science

The vision of NGSS differs in a number of important ways from current common practice in schools and classrooms across the country. Teaching about local and regional Earth and environmental science can and has worked well for many teachers under more traditional standards, but by attending to the three dimensions of the NGSS (see below), we believe it can work even better. Deep understandings of why your local environment looks the way it does requires understanding the local environment from multiple disciplinary perspectives, and understanding the connections amongst these different disciplinary ideas. That is, to understand your local environment, a systems perspective is needed. Scientifically accurate meaningful understanding can and does come out of single lessons, single units, and single courses, but these understandings become richer, deeper, and more durable if they are connected across courses. The NGSS vision includes recognition that building a deep understanding of big ideas is both very important and a process that takes years of coordinated effort. Fortunately, the many processes that shape the local environment are part and parcel of existing curricula, and especially for Earth science, biology, and environmental science courses, nearly every unit has central aspects that play out on a human scale just outside the school door. A coordinated approach to the study of the local environment across units within a single course and across grade levels

CHAPTER AUTHOR

Don Duggan-Haas

and courses can be a fairly subtle change in each teacher's daily routines, but it has the potential for big returns in terms of the depth of student understanding. This deeper understanding pertains not only to the local environment and the way course topics are represented within it, but also to systems more generally, to the nature and importance of scale, and to much, much more.

NGSS builds upon the earlier work in the National Science Education Standards (NSES), but brings more of a systems approach not only to its representation of science, but to the standards themselves. NSES defined science not just as a body of ideas, but an evolving body of ideas extended by inquiry. NGSS continues this work by clarifying inquiry and the sciences as a set of relationships amongst three dimensions: Disciplinary Core Ideas (DCIs), Scientific and Engineering Practices and Crosscutting Concepts." Each of the three dimensions is judged to be of roughly equal importance and they are seen as interdependent. To truly, deeply, understand science and how scientific understandings develop, learners must not only understand each dimension, but how the dimensions are related to one another—the whole is greater than the sum of the parts. By coming to understand these interconnections, teachers and students will also come to better understand the nature of both scientific inquiry and of complex systems.

A Perspective on Science Education Priorities

The bulk of the NGSS is a series of Standards, each a page or two in length, with "Performance Expectations" (PEs) at the top of the first page, followed "Foundation Boxes" and "Connection Boxes" supporting the PEs. It's tempting to jump into the discussion of NGSS by starting there. It's also tempting to start with the Disciplinary Core Ideas (DCIs), especially for those who specialize in a particular scientific discipline. But readers shouldn't do either of those things. Appendix K of NGSS notes, "The goal is not to teach the PEs, but rather to prepare students to be able to perform them by the end of the grade band course sequence." It's important to understand the basic three-dimensional structure of the NGSS before looking at the PEs or DCIs. We will give them both their due, but we won't start with either of them.

If you have a degree in a particular science, and this is the science that makes up the bulk of your teaching load, it's natural to go straight for your area of expertise in the NGSS, to see how that's addressed. But don't do that, or, if you already have, try to imagine that you haven't. Before considering the concepts and practices essential to being literate in your discipline, consider what you think everyone needs to know about science disciplines *outside your area of specialization*, and consider the ideas that are broadly applicable across all the sciences. That is, think about the fundamentals of science.

Imagine having magical powers that allowed you to make every American understand six or eight profound scientific ideas – ideas that, if everyone understood them, would help people make the world a better place because they would make better decisions. Imagine again that this power could also be used to give everyone a small set of well-developed scientific skills. What should these ideas and skills be? Ponder what these ideas and skills are before reading further, perhaps going so far as to put them down on paper. Ask your colleagues, and your former students the same question. What are the most important ideas and skills for everyone to understand or be able to do related to science?

The profound scientific ideas you thought of are likely to be something like NGSS's Crosscutting Concepts, and the scientific skills are likely to be something like the Scientific and Engineering Practices (*Table A.1*). In reviewing the NGSS, teachers at the secondary and college levels who specialize in a particular subject are often naturally drawn first to the Disciplinary Core Ideas for their discipline, and when they find a favorite topic that is not addressed to what they consider an appropriate depth, they are upset that NGSS is not providing the content necessary to prepare their students for the future. But, decades of educational practice teaching science courses with thousand-page textbooks and scores of key ideas has not yielded a scientifically literate populace. It is essential to focus on smaller sets of truly big ideas (see also the *Big Ideas* chapter) and work across grade-levels to build understandings over time. This may mean, however, that your favorite topics are no longer explicitly listed in the learning goals.

Table A.1 contains abbreviated versions of the Concepts, Practices, and Ideas. You can find longer descriptions within the NGSS, and we'll look at one as an illustrative example. Consider the full description of Crosscutting Concept #3:

> *Scale, proportion, and quantity.* In considering phenomena, it is critical to recognize what is relevant at different measures of size, time, and energy and to recognize how changes in scale, proportion, or quantity affect a system's structure or performance.

It seems likely that most Americans do not have a good and durable understanding of this concept, yet it has relevance to many aspects of their daily lives. The same could be said of most, if not all, of the remaining concepts on the list.

The Crosscutting Concepts are described in some detail in Appendix G of NGSS, and the Scientific and Engineering Practices are described in Appendix F.

Such understandings are almost certainly more important than knowing particular facts about geologic history or the nature of disease (two topics not given deep attention in the NGSS). Indeed, it's only possible to understand geologic history or the nature of disease if you also understand these concepts!

While your favorite topics may not be explicitly mentioned in NGSS, that doesn't necessarily preclude them from being taught. There's a tremendous amount of content in these *Teacher-Friendly Guides*[TM] that are not mentioned in NGSS, yet we believe that all of the contents of the Guides *support* teaching that is aligned with the NGSS. Different topics, such as glaciers or mineral resources, can serve as our pedagogical partners in building understandings of the Crosscutting Concepts, Scientific and Engineering Practices, and the Disciplinary Core Ideas that make up the NGSS. In other words, we can and should teach these topics, but understanding the particular topic isn't the primary goal. The primary goal is to use the teaching of these topics as a means to build an understanding of those bigger ideas.

It isn't clear if K–12 science curricula designed to bring the NGSS's vision to fruition will be more or less rigorous than today's common K–12 curricula, but rigor shouldn't be the goal of education. Education should develop citizens who can reason critically and use evidence to inform their actions. This isn't to say that schooling shouldn't be challenging, but rather that its challenges should be in the service of meeting other goals. Building deep and interconnected understandings of the three dimensions of NGSS will not be a simple task, but it has the potential to better prepare for students for citizenships, college, and careers.

Connecting "Why does this place look the way it does?" and Virtual Fieldwork to NGSS

This *Teacher-Friendly Guide*™ is one part of a large project designed to help educators teach about Regional and Local (ReaL) Earth system science in an inquiry-based way. This ReaL Earth Inquiry Project, and all of its related resources, support educators and students in the investigation of the project's driving question: "*Why does this place look the way it does?"* The "place" of the question is anywhere you happen to be, but we hope and expect users of these materials will start by studying areas outside their backdoor or their classroom door. The *Fieldwork* chapter (Chapter 11) addresses both actual and Virtual Fieldwork, and we believe the coupling of virtual and actual fieldwork is an excellent way to teach and learn, and it's an approach that is fully three dimensional, in the NGSS's sense of that term.

Read through the Practices outlined in **Table A.1** with an eye towards engaging in and documenting fieldwork. See the graphic organizer and the question list in Chapter 11 and consider how these questions can be asked of any site, and how they can serve to inspire new questions that are site-specific. Then, consider the making of Virtual Fieldwork Experiences (VFEs) to document the site, allowing for continued investigation after leaving the field, and sharing findings with others in the community and beyond. This approach provides opportunities to engage *all* of the practices. To build rich explanations of the range of processes at play in a field site requires application of *all* of the Crosscutting Concepts. There are also opportunities for using field sites to build understandings of *all* of the DCIs, though selected ones from the Life and Earth & Space Sciences have the most direct correspondence. The use of virtual and actual fieldwork is scalable to fit the educational need, so a particular lesson or activity would be

Scientific and Engineering Practices	Crosscutting Concepts
1. Asking Questions and Defining Problems 2. Developing and Using Models 3. Planning and Carrying Out Investigations 4. Analyzing and Interpreting Data 5. Using Mathematics and Computational Thinking 6. Constructing Explanations and Designing Solutions 7. Engaging in Argument from Evidence 8. Obtaining, Evaluating, and Communicating Information	1. Patterns 2. Cause and Effect 3. Scale, Proportion, and Quantity 4. Systems and System Models 5. Energy and Matter 6. Structure and Function 7. Stability and Change 8. Interdependence of Science, Engineering, and Technology 9. Influence of Engineering, Technology, and Science on Society and the Natural World

Disciplinary Core Ideas			
Physical Sciences	*Life Sciences*	*Earth and Space Sciences*	*Engineering, Technology, and the Applications of Science*
PS 1: Matter and its interactions **PS 2:** Motion and stability: Forces and interactions **PS 3:** Energy **PS 4:** Waves and their applications in technologies for information transfer	**LS 1**: From molecules to organisms: Structures and processes **LS 2**: Ecosystems: Interactions, energy, and dynamics **LS 3**: Heredity: Inheritance and variation of traits **LS 4**: Biological evolution: Unity and diversity	**ESS 1:** Earth's place in the universe **ESS 2:** Earth's systems **ESS 3:** Earth and human activity	**ETS 1:** Engineering design **ETS 2:** Links among engineering, technology, science, and society

Table A.1: Summary of NGSS's Three Dimensions. For more detailed descriptions, see the relevant appendices in The Next Generation Science Standards.

expected to target just one or two, but a program of fieldwork across a course would allow for the addressing of many of the Concepts, Practices, and Ideas.

Look again to the graphic organizers from Chapter 11: Fieldwork. It is easy to see how, especially in Earth science, biology, or environmental science courses, most of the units in these courses play out in some meaningful way outside the classroom door. As the DCIs are akin to umbrellas relative to a course's units, these too largely play out in meaningful ways outside the classroom door. The

Appendix

NGSS recognizes that in order to understand big ideas, years of coordinated study are required. The coordinated study of the local and regional environment provides an excellent opportunity for this. A field site can be studied using increasingly sophisticated approaches across the K–12 experience, and for the students, this does not entail repetition, but rather the opportunity to study a site from different disciplinary vantage points across all or part of the K–12 continuum. If such an approach is adopted broadly, kids who move during the course of their schooling can bring in new eyes, and information, to compare and contrast the environment in their new school with the environment where they used to live.

How to Read the NGSS

Each standard in the NGSS includes multiple interconnected parts. They have an architecture that can be seen in *Figure A.1*. This diagram is taken directly from the NGSS website's page, "How to Read the Next Generation Science Standards." This page includes a short written overview and an accompanying video as well as links to more detailed information. The standards are designed to be read online, with features like pop-ups, choices for highlighting different parts of the text (the different dimensions) in different colors, and links to related content elsewhere within the NGSS. If you're not familiar with how they work, you should follow the link above and then explore around the NGSS a bit before reading further.

Know that the appearance of the Standards can be a bit intimidating, with all the abbreviations, acronyms, codes, and different colors, but after a bit of time working with the text, its logic does become understandable.

Example of ReaL Connections to Performance Expectations

Earth and Space Science Disciplinary Core Idea #2 is "Earth's Systems," and it has five supporting concepts:

- ESS2.A: Earth Materials and Systems
- ESS2.B: Plate Tectonics and Large-Scale System Interactions
- ESS2.C: The Roles of Water in Earth's Surface Processes
- ESS2.D: Weather and Climate
- ESS2.E: Biogeology

In the middle school grade band of NGSS, there are six performance expectations associated with ESS2. All six are listed below, but not in their complete form. "Clarification Statements" and "Assessment Boundaries" are not included in the full list, but we'll look at one of the Performance Expectations in greater detail. See the full list (and the full standard) at http://nextgenscience.org/msess2-earth-systems.

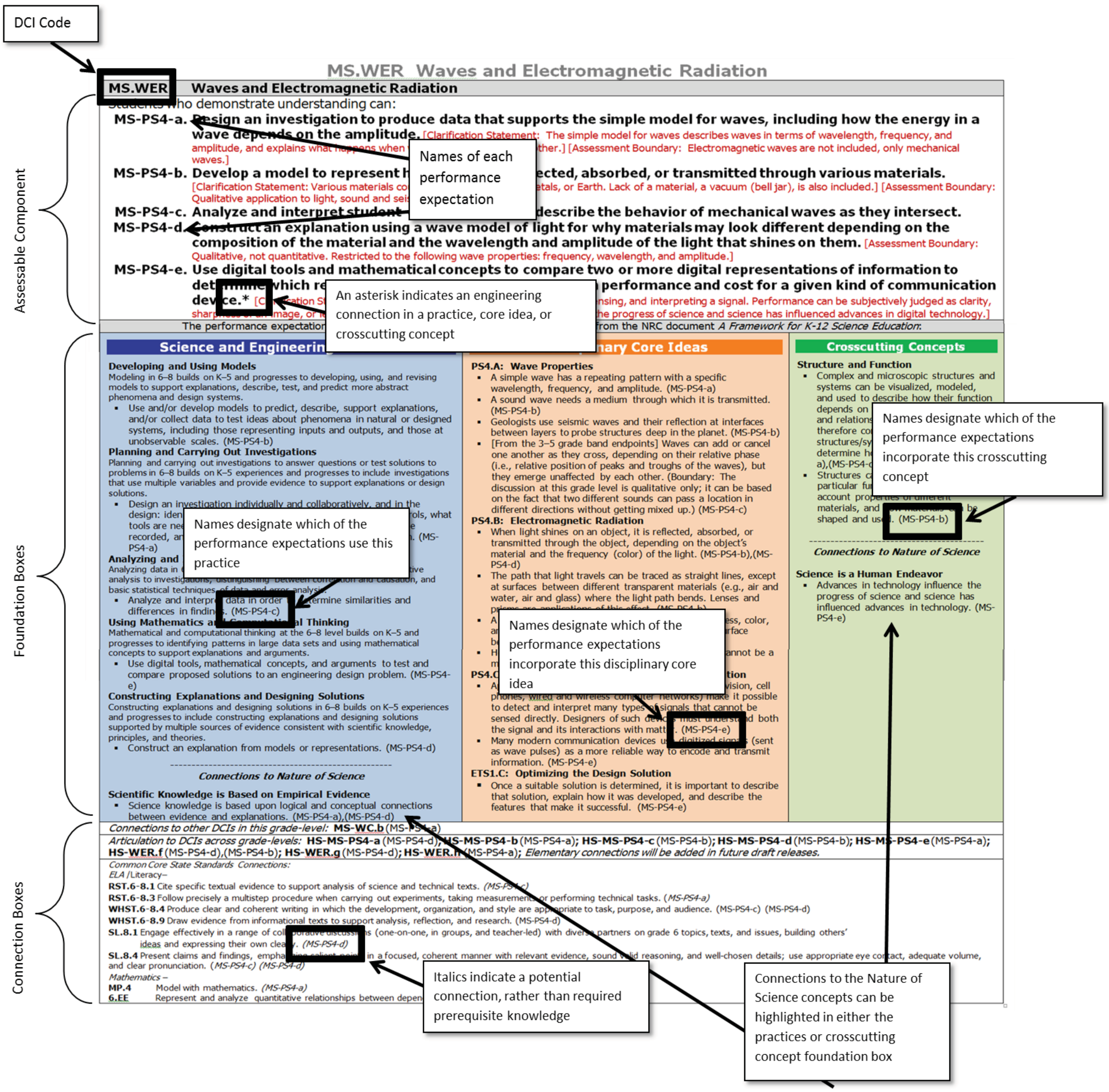


Figure A.1: The architecture of a standard. The NGSS is designed with the web in mind and features of its online architecture make it easier to understand than this diagram might indicate.

Appendix

MS-ESS2 Earth's Systems (Middle School-Earth System Science 2)
Students who demonstrate understanding can:

MS-ESS2-1. ***Develop a model to describe*** ***<u>the cycling of</u>*** **Earth's materials and the flow of energy that drives this process.**

MS-ESS2-2. ***Construct an explanation based on evidence for how*** **geoscience processes have changed Earth's surface** ***<u>at varying time and spatial scales</u>*****.**

MS-ESS2-3. ***Analyze and interpret data*** ***<u>on the distribution</u>*** **of fossils and rocks, continental shapes, and seafloor structures** ***<u>to provide evidence</u>*** **of the past plate motions.**

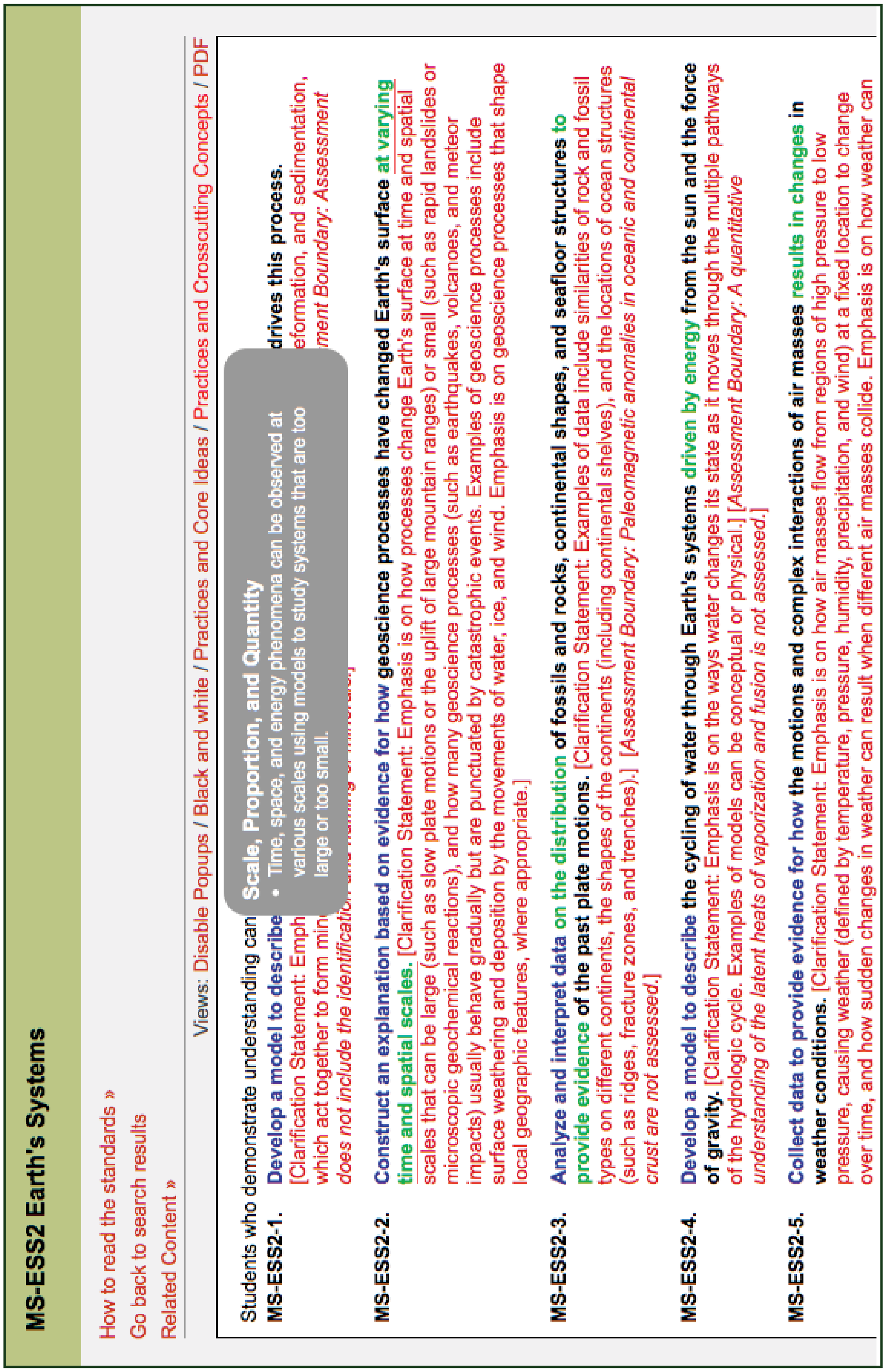
MS-ESS2-4. ***Develop a model to describe*** **the cycling of water through Earth's systems** ***<u>driven by energy</u>*** **from the sun and the force of gravity.**

MS-ESS2-5. ***Collect data to provide evidence for how*** **the motions and complex interactions of air masses** ***<u>results in changes</u>*** **in weather conditions.**

MS-ESS2-6. ***Develop and use a*** ***<u>model to describe how</u>*** **unequal heating and rotation of the Earth cause patterns of** ***<u>atmospheric and oceanic circulation that determine</u>*** **regional climates.**

Each of the six above Performance Expectations (PEs) incorporates aspects of each of the three dimensions. The color-coding helps to reveal some of that. "Science and Engineering Practices" are shown in blue (***italics*** here) and Crosscutting Concepts are shown in green (***<u>underlined italics</u>*** here). Disciplinary Core Ideas are in black. This is one of the color-coding options in the online presentation. Pop-ups (which can be disabled) appear when the different colored parts of the PE are scrolled over with the mouse. *Figure A.2* is a screen grab of the first three PEs for ESS2, with a pop-up showing the Crosscutting Concepts related to "MS-ESS2-2."

All of these Performance Expectations directly aligns with "*Why does this place look the way it does?*" We'll take a closer look at MS-ESS2-2, which addresses how geoscience processes have shaped the Earth's surface at varying time and spatial scales. This Guide coupled with the development of a VFE of a site local to your school, provides rich opportunities for addressing both this particular PE, along with all of the others within this standard. The Clarification Statements often provide helpful examples, and Assessment Boundaries indicate what will not be addressed in the assessments now under development. Importantly, this is not an indication that these topics are out of bounds. These standards represent minimum expectations—exceeding these expectations is often appropriate.


MS-ESS2 Earth's Systems

How to read the standards »
Go back to search results
Related Content »

Views: Disable Popups / Black and white / Practices and Core Ideas / Practices and Crosscutting Concepts / PDF

Students who demonstrate understanding can

MS-ESS2-1. **Develop a model to describe** ... **drives this process.** [Clarification Statement: Emph... eformation, and sedimentation, which act together to form min... *ment Boundary: Assessment does not include the identificatio...*

Scale, Proportion, and Quantity
- Time, space, and energy phenomena can be observed at various scales using models to study systems that are too large or too small.

MS-ESS2-2. **Construct an explanation based on evidence for how geoscience processes have changed Earth's surface at varying time and spatial scales.** [Clarification Statement: Emphasis is on how processes change Earth's surface at time and spatial scales that can be large (such as slow plate motions or the uplift of large mountain ranges) or small (such as rapid landslides or microscopic geochemical reactions), and how many geoscience processes (such as earthquakes, volcanoes, and meteor impacts) usually behave gradually but are punctuated by catastrophic events. Examples of geoscience processes include surface weathering and deposition by the movements of water, ice, and wind. Emphasis is on geoscience processes that shape local geographic features, where appropriate.]

MS-ESS2-3. **Analyze and interpret data on the distribution of fossils and rocks, continental shapes, and seafloor structures to provide evidence of the past plate motions.** [Clarification Statement: Examples of data include similarities of rock and fossil types on different continents, the shapes of the continents (including continental shelves), and the locations of ocean structures (such as ridges, fracture zones, and trenches).] [*Assessment Boundary: Paleomagnetic anomalies in oceanic and continental crust are not assessed.*]

MS-ESS2-4. **Develop a model to describe the cycling of water through Earth's systems driven by energy from the sun and the force of gravity.** [Clarification Statement: Emphasis is on the ways water changes its state as it moves through the multiple pathways of the hydrologic cycle. Examples of models can be conceptual or physical.] [*Assessment Boundary: A quantitative understanding of the latent heats of vaporization and fusion is not assessed.*]

MS-ESS2-5. **Collect data to provide evidence for how the motions and complex interactions of air masses results in changes in weather conditions.** [Clarification Statement: Emphasis is on how air masses flow from regions of high pressure to low pressure, causing weather (defined by temperature, pressure, humidity, precipitation, and wind) at a fixed location to change over time, and how sudden changes in weather can result when different air masses collide. Emphasis is on how weather can

Figure A.2: A screen-grab of part of the middle school standard on Earth Systems: MS-ESS2. Shown here are the first three PEs, with the first partially obscured by a pop-up related to the CC in the second.

Figure A.2 only shows a piece of the standard—only the first few Performance Expectations. Like the example in the previous section, this PE also includes Foundation Boxes, which highlight what pieces of each of the three dimensions is addressed in the standard and Connection Boxes, which highlight connections to other disciplines and grade levels. Drawing these connections is important in helping fortify understandings of both the particular content and how that content is contextualized in broader human and natural systems.

Resources

Following are some of the most commonly used and cited publications on science education standards and benchmarks.

AAAS, 1993, *Benchmarks for Science Literacy*, Oxford University Press. (AAAS is American Association for Advance of Science.)
Available online at http://www.project2061.org/publications/bsl/.

Bransford, J.D., Brown, A.L., and Cocking, R.R. (eds), 2000, *How People Learn: Brain, Mind, Experience, and School: Expanded Edition*, National Academies Press: Washington, DC.
Available online at http://www.nap.edu/openbook.php?record_id=9853.

Common Core State Standards Initiative. (While not focused on science education directly, standards on math and non-fiction reading impact are importantly related.)
http://www.corestandards.org.

NCSE, 2013, *Evolution and climate change in the NGSS*, National Center for Science Education.
http://ncse.com/news/2013/04/evolution-climate-change-ngss-0014800.

NGSS@NSTA website, National Science Teacher Association, http://ngss.nsta.org/.

NRC, 1996, *National Science Education Standards*. National Academies Press: Washington, DC. (NRC is National Research Council, and body of the National Academy of Sciences)
Available online at http://www.nap.edu/openbook.php?record_id=4962.

NRC, 2011, *Successful K-12 STEM Education: Identifying Effective Approaches in Science, Technology, Engineering, and Mathematics*. National Academies Press: Washington, DC.
Available online at http://www.nap.edu/openbook.php?record_id=13158.

NRC, 2012, *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*, National Academies Press: Washington, DC.
Available at http://www.nap.edu/openbook.php?record_id=13165.

NRC, 2013, *Next Generation Science Standards: For States, By States*. National Academies Press: Washington, DC.
Available online at http://www.nextgenscience.org/.

Wysession, M., 2013, The Next Generation Science Standards and the Earth and Space Sciences, *The Science Teacher*, April/May issue. (Duggan-Haas, author of this Appendix, worked with Wysession on NRC's Conceptual Framework for New Science Education Standards.)
Available at http://nstahosted.org/pdfs/ngss/resources/201304_NGSS-Wysession.pdf.

a

Glossary

acid rain	rain or other precipitation that contains high amounts of sulfuric and nitric acid. It occurs when sulfur dioxide and nitrogen oxide react with water, oxygen, and other chemicals in the atmosphere to form these acidic compounds. Acid rain can cause damage to trees, soils, and entire ecosystems, as well as accelerating the decay of human works such as paint and building materials.
active plate boundary	the boundary between two plates of the Earth's crust that are colliding, pulling apart, or moving past each other. See also: convergent boundary, subduction, transform boundary
aeolian	pertaining to, caused by, or carried by the wind. Aeolian sediments are often polished, giving them a "frosty" appearance. The name comes from Aeolus, the Greek god of wind. See also: wind
aerosol	tiny solid or liquid particles in the air. Examples include dust, smoke, mist, and human-made substances such as particles emitted from factories and cars.
agate	a crystalline silicate rock with a colorful banded pattern. It is a variety of chalcedony. Agates usually occur as nodules in volcanic rock. See also: chalcedony, nodule, silica, volcanic
Alfisols	a soil order; these are highly fertile and productive agricultural soils in which clays often accumulate below the surface. They are found in humid and subhumid climates. See also: climate, soil, soil orders
alluvial, alluvium	a thick layer of river-deposited sediment.

amniotes	the group of tetrapods distinguished from amphibians by the development of an egg capable of maturing entirely out of water. Amniotes include the reptiles, birds, and mammals.
amphibole	a group of dark colored silicate minerals, or either igneous or metamorphic origin. See also: igneous rock, mineral, metamorphism, silica
anthracite	a dense, shiny coal that has a high carbon content and little volatile matter. Anthracite is as much as 95% carbon. Found in deformed rocks, anthracite is the cleanest burning of the three types of coal, because it contains the highest amount of pure carbon. See also: coal
anthropogenic	caused or created by human activity.
Appalachian Basin	an inland basin, formed by the Taconic and Acadian mountain-building events. The crust was downwarped as a result of the colliding plates, and the basin was later filled with an inland sea. See also: crust, inland basin, inland sea, plate tectonics
aquifer	a water-bearing formation of gravel, permeable rock, or sand that is capable of providing water, in usable quantities, to springs or wells. See also: permeable
Archean	a geologic time period that extends from 4 billion to 2.5 billion years ago. It is part of the Precambrian. See also: geologic time scale, Precambrian

Glossary

arthropod	an invertebrate animal, belonging to the Phylum Arthropoda, and posessing an external skeleton (exoskeleton), body segments, and jointed appendages. Arthropods include crustaceans, arachnids, and insects, and there are over a million described arthropod species living today. Trilobites are a major group of extinct arthropods. See also: extinction, trilobite
asthenosphere	a thin semifluid layer of the Earth, below the outer rigid lithosphere, forming the upper part of the mantle. The heat and pressure created by the overlying lithosphere make the solid rock of the asthenosphere bend and move like metal when heated. The layer is thought to flow vertically and horizontally with circular convection currents, enabling sections of lithosphere to subside, rise, and undergo lateral movement. See also convection, lithosphere, mantle.
atmosphere	a layer of gases surrounding a planet. Earth's atmosphere protects living organisms from damage by solar ultraviolet radiation, and it is mostly composed of nitrogen. Oxygen is used by most organisms for respiration. Carbon dioxide is used by plants, algae and cyanobacteria for photosynthesis.
Baltica	a late-Proterozoic, early-Paleozoic continent that included ancient Europe (northern Europe without Ireland and Scotland). Baltica began moving towards North America in the Ordovician, starting the Taconic Orogeny. North America fully collided with Baltica in the Devonian, resulting in the Acadian Orogeny on the eastern edge of the continent. See also: orogeny, Paleozoic, Proterozoic

banded iron formation	rocks with regular, alternating thin layers of iron oxides (e.g., hematite and magnetite) and either shale or silicate minerals (e.g. chert, jasper, and agate). They are a primary source of iron ore. See also: agate, chert, jasper, hematite, iron, magnetite, ore, shale
basalt	an extrusive igneous rock, and the most common rock type on the surface of the Earth. It forms the upper surface of all oceanic plates, and is the principal rock of ocean/seafloor ridges, oceanic islands, and high-volume continental eruptions. Basalt is fine-grained and mostly dark-colored, although it often weathers to reds and browns because of its high iron content. Basaltic magmas are produced by partial melting of the upper mantle. Materials melt when we increase their temperature, but a second way to melt a solid is to decrease the pressure. In the interior of the Earth this second mechanism – decompression – is far more important. When pressure on the mantle is released as it is forced up through the crust due to subduction, it becomes basaltic magma. See also: igneous, iron, magma, mantle, plate tectonics
basement rocks	the foundation that underlies the surface geology of an area, generally composed of igneous or metamorphic crystalline rock. In certain areas, basement rock is exposed at the surface because of uplift or erosion. See also: erosion, igneous rock, metamorphic rock, uplift
bentonite	a clay, formed from decomposed volcanic ash, with a high content of the mineral montmorillonite. See also clay, mineral.

b

Glossary

biodiversity	the number of kinds of organisms at any given time and place. Global changes in biodiversity through geologic time tells paleontologists that something is happening to the rate of extinction or the rate of origin of new species. Regional changes are influenced by migration, or the number of species supported by available food and space resources. See also: extinction, geologic time scale
biofuel	carbon-based fuel produced from renewable sources of biomass like plants and garbage. Energy is obtained through combustion, so greenhouse gases are still produced. Because plants get their carbon from the air, burning them for energy and re-releasing it into the air has less effect on climate than fossil fuels, whose carbon is otherwise sequestered away from the atmosphere. See also: biomass, fuel
biomass	organic material from one or more organisms.
biostratigraphy	the use of fossils to determine relative age of sedimentary layers in geology.
biota	the organisms living in a given region, including plants, animals, fungi, protists, and bacteria.
bitumen	any of various flammable mixtures of hydrocarbons and other substances, occurring naturally or obtained by distillation from coal or petroleum, that are a component of asphalt and tar and are used for surfacing roads and for waterproofing. See also: coal, petroleum
bituminous coal	a relatively soft coal containing a tarlike substance called bitumen, which is usually formed as a result of high pressure on lignite. See also bitumen, coal, lignite.

bivalve	a marine or freshwater invertebrate animal belonging to the Class Bivalvia (or Pelecypoda) in the Phylum Mollusca. Bivalves are generally called “clams,” but they also include scallops, mussels, cockles, and oysters. Bivalves are characterized by right and left calcareous shells (valves) joined by a hinge. Most are filter feeders, collecting food particles from the water with their gills. During the Paleozoic, bivalves lived mostly on the surface of the ocean floor. In the Mesozoic, bivalves became extremely diverse and some evolved the ability to burrow into ocean floor sediments. See also: filter feeder, Mesozoic, mollusc, Paleozoic
body fossils	fossils that consist of an actual part of an organism, such as a bone, shell, or leaf. See also: fossil

Glossary

brachiopod	a marine invertebrate animal belonging to the Phylum Brachiopoda, and characterized by upper and lower calcareous shell valves joined by a hinge, and a crown of tentacles (lophophore) used for filter-feeding and respiration. Brachiopods are the most common fossil in Paleozoic sedimentary rocks. Brachiopods look somewhat similar to the clams that you find at the beach today. Brachiopods and bivalves both have a pair of hinged shells (valves) to protect themselves while feeding. However, the soft parts of modern brachiopods tell us that they are completely unrelated to bivalves. Brachiopods have a special structure formed by tissue with thousands of tiny hair-like tentacles stretched along a coiled piece of internal shell material. These tentacles catch and move small particles towards the mouth. This body plan is very different from that of bivalves, which have a larger fleshy body and collect particles with their gills. To tell the difference between a brachiopod and a bivalve, look for symmetry on the surface of the shell. Bivalve valves are of equal size and mirror image shapes. Brachiopods' bottom valves, however, are slightly bigger and often have a different shape. See also: filter feeder, bivalve, fossil, Paleozoic
braided stream	a stream consisting of multiple, small, shallow channels that divide and recombine numerous times, forming a pattern resembling strands of braided hair. A braided stream carries more sediment than a typical stream, causing the formation of sandbars and a network of crisscrossing streams.
brine	See hydrothermal solution

British Thermal Unit (BTU or Btu)	the most commonly used unit for heat energy. One Btu is approximately the amount of heat required to raise one pound of water by one degree Fahrenheit. A Btu is also about the amount of energy released by burning a single wooden match. See also: energy, heat
bryozoan	a marine or freshwater, colonial invertebrate animal belonging to the Phylum Bryozoa, and characterized by an encrusting or branching calcareous skeleton from which multiple individuals (zooids) extend from small pores to filter-feed using crowns of tentacles (lophophores). Bryozoans have a long and exemplary fossil record. One of the more common Paleozoic varieties looks like fine mesh cloth with numerous tiny holes in which the individual animals in the colony lived. Although they function somewhat like coral, and are often found in similar environments, bryozoans are more closely related to brachiopods. See also brachiopod, fossil
calcite	a carbonate mineral, consisting of calcium carbonate ($CaCO_3$). Calcite is a common constituent of sedimentary rocks, particularly limestone. See also: carbonate rocks, limestone, mineral, sedimentary rock
calyx	the head of a crinoid. See also: crinoid
Cambrian	a geologic time period lasting from 541 to 485 million years ago. During the Cambrian, multicellular marine organisms became increasingly diverse, as did their mineralized fossils. The Cambrian is part of the Paleozoic Era. See also: fossils, geologic time scale, Paleozoic

Glossary

Canadian Shield	the stable core of the North American continental landmass, containing some of the oldest rocks on Earth. The shield has experienced very little tectonic activity (faulting or folding) for millions of years. As the stable cores of all continents, shields are often covered by layers of younger material.
capstone, caprock	a harder, more resistant rock type that overlies a softer, less resistant rock. The harder rock typically helps to control the rate of erosion. See also: erosion
carbonate rocks	rocks formed by accumulation of calcium carbonate, often made of the skeletons of aquatic organisms such as corals, clams, snails, bryozoans, and brachiopods. These organisms thrive in warm, clear shallow waters common to tropical areas, therefore modern carbonate rocks are observed forming in places such as the Florida Keys and the Bahamas. They are also one of the dominant rock forms of the bottom of the ocean, where sediments form from the skeletons of planktonic organisms such as foraminifera. Carbonate rocks include limestone and dolostone. See also: brachiopod, bryozoan, dolostone, foraminifera, limestone
Carboniferous	a geologic time period that extends from 359 to 299 million years ago. It is divided into two subperiods, the Mississippian and the Pennsylvanian. By the Carboniferous, terrestrial life had become well established. The name Carboniferous means "coal-bearing," and it is during this time that many of today's coal beds were formed. The Carboniferous is part of the Paleozoic. See also: coal, geologic time scale, Mississippian, Pennsylvanian, Paleozoic

Cenozoic	the geologic time period spanning from 66 million years ago to the present. The Cenozoic is also known as the age of mammals, since extinction of the large reptiles at the end of the Mesozoic allowed mammals to diversify. The Cenozoic includes the Paleogene, Neogene, and Quaternary periods. See also: geologic time scale, Mesozoic, Neogene, Paleogene, Quaternary
cephalopod	a marine invertebrate animal belonging to the Class Cephalopoda in the Phylum Mollusca, and characterized by a prominent head, arms and tentacles with suckers, and jet propulsion locomotion. Cephalopods are swimming predators with beak-shaped mouthparts. The shells of cephalopods range from long straight cones to spirals, but some have internal shells or no significant shell at all, like the octopus. The group includes belemnites, ammonoids, nautilus, squid, and octopuses. A mass extinction between the Cretaceous and Paleogene eliminated many varieties of cephalopods. See also: Cretaceous, mass extinction, Paleogene
chalcedony	a crystalline silicate mineral that occurs in a wide range of varieties. See also: mineral, silica
chalk	a soft, fine-grained, easily pulverized, white-to-grayish variety of limestone, composed of the shells of minute planktonic single-celled algae. See also: limestone

Glossary

chemical fossils	chemicals produced by an organism that leave behind an identifiable record in the geologic record. Chemical fossils provide some of the oldest evidence for life on Earth. See also: fossil
chemical reaction	a process that involves changes in the structure and energy content of atoms, molecules, or ions but not their nuclei. See also: energy
chert	a sedimentary rock composed of microcrystaline quartz. It is often found as nodules or concretions in limestone and other marine sedimentary rocks. As these rocks form, water moving through them transports small amounts of silicon dioxide that accumulate into clumps of microscopic crystals. The resulting rocks are extremely hard and have no planes of weakness. For thousands of years, humans exploited these qualities, breaking chert nodules into blades and other tools See also: concretion, nodule, sedimentary rock, silica, quartz
chlorastrolite	a variety of pumpellyite with a distinctive “turtleback” pattern created by its interlocking green crystals. See also: pumpellyite
Cincinnati Arch	an uplifted region that existed between the Illinois Basin, the Michigan Basin, and the Appalachian Basin during the late Ordovician and Devonian. It stretched from southeastern Ontario all the way to northern Alabama. See also: Appalachian Basin, Devonian, Illinois Basin, Michigan Basin, Ordovician, uplift
clasper	an anatomical structure used by sharks for mating. See also: shark

clay	the common name for a number of very fine-grained, earthy materials that become plastic (flow or change shape) when wet. Chemically, clays are hydrous aluminum silicates. See also: silica
cleavage	a physical property of minerals. Cleavage occurs when a mineral breaks in a characteristic way along a specific plane of weakness. Mica and graphite have very strong cleavage, allowing them to easily break into thin sheets See also: graphite, mica, mineral
climate	a description of the average temperature, range of temperature, humidity, precipitation, and other atmospheric/ hydrospheric conditions a region experiences over a period of many years (usually more than 30). These factors interact with and are influenced by other parts of the Earth system, including geology, geography, insolation, currents, and living things. The climate of a region represents the average weather over a long period of time. See also: weather
climate change	See global warming
coal	a combustible, compact black or dark-brown carbonaceous rock formed by the compaction of layers of partially decomposed vegetation. By far the greatest abundance of coal is located in strata of Carboniferous age. See also: Carboniferous

C

Glossary

cold front	the boundary between the warm air and the cold air moving into a region. At this boundary, denser, colder air moves in, making the less dense, warm air rise. This displaced warm air cools as it rises because air pressure decreases with increasing height in the atmosphere. As the air cools, it becomes saturated with water vapor, and condensation begins to occur, eventually leading to dramatic rainstorms.
color (mineral)	a physical property of minerals. Color is determined by the presence and intensity of certain elements within the mineral. See also: mineral
color (soil)	a physical property of soils. Soil color is influenced by mineral content, the amount of organic material, and the amount of water it routinely holds. These colors are identified by a standard soil color chart called the Munsell chart. See also: soil
commodity	a good for which there is demand, but which is treated as equivalent across all markets, no matter who produces it.
compression, compressional force	a force acting on an object from all or most directions, resulting in compression (flattening or squeezing). Compressional forces occur by pushing objects together.
concretion	a hard, compact mass, usually of spherical or oval shape, found in sedimentary rock or soil. Concretions form when minerals precipitate around a particulate nucleus within the sediment. See also: mineral, sedimentary rock, soil

conglomerate	a sedimentary rock composed of multiple large and rounded fragments that have been cemented together in a fine-grained matrix. The fragments that make up a conglomeerate must be larger than grains of sand. See also: sand, matrix, sedimentary rock
conifer	a woody plant of the division Coniferophyta. Conifers bear cones that contain their seeds.
Conservation of Energy	a principle stating that energy is neither created nor destroyed, but can be altered from one form to another. See also: energy
contact metamorphism	a metamorphic rock that has been altered by direct contact with magma. Changes that occur due to contact metamorphism are greatest at the point of contact. The further away the rock is from the point of contact, the less pronounced the change. See also: magma, metamorphism
convection	the rise of buoyant material and the sinking of denser material. In the mantle, variations in density are commonly caused by the melting of subducting materials. See also: mantle, subduction
convergent boundary	an active plate boundary where two tectonic plates are colliding with one another. Subduction occurs when an oceanic plate collides with a continental plate or another oceanic plate. If two continental plates collide, mountain building occurs. See also: active plate boundary, plate tectonics, subduction
copper	a ductile, malleable, reddish-brown metallic element (Cu). Copper is used extensively as wiring in the electrical industry as well as in alloys such as brass and bronze.

Glossary

craton	the old, underlying portion of a continent that is geologically stable relative to surrounding areas. The portion of a craton exposed at the surface is termed a shield, while that overlain by younger layers is often referred to as a platform. A craton can be thought of as the heart of a continent—it is typically the oldest, thickest, and most stable part of the bedrock. It is also usually far from the margins of tectonic plates, where new rock is formed and old destroyed. This rock has usually been metamorphosed at some point during its history, making it resistant to erosion. See also: metamorphism
Cretaceous	a geologic time period spanning from 144 to 66 million years ago. It is the youngest period of the Mesozoic. The end of the Cretaceous bore witness to the mass extinction event that resulted in the demise of the dinosaurs. "Cretaceous" is derived from the Latin word, “creta” or “chalk.” The white (chalk) cliffs of Dover on the southeastern coast of England are a famous example of Cretaceous chalk deposits. See also: chalk, geologic time scale, mass extinction, Mesozoic
crevasse	a deep crack in an ice sheet or glacier, which forms as a result of shear stress between different sections of the moving ice. See also: glacier, ice sheet

crinoid	a marine invertebrate animal belonging to the Class Crinoidea of the Phylum Echinodermata, and characterized by a head (*calyx*) with a mouth on the top surface surrounded by feeding arms. Several groups of stemmed echinoderms appeared in the early Paleozoic, including crinoids, blastoids, and cystoids. Crinoids have 5-fold symmetry and feathery arms (sometimes held off the sea floor on a stem) that collect organic particles from the water. The stems, the most often preserved part, are made of a series of stacked discs. Upon death, these stems often fall apart and the individual discs are preserved separately in the rock. The crinoid's feathery arms make it look something like a flower on a stem. Thus, crinoids are commonly called “sea lilies,” although they are animals, not plants. See also: echinoderm
cross-bedding	layering within a bed in a series of rock strata that does not run parallel to the plane of stratification. Cross-beds form as flowing water or wind pushes sediment downcurrent, creating thin beds that slope gently in the direction of the flow as migrating ripples. The downstream slope of the ripple may be preserved as a thin layer dipping in the direction of the current, across the natural flat-lying repose of the beds. Another migrating ripple will form an additional layer on top of the previous one.

Glossary

crust	the uppermost, rigid outer layer of the Earth, composed of tectonic plates. Two types of crust make up the lithosphere. Oceanic crust is denser but significantly thinner than continental crust, while continental crust is much thicker but less dense (and therefore buoyant). When continental crust collides with oceanic crust, the denser oceanic crust will be dragged (subducted) under the buoyant continental crust. Although mountains are created by these oceanic/continental crust collisions due to the compression of the two plates, much taller ranges are produced by continental/continental collisions. When two buoyant continental crusts collide, there is nowhere for the crust to go but up! The modern Himalayas, at the collision site of the Asian and Indian plates, are a good example of very tall mountains formed by a collision between two continental crusts. See also: active plate boundary, compression, lithosphere, subduction
Cryogenian	a geologic period lasting from 850 to 635 million years ago, during the Precambrian. During this period, the Earth was subject to a 200-million-year-long ice age. See also: ice age, Precambrian
crystal form	a physical property of minerals, describing the shape of the mineral's crystal structure (not to be confused with cleavage). A mineral might be cubic, rhomboidal, hexagonal, or polyhedral. See also: cleavage, mineral
cyanobacteria	a group of bacteria, also called "blue-green algae," that obtain their energy through photosynthesis.
cyclothem	alternating sequences of marine and non-marine sedimentary rocks, usually including coal, and characterized by their light and dark colors. See also: coal

degrade (energy)	the transformation of energy into a form in which it is less available for doing work, such as heat. See also: energy
density	a physical property of minerals, describing the mineral's mass per volume. See also: mineral
derecho	a set of powerful straight-line winds that exceed 94 kph (58 mph) and can often approach 160 kph (100 mph). These powerful windstorms can travel over 400 kilometers (250 miles) and cause substantial wind damage, knocking down trees and causing widespread power outages. The lightning associated with these intense storms can cause both forest fires and house fires. *Derecho* is the Spanish word for "straight ahead." See also: wind
Devonian	a geologic time period spanning from 419 to 359 million years ago. The Devonian is also called the "age of fishes" due to the diversity of fish that radiated during this time. On land, seed-bearing plants appeared and terrestrial arthropods became established. The Devonian is part of the Paleozoic. See also: geologic time scale, Paleozoic
diamond	a mineral form of carbon, with the highest hardness of any material. Most natural diamonds are formed at high temperature and pressure deep in the Earth's mantle. See also: hardness, mantle, mineral

Glossary

dinosaurs	a group of terrestrial reptiles with a common ancestor and thus certain anatomical similarities, including long ankle bones and erect limbs. All of the large reptile groups , including the dinosaurs, disappeared at or before the mass extinction at the end of the Cretaceous. See also: Cretaceous, mass extinction
dolomite	a carbonate mineral, consisting of calcium magnesium carbonate ($CaMg(CO_3)_2$). Dolomite is an important reservoir rock for petroleum, and also commonly hosts large ore deposits. See also: mineral, ore, petroleum
dolostone	a rock (also known as dolomitic limestone and once called magnesian limestone) primarily composed of dolomite, a carbonate mineral. It is normally formed when magnesium bonds with calcium carbonate in limestone, forming dolomite. See also: dolomite, limestone
double refraction	the result of light passing through a material that splits it into two polarized sets of rays, doubling images viewed through that material. For example, a single line on a sheet of paper will appear as two parallel lines when viewed through a clear calcite crystal. See also: calcite, mineral

Driftless Area	a region that did not experience glaciation, located in parts of southwestern Wisconsin, eastern Minnesota, and northeastern Illinois and Iowa. This region is known as the Driftless Area since it lacks glacial deposits, which are collectively called drift. Glaciers are known to have reached all sides of the Driftless Area at various times throughout the Quaternary Ice Age, but are not known to have completely encompassed the area at any time. The Driftless Area is also called the Paleozoic Plateau. See also: glacier, ice age
drumlin	a teardrop-shaped hill of till that was trapped beneath a glacier and streamlined in the direction of the flow of the ice moving over it. The elongation of a drumlin is an excellent clue to the direction of flow during an ice sheet's most recent advance. See also: glacier, till
dynamic metamorphism	See regional metamorphism
earthquake	a sudden release of energy in the Earth's crust that creates seismic waves. Earthquakes are common at active plate boundaries. See also: active plate boundary, seismic waves
echinoderms	members of the Phylum Echinodermata, which includes starfish, sea urchins, and crinoids. Echinoderms have radial symmetry (which is usually five-fold), and a remarable ability to regenerate lost body parts, See also: crinoid
edrioasteroids	an extinct class of echinoderm that had a simple, cushion-shaped body and five arms. See also: echinoderm

Glossary

effervesce	to foam or fizz while releasing gas. Carbonate minerals will effervesce when exposed to hydrochloric acid. See also: carbonate rock, mineral
efficiency	the use of a relatively small amount of energy for a given task, purpose, or service; achieving a specific output with less energy input. See also: energy
energy	the power derived from the use of physical or chemical resources. Everything we do depends upon energy - without it there would be no civilization, no sunlight, no food and no life. Energy moves people and goods, produces electricity, heats our homes and businesses, and is used in manufacturing and other industrial processes.
energy carrier	a source of energy, such as electricity, that has been subject to human-induced energy transfers or transformations. See also: energy
Entisols	a soil order; these are soils of relatively recent origin with little or no horizon development. They are commonly found in areas where erosion or deposition rates outstrip rates of soil development, such as floodplains, mountains, and badland areas. See also: erosion, horizon, soil, soil orders

erosion	the transport of weathered materials. Rocks are worn down and broken apart into finer grains by wind, rivers, wave action, freezing and thawing, and chemical breakdown. Over millions of years, weathering and erosion can reduce a mighty mountain range to low rolling hills. Some rocks wear down relatively quickly, while others can withstand the power of erosion for much longer. Softer, weaker rocks such as shale and poorly cemented sandstone and limestone are much more easily worn than hard, crystalline igneous and metamorphic rocks, or well-cemented sandstone and limestone. Harder rocks are often left standing as ridges because the surrounding softer, less resistant rocks were more quickly worn away. See also: igneous rock, metamorphic rock, sedimentary rock, weathering
erratic, glacial erratic	a piece of rock that differs from the type of rock native to the area in which it rests, carried there by glaciers often over long distances. Erratics are often distinctive because they are a different type of rock than the bedrock in the area to which they've been transported. For example, boulders and pebbles of igneous and metamorphic rocks are often found in areas where the bedrock is sedimentary; it is sometimes possible to locate the origin of an erratic if its composition and textures are highly distinctive. See also: glacier, igneous rock, metamorphic rock, sedimentary rock

Glossary

esker	a sinuous, elongated ridge of sand and gravel. Most eskers formed within ice-walled tunnels carved by streams flowing beneath a glacier. After the ice melted away, the stream deposits remained as long winding ridges. Eskers are sometimes mined for their well-sorted sand and gravel. See also: glacier, gravel, sand
eukaryotes	organisms with complex cells containing a nucleus and organelles. Protists and all multicellular organisms are eukaryotes. See also: protist
evaporite	a sedimentary rock created by the precipitation of minerals directly from seawater, including gypsum, carbonate, and halite. See also carbonate, gypsum, mineral, sedimentary rock
extinction	the end of species or other taxonomic groups, marked by death of the last living individual. Paleontologists estimate that over 99% of all species that have ever existed are now extinct. The species of modern animals that we study in biology today represent less than 1% of what has lived throughout geologic time.
extrusion, extrusive rock	an igneous rock formed by the cooling of lava after magma escapes onto the surface of the Earth through volcanic craters and cracks in the Earth's crust. See also crust, igneous rocks, magma.
fault	a fracture in the Earth's crust in which the rock on one side of the fracture moves measurably in relation to the rock on the other side. See also: crust

feldspar	an extremely common, rock-forming mineral found in igneous, metamorphic and sedimentary rocks. There are two groups of feldspar: alkali feldspar (which ranges from potassium-rich to sodium-rich) and plagioclase feldspar (which ranges from sodium-rich to calcium-rich). Potassium feldspars of the alkali group are commonly seen as pink crystals in igneous and metamorphic rocks, or pink grains in sedimentary rocks. Plagioclase feldspars are more abundant than the alkali feldspars, ranging in color from light to dark. Feldspars are commercially used in ceramics and scouring powders. See also: igneous rock, metamorphic rock, mineral, sedimentary rock
felsic	igneous rocks with high silica content and low iron and magnesium content. They are light in color and are typically found in continental crust. See also: crust, igneous rock, iron, silica
filter feeder	an animal that feeds by passing water through a filtering structure that traps food. The water may then be expelled and the food digested. This strategy is employed by a wide range of animals today, from clams and krill to flamingos and whales.
firn	compacted glacial ice, formed by the weight of snow on top. Individual flakes break down by melting, refreezing, and bonding to the snow around them, eventually forming compacted grains. See also: glacier

Glossary

flint	a hard, high-quality form of chert that occurs mainly as nodules and masses in sedimentary rock. Due to its hardness and the fact that it splits into thin, sharp flakes, flint was often used to make tools during the Stone Age. Flint will also create sparks when struck against steel, and has been used to ignite gunpowder in more modern times. See also: chert, sedimentary rock, nodule
floodplain	the land around a river that is prone to flooding. This area can be grassy, but the sediments under the surface are usually deposits from previous floods.
fluorite, fluorspar	the mineral form of calcium fluoride (CaF_2). Fluorite is used in a variety of commercial applications, including as lenses for microscopes, the production of some glass, and the chemical industry. Fluorite lent its name to the phenomenon of fluorescence, which occurs in some fluorites due to impurities in the crystal. See also: mineral
fluvial	See outwash plain
foliation	the arrangement of the constituents of a rock in leaflike layers, as in schists. During metamorphism, the weight of overlying rock can cause minerals to realign perpendicularly to the direction of pressure, layering them in a banded pattern. See also: metamorphism, schist
foraminifera	a class of aquatic protists that possess a calcareous or siliceous exoskeleton. Foraminifera have an extensive fossil record. See also: protist

fossil	preserved evidence of ancient life, including, for example, preserved skeletal or tissue material, molds or casts, and traces of behavior. Fossilization may alter biological material in a variety of ways, including permineralization, replacement, and compression. Remains are often classified as fossils when they are older than 10,000 years, the traditional start of the Holocene (recent) epoch. However, this date is only a practical guideline - scientists studying successions of plant or animal remains would not recognize any sudden change in the material at 10,000 years, and would typically refer to all material buried in sediments as fossil material. The word fossil is derived from the Latin word fossilis, meaning “dug up.” See also: compression, Holocene, permineralization, replacement
fossil fuels	fuel for human use that is made from the remains of ancient biomass, referring to any hydrocarbon fuel source formed by natural processes from anaerobically decomposed organisms, primarily coal, petroleum, and natural gas (methane). Fossil fuels are non-renewable, meaning that because they take thousands to millions of years to form, the rate of use is far greater than the rate of formation, and eventually we will run out. See also: biomass, coal, fuel, natural gas, petroleum
fracture	a physical property of minerals, formed when a mineral crystal breaks; also a crack in rocks, sometimes known as a joint. See also: mineral
frost wedging	weathering that occurs when water freezes and expands in cracks. See also: weathering

Glossary

fuel	a material substance that possesses internal energy that can be transferred to the surroundings for specific uses—included are petroleum, coal, and natural gas (the fossil fuels), and other materials, such as uranium, hydrogen, and biofuels. See also: biofuel, coal, energy, fossil fuel, natural gas, petroleum
gabbro	a usually coarse-grained, mafic and intrusive igneous rock. Most oceanic crust contains gabbro. See also: crust, igneous rock, intrusion, mafic
galena	an abundant sulfide mineral with cubic crystals. It is the most important ore of lead, as well as an important source of silver. See also: lead, mineral, ore, silver, sulfur
gastropod	a marine, freshwater, or terrestrial invertebrate animal belonging to the class Gastropoda of the phylum Mollusca, and characterized by a single, coiled, calcareous shell, a muscular foot for gliding, and internal asymmetry caused by an embryonic process (*torsion*). Gastropods include snails and slugs.
geode	a hollow, roughly spherical node of crystal that forms when minerals precipitate within hardened vesicles (gas bubbles) in volcanic rocks, or within dissolved nodules that leave openings within sedimentary rock. These geological structures occur in certain sedimentary and igneous rocks. See also: igneous rock, mineral, sedimentary rock, vesicular

geologic time scale	a standard timeline used to describe the age of rocks and fossils, and the events that formed them. It spans Earth's entire history, and is often subdivided into four major time periods: the Precambrian, Paleozoic, Mesozoic, and Cenozoic. See also: Cenozoic, Mesozoic, Paleozoic, Precambrian
glacier	a body of dense ice on land that does not melt away annually and has sufficient mass to move under its own weight. Glaciers form when snow accumulates faster than it melts over many years. As long as melt does not exceed accumulation, the ice and snow pile up and become a self-sustaining system. As glaciers slowly flow, they abrade and erode the landscape around them to create crevasses, moraines, and other distinguishing features. Glaciers form only on land, and are much thicker than ice that forms on the surface of water. 99% of Earth's glacial ice exists as vast polar ice sheets, but glaciers are also found high in the mountains of every continent except Australia. See also: crevasse, erosion, ice sheet, moraine
glassy rock	a volcanic rock that cooled almost instantaneously, resulting in a rock with tiny crystals or no crystals at all. Obsidian, tuff, and scoria are examples of glassy rocks. See also: igneous rock, obsidian, scoria, tuff, volcanic

g

Glossary

global warming	the current increase in the average temperature worldwide, caused by the buildup of greenhouse gases in the atmosphere. With the coming of the Industrial Age and exponential increases in human population, large amounts of gases have been released into the atmosphere (especially carbon dioxide) that give rise to global warming. The term "climate change" is preferred because warming contributes to other climatic changes such as precipitation and storm strength. See also: climate, greenhouse conditions, greenhouse gases
gneiss	a metamorphic rock that may form from granite or layered sedimentary rock such as sandstone or siltstone. Parallel bands of light and dark minerals give gneiss its striated texture. See also granite, metamorphic rock, mineral, sedimentary rock
gold	a soft, yellow, corrosion-resistant element (Au), which is the most malleable and ductile metal on Earth. Gold has an average abundance in the crust of only 0.004 parts per million. It can be profitably mined only where hydrothermal solutions have concentrated it. See also: crust, hydrothermal solution
Gondwana, Gondwanaland	the supercontinent of the Southern Hemisphere, composed of Africa, Australia, India, and South America. It combined with the North American continent to form Pangaea during the late Paleozoic. See also: Pangaea, Paleozoic
granite	a common and widely occurring type of igneous rock. Granite usually has a medium- to coarse-grained texture, and is at least 20% quartz by volume. See also: igneous

graphite	a mineral, and the most stable form of carbon. Graphite means "writing stone," a reference to its use as pencil lead. Graphite occurs in metamorphic rocks, igneous rocks, and meteorites. See also: igneous rock, metamorphic rock, mineral
graptolite	an extinct colonial invertebrate animal belonging to the Class Graptolithina of the Phylum Hemichordata, and characterized by individuals housed within a tubular or cup-like structure. The soft parts of a graptolite's body have never been clearly identified. See also: extinction
Great Lakes	the largest group of freshwater lakes on Earth (by total surface area and volume), located on the US-Canadian border, and consisting of Lakes Superior, Michigan, Huron, Erie, and Ontario. Prior to glaciation, the Great Lakes were river valleys that had been scoured and deepened repeatedly by the many ice advances during the Quaternary period. Many sizable glacial lakes were formed at the edge of the melting ice sheet that no longer exist today or have significantly shrunk in size. See also: ice sheet, Quaternary
greenhouse conditions	time periods when atmospheric greenhouse gas concentrations are high and global temperatures are elevated. Sea levels are generally higher and glaciers diminish during these conditions. See also: glacier, global warming, greenhouse gases

Glossary

greenhouse gas	a gas in the atmosphere that absorbs and emits heat. The primary greenhouse gases in the Earth's atmosphere are water vapor, carbon dioxide, methane, nitrous oxide, and ozone. See also: atmosphere, heat
gypsum	a soft sulfate mineral that is widely mined for its use as fertilizer and as a constituent of plaster. Alabaster, a fine-grained light colored variety of gypsum, has been used for sculpture making by many cultures since ancient times. See also: mineral, sulfur
halite	See salt
hardness	a physical property of minerals, specifying how hard the mineral is. Hardness helps us understand why some rocks are more or less resistant to weathering and erosion See also: erosion, mineral, Moh's Scale of Hardness, weathering
heat	the transfer of energy from one body to another as a result of a difference in temperature or a change in phase. Heat is transmitted through solids and fluids by conduction, through fluids by convection, and through empty space by radiation. See also: convection, energy
heat island effect	a phenomenon in which cities experience higher temperatures than surrounding rural communities do.

heat wave	a period of excessively hot weather that may also accompany high humidity. Temperatures of just 3°C (6°F) to 6°C (11°F) above normal are enough to reclassify a warm period as a heat wave. Under high humidity, the mechanism of sweating does little to cool people down because the humidity prevents sweat from evaporating and cooling off the skin. See also: weather
hematite	a mineral form of iron oxide (Fe_2O_3). The name hematite has its origins in the Greek word *haimatos*, meaning blood. It is very common in Precambrian banded iron formations. Iron from hematite is used in the manufacture of steel. The vivid red pigments that iron lends to the mineral also makes it valuable as a commercial pigment. See also: iron, Precambrian
Histosols	a soil order; these are organic-rich soils found along lake coastal areas where poor drainage creates conditions of slow decomposition and peat (or muck) accumulates. See also: peat, soil, soil orders
Holocene	the most recent portion of the Quaternary, beginning about 11,700 years ago and continuing to the present. It is the most recent (and current) interglacial, an interval of glacial retreat. The Holocene also encompasses the global growth and impact of the human species. See also: interglacial, Quaternary

h

Glossary

horizon (soil)	a layer in the soil, usually parallel to the surface, which has physical characteristcs (usually color and texture) that are different from the layers above and below it. Each type of soil usually contains three or four horizons. See also soil
hornblende	a dark silicate mineral that can occur in a variety of forms. Hornblende is a common constituent of many igneous and metamorphic rocks. See also: igneous rock, metamorphic rock
hot spot	a volcanic region thought to be fed by underlying mantle that is anomalously hot compared with the mantle elsewhere. Hot spots form from plumes of magma rising off the mantle. Magma from the hot spot pushes its way up through the crust, creating an igneous intrusion and sometimes a volcano. Although the hot spot remains fixed, the plates of the lithosphere continue to move above it. As a plate continues to move over the hot spot, the original volcano shifts off of the hot spot and a new intrusion or volcano is formed. This gradually produces a chain of volcanic islands such as the Hawaiian Islands. Erosion of volcanoes may eventually wear down the crust to reveal the igneous intrusions that formed the volcano's magma chamber. See also: crust, erosion, igneous rocks, intrusion, lithosphere, magma, mantle, volcanic islands
Huronian glaciation	a glaciation beginning about 2.4 billion years ago, that covered the entire surface of the Earth in ice for as long as 300 million years. See also: glacier, ice age

hurricane	a rapidly rotating storm system with heavy winds, a low-pressure center, and a spiral arrangement of thunderstorms. These storms tend to form over large, warm bodies of water. Once winds have reached 119 kph (74 mph), such a storm is classified as a hurricane. Hurricanes usually develop an eye, which is visible as a small, round, cloud-free area at the center of the storm. The eye is an area of relative calm and low atmospheric pressure. The strongest thunderstorms and winds circulate just outside the eye, in the eyewall. See also: wind
hydrothermal solution	hot, salty water moving through rocks.These solutions are always enriched in salts (such as sodium chloride, potassium chloride, and calcium chloride) and thus are called “brines.” The brine is as salty or even saltier than seawater. Salty water can contain minute amounts of dissolved minerals such as gold, lead, copper, and zinc. The presence of salt in the water suppresses the precipitation of the metallic minerals from the brine because the chlorides in the salt preferentially bond with metals. Additionally, because the brine is hot, minerals are more easily dissolved, just as hot tea dissolves sugar more easily than cold tea. See also: copper, gold, lead, mineral, salt, zinc
hyolith	animals with cone-shaped shells that existed throughout the Paleozoic. Their affinities to other animals are uncertain, with some scientists classifying them as mollusks and others placing them in their own phylum. See also: Paleozoic

Glossary

Iapetus Ocean	the proto-Atlantic Ocean, located against the eastern coast of North America's ancestral landmass before Pangaea formed. In Greek mythology, Iapetus was the father of Atlantis. See also: Pangaea
ice age	a period of global cooling of the Earth's surface and atmosphere, resulting in the presence or expansion of ice sheets and glaciers. Throughout the Earth's history, it has been periodically plunged into ice ages, dependent upon the climate and position of the continents. Over the past 2.6 million years, North America has experienced about 50 glacial advances and retreats. The most recent ice age ended about 12,000 years ago. See also: atmosphere, climate, ice sheet, glacier
ice dome	the spreading center of an ice sheet. Glacial ice flows outward from the ice dome, where snow continues to accumulate, like like the pouring of pancake batter onto a griddle. See also: glacier, ice sheet
ice sheet	a mass of glacial ice that covers part of a continent and has an area greater than 50,000 square kilometers (19,000 square miles). See also: glacier
ichthyosaurs	extinct Mesozoic marine reptiles that were probably similar in size and habitat to the toothed whales, dolphins, and large sharks of today. See also: extinction, Mesozoic

igneous rocks	rocks derived from the cooling of magma underground or molten lava on the Earth's surface. Igneous rocks differ not only in their cooling rates and subsequent crystal sizes, but also in their chemical compositions. Rocks found in continental crust, such as granite, have high silica content and low iron and magnesium content. They are light in color and are called felsic. Rocks found in oceanic crust, like basalt, are low in silica and high in iron and magnesium. They are dark in color and are called mafic. Although the composition of magma can be the same as lava, the texture of the rocks will be quite different due to different rates of cooling. It is because of this difference in genesis that geologists are able to make the distinction between extrusive and intrusive igneous rocks when encountered at an outcrop at the Earth's surface. See also: extrusion, felsic, intrusion, mafic, magma, lava
Illinoian glaciation	a period of glaciation that occurred during the Pleistocene, 191 to 131 thousand years ago. See also: glacier, Pleistocene
Illinois Basin	an inland basin centered in the state of Illinois, which formed when Baltica approached North America in the Ordovician. More than four billion barrels of petroleum have been extracted from the Illinois Basin. See also: inland basin, Ordovician, petroleum
Inceptisols	a soil order; these are soils that exhibit only moderate weathering and development. They are often found on steep (relatively young) topography and overlying erosion-resistant bedrock. See also: soil, soil orders, topography, weathering

Glossary

index fossil	a fossil used to determine the relative age of sedimentary deposits. An ideal index fossil lived during a short period of time, was geographically and environmentally widespread, and is easy to identify. Some of the most useful index fossils are hard-shelled organisms that were once part of the marine plankton. See also: fossil, sedimentary rock
inland basin	a depression located inland from the mountains, and formed by the buckling (downwarping) of the Earth's crust. Basins naturally preserve thick sediment layers because they accumulate eroded sediment and commonly continue to subside under the weight of the sediment. See also: crust
inland sea	a shallow sea covering the central area of a continent during periods of high sea level. An inland sea is located on continental crust, while other seas are located on oceanic crust. An inland sea may or may not be connected to the ocean. For example, Hudson Bay is on the North American plate and connects to the Atlantic and Arctic Oceans, while the Caspian Sea is on the European plate but does not drain into any ocean at all. See also: crust
interglacial	a period of geologic time between two successive glacial stages. See also: glacier

intrusion, intrusive rock	a plutonic igneous rock formed when magma from within the Earth's crust escapes into spaces in the overlying strata. As the magma rises, pushing through overlying layers of rock, it begins to cool. The cooling magma can crystallize and harden to become intrusive igneous rock, locked within layers of older rock. See also: crust, igneous, magma, pluton
iron	a metallic chemical element (Fe). Iron is most often found in combination with other elements, such as oxygen and sulfur, to form ores like hematite, magnetite, siderite, and pyrite. The ready availability of iron at Earth's surface made it one of the earliest mined mineral resources in the US. See also: hematite, magnetite, ore, pyrite, sulfur
isostasy	an equilibrium between the weight of the crust and the buoyancy of the mantle. See also: crust, mantle
jasper	a speckled or patterned silicate stone that appears in a wide range of colors. It is a variety of chalcedony. Jasper forms when silica precipitates in a fine particulate material such as soft sediment or volcanic ash. The particulates give the stone its color and patterns. See also: chalcedony, sedimentary rock, silica
joule (J)	the energy expended (or work done) to apply a force of one newton over a distance of one meter. See also: energy

Glossary

Jurassic	the geologic time period lasting from 201 to 145 million years ago. During the Jurassic, dinosaurs dominated the landscape and the first birds appeared. The Jurassic is the middle period of the Mesozoic. See also: geologic time scale, Mesozoic
kame	an irregularly shaped mound made up of sediment that accumulated in a depression on a retreating glacier. The mound-like deposits of sorted sediment are then deposited on the land after the glacier retreats. See also: glacier
karst topography	a kind of landscape defined by bedrock that has been weathered by dissolution in water, forming features like sinkholes, caves, and cliffs. Karst primarily forms in limestone bedrock. See also: limestone, topography, weathering
kettle	a lake formed where a large, isolated block of ice became separated from the retreating ice sheet. The weight of the ice leaves a shallow depression in the landscape that persists as a small lake. See also: ice sheet
kinetic energy	the energy of a body in motion (e.g., via friction). See also: energy

Köppen system	a commonly used system of climate categorization developed by Russian climatologist Wladimir Köppen. It is based on the kinds of vegetation that areas sustain, and defines 12 climate types: rainforest, monsoon, tropical savanna, humid subtropical, humid continental, oceanic, Mediterranean, steppe, subarctic, tundra, polar ice cap, and desert. Updated by Rudolf Geiger, it has been refined to five groups each with two to four subgroups. See also: climate
lagerstätte (pl. lagerstätten)	fossil deposit containing animals or plants that are preserved unusually well, sometimes even including the soft organic tissues. Lagerstatten form in chemical environments that slow decay of organic tissues or enhance preservation through mineralization. Also, quick burial of the organism leaves no opportunity for disturbance of the fossils. Lagerstatten are important for the information they provide about soft-bodied organisms that we otherwise would know nothing about. See also: fossil
Lake Superior agate	the Minnesota state gemstone. This stone formed in magma containing bubbles created by water and carbon dioxide that had been trapped in the magma. After the magma cooled, these bubbles were slowly filled by mineral-rich water, depositing layers of fine quartz crystals and enough iron to color the resulting rocks red. See also: iron, magma, quartz
last glacial maximum	the most recent time the ice sheets reached their largest size and extended farthest towards the equator, about 26,000 to 19,000 years ago. Ice sheets over North America melted back until about 10,000 years ago—they have been relatively stable since that time. See also: ice sheet

Glossary

Laurentide Ice Sheet	an ice sheet that covered most of Canada during the last major glaciation. In its prime, the Laurentide was more than 5 kilometers (3.1 miles) thick at its thickest point on what is now the Hudson Bay. The sheet began to melt about 13,000 years ago. See also: glacier, ice sheet
lava	molten rock located on the Earth's surface. When magma rises to the surface, typically through a volcano or rift, it becomes lava. Lava cools much more quickly than magma because it is at the surface, exposed to the atmosphere or ocean water where temperatures are much cooler. Such rocks, with little time to crystallize, have small or no crystals. See also: magma, rift, volcanism
Law of Superposition	the geological principle that states that unless rock layers have been overturned or intruded, older rocks are found at the bottom and younger rocks are found at the top of a sedimentary sequence. See also: intrusion, stratigraphy
lead	a metallic chemical element (Pb). Lead was one of the first metals mined in North America, where it was sought after especially for making shot. It is used in batteries, communication systems, and building construction.
lignite	a soft, brownish-black coal in which the alteration of plant matter has proceeded farther than in peat but not as far as in bituminous coal. See also: bituminous coal, coal, peat

limestone	a sedimentary rock composed of calcium carbonate ($CaCO_3$). Most limestones are formed by the deposition and consolidation of the skeletons of marine invertebrates; a few originate in chemical precipitation from solution. Limestone is ordinarily white but can be colored by impurities such as iron oxide (making it brown, yellow, or red), or organic carbon (making it blue, black, or gray). The rock's texture varies from coarse to fine. See also: iron, sedimentary rock
lithification	the process of creating sedimentary rock through the compaction or sementation of soft sediment. The word comes from the Greek *lithos*, meaning “rock.” See also: sedimentary rock
lithosphere	the outermost layer of the Earth, comprising a rigid crust and upper mantle broken up into many plates. The plates of the lithosphere move with the underlying asthenosphere, on average about 5 centimeters (2 inches) per year and as much as 18 centimeters (7 inches) per year. See also asthenosphere, crust, mantle
loam	a soil containing equal amounts of clay, silt, and sand. See also: clay, soil, sand, silt
loess	very fine grained, wind-blown sediment, usually rock flour left behind by the grinding action of flowing glaciers. See also: rock flour
luminescence	to give off light.

Glossary

luster	a physical property of minerals, describing the appearance of the mineral's surface in reflected light, and how brilliant or dull it is. Luster can range from metallic and reflective to opaque, vitreous like glass, translucent, or dull and earthy. See also: mineral
lycopod	an extinct, terrestrial tree belonging to the plant division Lycopodiophyta, and characterized by a tall, thick trunk covered with a pattern of diamond-shaped leaf scars, and a crown of branches with simple leaves. Lycopods, or "scale trees," grew up to 98 feet (30 meters) high in Mississippian and Pennsylvanian forests. The plant division Lycopodiophyta survives today but only as very small plants on the forest floor, sometimes called “ground pines.” See also: Mississippian, Pennsylvanian, tree
mafic	igneous rocks that contain a group of dark-colored minerals, with relatively high concentrations of magnesium and iron compared to felsic igneous rocks. See also: felsic, igneous rock
magma	molten rock located below the surface of the Earth. Magma can cool beneath the surface to form intrusive igneous rocks. However, if magma rises to the surface without cooling enough to crystallize, it might break through the crust at the surface to form lava. See also: crust, igneous, intrusive rock, lava
magnetic	affected by or capable of producing a magnetic field.

magnetite	a mineral form of iron oxide (Fe_3O_4). It is the most magnetic naturally occurring mineral. The molecules in magnetite align with the North and South Poles when rocks containing magnetite ore are formed. By examining the alignment today, scientists can reconstruct how the rocks have moved since their formation, giving them clues about the previous arrangement of the continents. Magnetite lodestones were used as an early form of compass. Huge deposits of magnetite have been found in Precambrian banded iron formations. See also: banded iron formations, iron, mineral, ore, Precambrian
mammoth	an extinct terrestrial vertebrate animal belonging to the Order Proboscidea of the Class Mammalia. Mammoths are from the same line of proboscideans that gave rise to African and Asian elephants. They had tall bodies with a rather high “domed” skull, and teeth with numerous parallel rows of ridges. Mammoths are among the most common Pleistocene vertebrate fossils in North America, Europe, and Asia. See also: extinction, fossil, Pleistocene
mantle	the layer of the Earth between the crust and core. It consists of solid silicate rocks that, over long intervals of time, flow like a highly viscous liquid. Convection currents within the mantle drive the motion of plate tectonics. See also: convection, magma, plate tectonics, silica
marble	a metamorphic rock composed of recrystallized carbonate minerals, most commonly calcite or dolomite. Not everything commercially called a marble is “true marble,” which lacks fossils and is recrystallized from limestone. See also: calcite, dolomite, limestone, metamorphic, mineral

Glossary

mass extinction	the extinction of a large percentage of the Earth's species over a relatively short span of geologic time. Unfortunately, this is not just a phenomenon of the past: it is estimated that the extinction rate on Earth right now may be as much as 1000 times higher than normal, and that we are currently experiencing a mass extinction event. See also: geologic time scale, extinction
mass wasting	a process in which soil and rock move down a slope in a large mass. This can occur both on land (such as a landslide) or underwater (such as a turbidity current). See also: turbidity current
mastodon	an extinct terrestrial vertebrate animal belonging to the Order Proboscidea of the Class Mammalia, and characterized by an elephant-like shape and size, and massive molar teeth with conical projections. Mastodons are among the most common Pleistocene vertebrate fossils in North America. See also: extinction, fossil, Pleistocene
matrix	a fine-grained mass of material around and embedding larger grains or crystals. The term matrix can also describe sediment or rock in which a fossil is embedded. See also: fossil

Mesozoic	a geologic time period that spans from 252 to 66 million years ago. This period is also called the "age of reptiles" since dinosaurs and other reptiles dominated both marine and terrestrial ecosystems. During this time, the last of the Earth's major supercontinents, Pangaea, formed and later broke up, producing the Earth's current geography. The Mesozoic contains the Triassic, Jurassic, and Cretaceous periods. See also: Cretaceous, geologic time scale, Jurassic, Pangaea, Triassic
metamorphism, metamorphic rocks	rocks formed by the recrystallization and realignment of minerals in pre-existing sedimentary, igneous, and metamorphic rocks when exposed to high enough temperature and/or pressure. This can be a result of plate movements, very deep burial, or contact with molten rock or superheated water. This process destroys many features in the rock that would have revealed its previous history, transforming it into an entirely new form. Tectonic forces can cause minerals to realign perpendicularly to the direction of pressure, layering them in a pattern called foliation, as exemplified in gneiss and schist. Recrystallization, as seen in marble and quartzite, results as rock is heated to high temperatures, and individual grains reform as interlocking crystals, making the resulting metamorphic rock harder than its parent rock. See also: gneiss, igneous rock, marble, quartzite, schist, sedimentary rock
mica	a large group of sheetlike silicate minerals. See also: mineral

Glossary

Michigan Basin	an inland basin centered on Michigan's Lower Peninsula, which formed when Baltica approached North America in the Ordovician. The rocks of the Michigan Basin are a commercial source of petroleum. See also: Baltica, inland basin, petroleum
Michigan Formation	a ring-like stratum in the rock of the Michigan Basin, where most of the state’s gypsum is mined. It can be found in a nearly continuous band around the center of the Lower Peninsula. See also: gypsum, Michigan Basin
Milankovitch Cycles	cyclical changes in the amount of heat received from the sun, associated with how the Earth’s orbit, tilt, and wobble alter its position with respect to the sun. These changes affect the global climate, most notably alterations of glacial and interglacial intervals. See also: climate
mineral	a naturally occurring solid with a specific chemical composition and crystalline structure. Minerals are identified based on their physical properties, including hardness, luster, color, crystal form, cleavage, density, and streak. There are over 4,900 identified minerals. However, the number of common rock-forming minerals is much smaller. The most common minerals that form igneous, metamorphic, and sedimentary rocks include quartz, feldspar, mica, pyroxenes, and amphiboles. See also: amphibole, color (mineral), cleavage, crystal form, density, feldspar, igneous rock, luster, metamorphic rock, mica, pyroxene, quartz, sedimentary rock, streak

mineralogy	The branch of geology that studies the chemical and physical properties and formation of minerals. See also: mineral
Mississippian	a subperiod of the Carboniferous, spanning from 359 to 323 million years ago. See also: Carboniferous
Mohs Scale of Hardness	the scale of relative hardness of minerals, developed by the Austrian mineralogist, Frederich Mohs, in 1824. The scale is very useful as a means for identifying minerals or quickly determining hardness. A piece of glass has a hardness of approximately 5 on the scale; our fingernails are just over 2; a knife blade is just over 5. Diamond ranks at 10 as the hardest mineral. See also: hardness, mineral
Mollisols	a soil order; these are agricultural soils made highly productive due to a very fertile, organic-rich surface layer. See also: soil, soil orders
moraine	an accumulation of unconsolidated glacial debris (soil and rock) that can occur in currently glaciated and formerly glaciated regions, such as those areas acted upon by a past ice age. The debris is scraped from the ground and pushed forward by the glacier, to be left behind when the ice melts. Thus, many moraines mark the terminus or edge of a glacier. Lateral moraines can also occur in between and at the sides of glaciers or ice lobes. See also: glacier, ice age, soil
Morton Gneiss	the oldest rock in the United States. It was formed 3.6 billion years ago, during the Archean. See also: Archean, gneiss

Glossary

mosasaurs	extinct, carnivorous, marine vertebrate reptiles. Mosasaurs were characterized by a streamlined body for swimming, a powerful fluked tail, and reduced, paddle-like limbs. They were common in Cretaceous seas and were were powerful swimmers, reaching 40-59 feet (12-18 meters) in length. See also: Cretaceous, extinction
natural gas	a hydrocarbon gas mixture composed primarily of methane (CH_4), but also small quantites of hydrocarbons such as ethane and propane. See also: fossil fuel
natural hazard	events that result from natural processes and that have significant impacts on human beings.
Neogene	the geologic time period extending from 23 to 2.6 million years ago. During the Neogene, global climate cooled, the continents moved close to their current positions, mammals and birds continued to evolve, and the first hominins appeared. The Neogene is a portion of the Cenozoic. See also: Cenozoic
nickel	a ductile, silvery-white metallic element (Ni). Nickel in its pure form is rarely found on Earth's surface; large quantites of nickel are typically found in meteorites. On Earth, nickel is generally found in combination with iron. Nickel is resistant to corrosion and is commonly used to plate metals, coat chemistry equipment, and manufacture alloys such as electrum. See also: iron

nodule	a small, irregular or rounded mineral deposit that has a different composition from the sedimentary rock that encloses it. Nodules typically form when minerals precipitate from a supersaturated solution within or around features such as biotic remains. See also: mineral, sedimentary rock
nuclear	a reaction, as in fission, fusion, or radioactive decay, that alters the energy, composition, or structure of an atomic nucleus. See also: radioactive
obsidian	a glassy volcanic rock, formed when felsic lava cools rapidly. Although obsidian is dark in color, it is composed mainly of silicon dioxide (SiO_2), and its dark color is a result of the rapid cooling process. Obsidian is extremely brittle and breaks with very sharp edges. It was valuable to Stone Age cultures for its use as cutting implements or arrowheads. See also: felsic, glassy, lava, volcanic
oil	See petroleum
Ordovician	a geologic time period spanning from 485 to 443 million years ago. During the Ordovician, invertebrates dominated the oceans and fish began to diversify. The Ordovician is part of the Paleozoic. See also: geologic time scale, Paleozoic
ore	a type of rock that contains minerals with valuable elements, including metals, that are economically viable to extract. See also: mineral

Glossary

orogeny	a mountain-building event generally caused by colliding plates and compression of the edge of the continents. Orogeny is derived from the Greek word *oro*, meaning mountain. See also: compression, plate tectonics
outwash plain	large sandy flats created by sediment-laden water deposited when a glacier melts. Outwash sediments are also called fluvial material. See also: glacier, sand
paleoecology	the study of the relationships of fossil organisms to one another and their environment. See also: fossil
Paleogene	the geologic time period extending from 66 to 23 million years ago. During the Paleogene, mammals and birds diversified into many of the niches that had previously been held by dinosaurs. The Paleogene is the first part of the Cenozoic. See also: dinosaur, geologic time scale, Cenozoic
Paleozoic	a geologic time period that extends from 541 to 252 million years ago. Fossil evidence shows that during this time period, life evolved in the oceans and gradually colonized the land. The Paleozoic includes the Cambrian, Ordovician, Silurian, Devonian, Carboniferous, and Permian periods. See also: Cambrian, Carboniferous, Devonian, geologic time scale, Ordovician, Permian, Silurian

Pangaea	supercontinent, meaning "all Earth," which formed over 250 million years ago and lasted for almost 100 million years. All of the Earth's continents were joined in a giant supercontinent. Pangaea eventually rifted apart and separated into the continents in their current configuration.
parent material	the original geologic material from which soil formed. This can be bedrock, preexisting soils, or other materials such as till or loess. See also: loess, soil, till
patterned ground	patterns and sorting in the soil caused by repeated freezing and thawing, which causes repeated heaving upwards and settling of the rocks and pebbles in the soil. See also: soil
peat	an accumulation of partially decayed plant matter. Under proper heat and pressure, it will turn into lignite coal over geologic periods of time. As much as 30 feet (9 meters) of peat might need to accumulate to produce an economically profitable coal seam. By the time that a peat bed has been turned into a layer of anthracite, the layer is one-tenth its original thickness. See also: anthracite, coal, lignite
peds	clumps of soil, identified by their shape, which may take the form of balls, blocks, columns, and plates. These structures are easiest to see in recently plowed fields, where the soil is often granular and loose or lumpy. See also: soil
Pennsylvanian	a subperiod of the Carboniferous, spanning from 323 to 299 million years ago. See also: Carboniferous

Glossary

periglacial zone	a region directly next to an ice sheet, which, although it was never covered or scoured by ice, has its own distinctive landscape and features because it was next to the ice margin. The average annual air temperature in a periglacial area is between -12° and 3°C (10° and 37°F). Though the surface of the ground may melt in the summer, it refreezes in the winter. See also: ice sheet
permafrost	a layer of soil below the surface that remains frozen all year round. Its thickness can range from tens of centimeters to a few meters. See also: soil
permeable, permeability	a capacity for fluids and gas (such as water, oil and natural gas) to move through fractures within a rock, or the spaces between its grains. Sandstone, limestone, and fractured rocks of any kind generally are permeable. Shale, on the other hand, is usually impermeable because the small, flat clay particles that make up the rock are tightly packed into a dense rock with very little space between particles. Poorly sorted sedimentary rocks can also be impermeable because smaller grains fill in the spaces between the bigger grains, restricting the movement of fluids. See also: clay, limestone, petroleum, sandstone, sedimentary rocks, shale

Permian	the geologic time period lasting from 299 to 252 million years ago. During the Permian, the world's landmass was combined into the supercontinent Pangaea. The Permian is the last period of the Paleozoic. It ended with the largest mass extinction in Earth's history, which wiped out 70% of terrestrialanimal species and 90% of all marine animal species. See also: geologic time scale, mass extinction, Paleozoic, Pangaea
permineralization	a fossilization method where empty spaces (such as in a bone or shell) are filled by minerals. See also: fossil
petroleum	a naturally occurring, flammable liquid found in geologic formations beneath the Earth's surface and consisting primarily of hydrocarbons. Petroleum, also called oil, is a fossil fuel, formed when large masses of dead organisms (usually algae or plankton) are buried underneath sediments and subjected to intense heat and pressure. Today, petroleum is used to manufacture a wide variety of materials, and it is commonly refined into various types of fuels. It is estimated that 90 million barrels are consumed globally every day. See also: fossil fuel
Phanerozoic	a generalized term used to describe the entirety of geological history after the Precambrian, from 541 million years ago to the present. See also: geologic time scale
placoderms	an extinct class of heavily armored fishes. Placoderms lived from the Silurian to the Devonian. See also: Devonian, extinction, Silurian

Glossary

plate tectonics	the way by which the plates of the Earth's crust move and interact with one another at their boundaries. The Earth is dynamic, consisting of constantly moving plates that are made of rigid continental and oceanic lithosphere overlying a churning, plastically flowing asthenosphere. These plates are slowly pulling apart, colliding, or sliding past one another with great force, creating strings of volcanic islands, new ocean floor, earthquakes, and mountains. See also: asthenosphere, crust, earthquake, lithosphere, volcanic islands
plates	large, rigid pieces of the Earth's crust and upper mantle, which move and interact with one another at their boundaries. See also: crust, mantle, plate tectonics
platform	See craton
Pleistocene	a subset of the Quaternary, lasting from 2.5 million to about 11,700 years ago. During the Pleistocene, continental ice sheets advanced south and retreated north several dozen times. See also: ice age, ice sheet, Quaternary
plesiosaurs	a group of extinct long-necked Mesozoic marine reptiles. See also: dinosaur, extinction, Mesozoic
plucking	process in which a glacier "plucks" sediments and larger chunks of rock from the bedrock. The flowing ice cracks and breaks rock as it passes over, pieces of which become incorporated into the sheet or bulldozed forward, in front of the glacier's margin. See also: glacier
plunge pool	a stream pool, lake, or pond that is small in diameter, but deep.

pluton, plutonic rock	a large body of intrusive igneous rock that formed under the Earth's surface through the slow crystallization of magma. The term comes from the name of Pluto, Roman god of the underworld. See also: igneous rock, intrusion, magma
polar vortex	a regularly occurring area of low pressure that circulates in the highest levels of the upper atmosphere. Typically, the polar vortex hovers above Canada. However, a pocket of the counter-clockwise rotating low-pressure center can break off and shift southward at a lower altitude. The jet stream then shifts to a more southward flow than usual. A polar vortex can lock the jet stream in this new pattern for several days to more than a week
potash	a name used for a variety of salts containing potassium, with mined potash being primarily potassium chloride (KCl). The majority of potash is used as fertilizer, but an increasing amount is being used in a variety of other ways: water softening, snow melting, a variety of industrial processes, as a medicine, and to produce potassium carbonate (K_2CO_3). See also: carbonate, salt
pothole	a shallow, rounded depression eroded in bedrock by a glacier. See also: erosion, glacier
power	the rate at which energy is transferred, usually measured in watts or, less frequently, horsepower. See also: energy, watt
Pre-Illinoian glaciation	a grouping of the Midwestern glacial periods that occurred before the Wisconsinian and Illinoian glaciations. See also: glacier, Illinoian glaciation, Wisconsinian glaciation

Glossary

Precambrian	a geologic time period that spans from the formation of Earth (4.6 billion years ago) to the beginning of the Cambrian (541 million years ago). Relatively little is known about this time period since very few fossils or unaltered rocks have survived. What few clues exist indicate that life first appeared on the planet as long as 3.9 billion years ago in the form of single-celled organisms. The Precambrian contains the Hadean, Archean and Proterozoic eons. See also: Archean, geologic time scale, Proterozoic
primary energy source	a source of energy found in nature, that has not been subject to any human-induced energy transfers or transformations (like conversion to electricity). Examples include fossil fuels, solar, wind, and hydropower. See also: energy, fossil fuel
prokaryotes	single-celled organisms, with simple cells containing no nucleus or organelles.
Proterozoic	a geologic time interval that extends from 2.5 billion to 541 million years ago. It is part of the Precambrian. During this eon, the Earth transitioned to an oxygenated atmosphere and eukaryotic cells, including fungi, plants, and animals, originated. See also: geologic time scale, Precambrian
protists	a diverse group of single-celled eukaryotes. See also: eukaryote
pterosaurs	extinct flying reptiles with wingspans of up to 15 meters. They lived during the same time as the dinosaurs. See also: dinosaur, extinction

pumpellyite	a group of metamorphic silicate minerals that produce translucent green crystals with a fibrous texture. See also: metamorphic rock, mineral, silica
pyrite	the iron sulfide mineral (FeS_2). Pyrite's superficial resemblance to gold has led to the common nickname "fool's gold." See also: iron, mineral, sulfur
pyroclastic	rocks that form during explosive volcanic eruptions, and are composed from a variety of different volcanic ejecta. The term comes from Greek, and means “broken fire.” Pyroclastic debris of all types is known as tephra. See also: volcanism
pyroxene	dark-colored rock-forming silicate minerals containing iron and magnesium, found in many igneous and metamorphic rocks. They are often present in volcanic rocks. See also: igneous rock, iron, metamorphic rock, silica, volcanic

Glossary

quartz	the second most abundant mineral in the Earth's continental crust (after feldspar), made up of silicon and oxygen (SiO_2). It makes up more than 10% of the crust by mass. There are a wide variety of types of quartz: onyx, agate, and petrified wood are fibrous, microcrystalline varieties collectively known as chalcedony. Although agate is naturally banded with layers of different colors and porosity, commercial varieties of agate are often artificially colored. Flint, chert and jasper are granular microcrystalline varieties of quartz, with the bright red color of jasper due to the inclusion of small amounts of iron within the mineral structure. The most common, coarsely crystalline varieties include massive quartz veins, the distinct, well formed crystals of "rock crystal", and an array of colored quartz, including amethyst (purple), rose quartz (pink), smoky quartz (gray), citrine (orange), and milky quartz (white). See also: chalcedony, chert, crust, flint, iron, jasper, mineral
quartzite	a hard metamorphic rock that was originally sandstone. Quartzite usually forms from sandstone that was metamorphosed through tectonic compression within orogenic belts. Quartzite is quarried for use as a building and decorative stone. See also: compression, metamorphism, orogeny, sandstone
Quaternary	a geologic time period that extends from 2.6 million years ago to the present. This period is largely defined by the periodic advance and retreat of continental glaciers. The Quaternary is part of the Cenozoic. See also: Cenozoic, geologic time scale, glacier

radioactive	when an unstable atom loses energy by emitting radiation.
radon	a naturally occurring radioactive, colorless, odorless gas. It is one of the products of decay from the breakdown of radioactive elements in soil, rock, and water, released by weathering. See also: radioactive, weathering
recrystallization	the change in structure of mineral crystals that make up rocks, or the formation of new mineral crystals within the rock. Recrystallization commonly occurs during metamorphism. When rocks are metamorphosed, individual grains that make up the original rock are melted slightly and recrystallize. The pressure allows crystals to grow into a tighter, interlocking arrangement than in an unmetamorphosed rock. See also: metamorphism, mineral
recurrence interval	the time elapsed between major events, such as floods.
reef	a feature lying beneath the surface of the water, which is a buildup of sediment or other material built by organisms, and which has positive relief from the sea floor. While some reefs result from abiotic processes such as deposition or wave action, the best-known reefs are built by corals and other marine organisms.
regional metamorphism	a metamorphic rock that has been altered due to deep burial and great pressure. This type of metamorphic rock tends to occur in long belts at the center of mountain ranges. Different types of metamorphic rock are created depending on the gradients of heat and pressure applied. See also: metamorphism
regression	a drop in sea level.

Glossary

renewable energy, renewable resource	energy obtained from sources that are virtually inexhaustible (defined in terms of comparison to the lifetime of the Sun) and replenish naturally over small time scales relative to human life spans. See also: energy
replacement	a fossilization method by which the original material is chemically replaced by a more stable mineral. See also: fossil
rhyolite, rhyolitic	a felsic volcanic rock high in abundance of quartz and feldspar. See also: feldspar, felsic, quartz, volcanic
rift	a break or crack in the crust that can be caused by tensional stress as a landmass breaks apart into separate plates. See also: crust, plate tectonics
rift basin	a topographic depression caused by subsidence within a rift; the basin, since it is at a relatively low evelation, usually contains freshwater bodies such as rivers and lakes. See also: rift
ripple marks	surface features created when sediment deposits are agitated, typically by water currents or wind. The crests and troughs formed by this agitation are occasionally preserved, providing information about the flow of water or wind in the paleoenvironment. See also: lithification, sedimentary rock
rock flour	very fine sediments and clay resulting from the grinding action of glaciers. See also clay, glacier.

Rodinia	a supercontinent that contained most or all of Earth's landmass, between 1.1 billion and 750 million years ago, during the Precambrian. Geologists are not sure of the exact size and shape of Rodinia. It was analagous to but not the same supercontinent as Pangaea, which formed was assembled several hundred million years later during the Permian. See also: Pangaea, Permian, Precambrian
salt	a mineral composed primarily of sodium chloride (NaCl). In its natural form, it is called rock salt or halite. Salt is essential for animal life, and is a necessary part of the diet. In addition, salt is used for de-icing roads in winter and is also an important part of the chemical industry. See also: mineral
sand	rock material in the form of loose, rounded, or angular grains, and formed as a result of the weathering and decomposition of rocks. Particles of sand are between 0.05-2 millimeters in diameter. See also: weathering
sandstone	sedimentary rock formed by cementing together grains of sand. See also: sand, sedimentary rocks
schist	a medium grade metamorphic rock with sheet-like crystals flattened in one plane. The flattened crystals are often muscovite or biotite mica, but they can also be talc, graphite, or hornblende. See also: graphite, hornblende, metamorphism, mica, talc

Glossary

scleractinian coral	a modern "stony" coral; a colonial or solitary marine invertebrate animal belonging to the Order Scleractinia in the Class Anthozoa of the Phylum Cnidaria, and characterized by an encrusting calcareous skeleton from which multiple individuals (*polyps*) extend from small pores to capture prey with small tentacles equipped with stinging cells (*nematocysts*). Although scleractinians look somewhat similar to extinct rugose and tabulate corals, each group possesses distinctive features in the shape of the skeletal cup holding the individual polyps. Modern scleractinians host commensal algae (*zooxanthellae*) whose photosynthetic activities supply the coral with energy.
scoria	a highly vesicular form of basalt. It tends to form as cinders in the early stages of a volcanic eruption, when gas bubbles are still caught up in the frothy erupting magma. Once the gas has escaped, the remaining magma can flow out, creating basalt lava flows that spread out over the landscape. See also: basalt, magma, vesicular, volcanic
scour, scouring	erosion resulting from glacial abrasion on the landscape. See also: erosion, glacier

sedimentary rocks	rocks formed through the accumulation and consolidation of grains of broken rock, crystals, skeletal fragments, and organic matter. Sediment that forms from weathering is transported by wind or water to a depositional environment such as a lakebed or ocean floor; here they build up, burying and compacting lower layers. As water permeates the sediment, dissolved minerals may precipitate out, filling the spaces between particles and cementing them together. Sedimentary rocks may also accrete from fragments of the shells or skeletal material of marine organisms like clams and coral. Sedimentary rocks are classified by their sediment size or their mineral content. Each one reveals the story of the depositional environment where its sediments accumulated and the history of its lithification. See also: erosion, lithification, mineral, weathering
seed fern	an extinct terrestrial plant belonging to the plant division Pteridospermatophyta, and characterized by a fern-like appearance, but bearing seeds instead of spores. Seed ferns lived from the Mississippian to the Jurassic. See also: Jurassic, Mississippian
seismic waves	the shock waves or vibrations radiating in all directions from the center of an earthquake or other tectonic event. See also: earthquake
seismic zone	a regional zone that encompasses areas prone to seismic hazards, such as earthquakes or landslides.

Glossary

seismometer	an instrument that measures seismic waves (movements) within the ground. These measurements help us map the interior of the Earth, as well as locate the areas where earthquakes and other seismic events begin. See also: seismic waves
shale	a dark, fine-grained, laminated sedimentary rock formed by the compression of successive layers of silt- and clay-rich sediment. Shale is weak and often breaks along thin layers. Shale that is especially rich in unoxidized carbon is dark grey or black. These organic-rich black shales are often source rocks for petroleum and natural gas. See also: clay, compression, natural gas, petroleum, sedimentary rock, silt
shark	a large fish characterized by a cartilaginous skeleton and five to seven gill slits on the side of the head. Sharks first appeared 420 million years ago, and have since diversified to over 470 species.
shield	See craton
silica	a chemical compound also known as silicon dioxide (SiO_2). Silica is most commonly found as quartz, and is also secreted as skeletal material in various organisms. It is one of the most abundant materials in the crust. See also: quartz
silt	granular sediment most commonly composed of quartz and feldspar crystals. Particles of silt have diameters of less than 0.074 millimeters. See also: feldspar, quartz

Silurian	a geologic time period spanning from 443 to 419 million years ago. During the Silurian, jawed and bony fish diversified, and life first began to appear on land. The Silurian is part of the Paleozoic. See also: geologic time scale, Paleozoic
silver	a metallic chemical element (Ag). Silver is used in photographic film emulsions, utensils and other tableware, and electronic equipment.
snail	see gastropod
soil	the collection of natural materials that collect on Earth's surface, above the bedrock. Soil consists of layers (horizons) of two key ingredients: plant litter, such as dead grasses, leaves, and fallen debris, and sediment derived from the weathering of rock. Both of these components can influence the texture and consistency of the soil, as well as the minerals available for consumption by plants. The word is derived from the Latin "*solum*," which means “floor” or “ground." See also: horizon (soil), mineral, weathering
soil orders	the twelve major units of soil taxonomy, which are defined by diagnostic horizons, composition, soil structures, and other characteristics. Soil orders depend mainly on climate and the organisms within the soil. These orders are further broken down into 64 suborders based on properties that influence soil development and plant growth, with the most important property being how wet the soil is throughout the year. See also soil, soil taxonomy
soil taxonomy	The system used to classify soils based on their properties. See also: soil

Glossary

solifluction	a type of mass wasting where waterlogged sediment moves slowly downslope, over impermeable material. Solifluction is similar to a landslide or mudslide. See also: mass wasting
sphenopsid	a terrestrial plant belonging to the Family Equisetaceae in the plant division Pteridophyta, and characterized by hollow, jointed stems with reduced, unbranched leaves at the nodes. Sphenopsids, or horsetails, reached over 33 feet (10 meters) high during the Pennsylvanian. See also: Pennsylvanian
Spodosols	a soil order; these are acidic soils in which aluminum and iron oxides accumulate below the surface. They typically form under pine vegetation and sandy parent material. See also: iron, sand, soil, soil orders
St. Peter Sandstone	a pure, quartz-rich sandstone that covers much of the Midwest and was deposited during the Ordovician. It is an enduring enigma to geologists because it is not clear how all the non-quartz minerals could have been removed. See also: Ordovician, quartz, sandstone
stratigraphy, stratigraphic	the branch of geology specifically concerned with the arrangement and age of rock units. See also: Law of Superposition
streak	a physical property of minerals, obtained by dragging the mineral across a porcelain plate and effectively powdering it. During identification, the color of the powder eliminates the conflating variables of external weathering, crystal form, or impurities. See also: crystal form, mineral, weathering

striations	long, parallel scratch marks that are the result of the grinding of sediments in glacial ice sliding across a rock surface. See also: glacier
stromatolite	regularly banded accumulations of sediment created by the trapping and cementation of sediment grains in bacterial mats (especially photosynthetic cyanobacteria). Cyanobacteria emit a sticky substance that binds settling clay grains and creates a chemical environment leading to the precipitation of calcium carbonate. The calcium carbonate then hardens the underlying layers of bacterial mats, while the living bacteria move upward so that they are not buried. Over time, this cycle of growth combined with sediment capture creates a rounded structure filled with banded layers. Stromatolites peaked in abundance around 1.25 billion years ago, and likely declined due to the evolution of grazing organisms. Today, stromatolites exist in only a few locations worldwide, such as Shark Bay, Australia. Modern stromatolites form thick layers only in stressful environments, such as very salty water, that exclude animal grazers. Even though there are still modern stromatolites, the term is often used to refer specifically to fossils. See also: fossil
stromatoporoid	a type of calcareous sponge that acted as an important reef-builder throughout the Paleozoic and the late Mesozoic. See also: Mesozoic, Paleozoic, reef
subduction	the process by which one plate moves under another, sinking into the mantle. This usually occurs at convergent plate boundaries. Denser plates are more likely to subduct under more buoyant plates, as when oceanic crust sinks beneath continental crust. See also: active plate boundary, convergent boundary, crust, mantle

Glossary

sulfur	a bright yellow chemical element (S) that is essential to life. It acts as an oxidizing or reducing agent, and occurs commonly in raw form as well as in minerals. See also: mineral
sustainable	able to be maintained at a steady level without exhausting natural resources or causing severe ecological damage, as in a behavior or practice.
suture	the area where two continental plates have joined together through continental collision. See also: convergent boundary, plate tectonics
system	a set of connected things or parts forming a complex whole - in particular, a set of things working together as parts of a mechanism or an interconnecting network.
talc	hydrated magnesium silicate, formed during hydrothermal alteration accompanying metamorphism. Talc can be formed from calcite, dolomite, silica, and some ultramafic rocks. See also: calcite, dolomite, mafic, metamorphism, silica
talus	debris fields found on the sides of steep slopes, common in periglacial environments. See also: periglacial
terrane	a piece of crustal material that has broken off from its parent continent and become attached to another plate. Due to their disparate origins, terranes have distinctly different geologic characteristics than the surrounding rocks. Florida is a good example of an exotic terrane, originating as part of the supercontinent Gondwana. Parts of the western coast of North America (including Alaska and the Northeastern US) are also terranes that have been sutured onto the coast. See also crust, plate tectonics, suture

Tertiary	an unoffical but still commonly used term for the time period spanning from 66 million to 2.5 million years ago, including the Paleogene, Neogene, and part of the Pleistocene. Although the Tertiary period was officially phased out in 2008 by the International Commission on Stratigraphy, it can still be found in scientific literature. (In contrast, the Carboniferous and Pennsylvanian & Mississippian periods all enjoy official status, with the latter pair being more commonly used in the US.) See also: Carboniferous, Mississippian, Neogene, Paleogene, Pennsylvanian, Pleistocene, stratigraphy
till	unconsolidated sediment that is eroded from the bedrock, then carried and eventually depositied by glaciers as they recede. Till may include a mixture of clay, sand, gravel, and even boulders. The term originated with farmers living in glaciated areas who were constantly removing rocks from their fields while breaking the soil for planting, a process known as tilling. See also: clay, erosion, glacier, sand
topography	the landscape of an area, including the presence or absence of hills and the slopes between high and low areas. These changes in elevation over a particular area are generally the result of a combination of deposition, erosion, uplift and subsidence. These processes that can happen over an enormous range of timescales. See also: erosion, uplift
tornado	a vertical funnel-shaped storm with a visible horizontal rotation. The word tornado has its roots in the Spanish word *tonar*, which means "to turn."

Glossary

trace fossils	fossils that record the actions of organisms, such as footprints, trails, trackways, and burrows. Trace fossils cannot always be associated at least with a group of organisms or way of life. The first trace fossils appear a couple hundred million years before the first animal (body) fossils. See also: fossil
transform boundary	an active plate boundary in which the crustal plates move sideways past one another. See also: active plate boundary
transgression	a relative rise in sea level in a particular area, through global sea level rise or subsidence of land.
tree	any woody perennial plant with a central trunk. Not all trees are closely related; different kinds of plants have evolved the tree form through geological time. The trees of the Paleozoic were more closely related to club mosses or ferns than they were to today's trees. See also: Paleozoic
Triassic	a geologic time period that spans from 252 to 201 million years ago. During this period, dinosaurs, pterosaurs, and the first mammals appear and begin to diversify. The Triassic begins directly after the Permian-Triassic mass extinction event, and is the first period of the Mesozoic. See also: geologic time scale, mass extinction, Mesozoic

trilobite	an extinct marine invertebrate animal belonging to the Class Trilobita of the Phylum Arthropoda, and characterized by a three-part body and a chitinous exoskeleton divided longitudinally into three lobes. Trilobites have been extinct since the end of the Paleozoic. Trilobites were primitive arthropods distantly related to horseshoe crabs. As bottom dwellers, they were present in a variety of environments. Like crabs and lobsters, trilobites molted their exoskeletons when they grew. Most fossils of trilobites are actually molts, broken as they were shed off the trilobite. Thus, it is common to find only parts of trilobites, such as the head, mid-section, or tail. See also: extinction, Paleozoic
tropical depression	an organized, rotating system of clouds and thunderstorms. A tropical storm has wind speeds of less than 63 kph (39 mph). It has no eye, and lacks the shape and organization of a more powerful hurricane. See also: hurricane
tuff	a pyroclastic rock made of consolidated volcanic ash. Tuff is the result of pyroclastic flows, in which the violent expansion of hot gas shreds the erupting magma into tiny particles that cool in the air to form dense clouds of volcanic ash. The tremendous explosions that are necessary to create ash-flow tuffs are caused by rhyolitic magma, which is felsic. High silica content makes the magma quite viscous, preventing gas bubbles from easily escaping, thus leading to pressure build-ups that are released by explosive eruptions. The ash flows from these violent explosions tend to hug the ground, eventually solidifying into tuffs. Tuffs and other pyroclastic materials are vesicular (porous) due to gases expanding within the material as it cools. See also: felsic, magma, pyroclastic, rhyolitic, silica, vesicular

Glossary

turbidity current	a submarine sediment avalanche. These fast-moving currents of sediment are often caused by earthquakes or other geological disturbances that loosen sediment on a continental shelf. These massive sediment flows have extreme erosive potential, and often carve out underwater canyons. Turbidity currents deposit huge amounts of sediment during flow; such deposits are called turbidites. Because of the rate at which turbidity currents deposit dense sediments, they are often responsible for the effective preservation of many fossil organisms, which are swept up from shallow marine environments and buried in the deep sea. See also: fossil
uplift	upward movement of the crust due to compression, subduction, or mountain building. Uplift can also occur as a rebounding effect after the removal of an ice sheet reduces the amount of weight pressing on the crust. See also: compression, crust, ice sheet, subduction
Utica Formation	an organic-rich black shale from the Middle Ordovician. It is found throughout New York, Pennsylvania, Ohio, West Virginia, and other portions of eastern North America. The Utica Formation is an extremely rich source rock for oil and natural gas. See also: natural gas, petroleum, shale
vesicular	porous or pitted with vesicles (cavities). Some extrusive igneous rocks have a vesicular texture. See also: extrusive, igneous rock

volcanic islands	a string of islands created when molten rock rises upwards through oceanic crust. Volcanic islands are common in several contexts, including at subduction zones between colliding oceanic plates, above oceanic hot spots, and along mid-ocean ridges. At subduction zones, the friction between the plates generates enough heat and pressure to melt some of the crust. In the case of hot spots, islands form as magma from the mantle breaks through the sea floor. See also: crust, hot spot, magma, mantle, plate tectonics, subduction, volcanism
volcanic, volcanism	the eruption of molten rock onto the surface of the crust. Most volcanic eruptions occur along tectonic plate boundaries, but may also occur at hot spots. Rocks that form from molten rock on the surface are also called volcanic. Prior to eruption, magma ascends from the mantle to a relatively shallow (1-10 km / 0.5-6 mi) magma chamber. Upward movement reduces the pressure on the magma until it is low enough to permit dissolved gas to exsolve (come out of solution and form bubbles). All eruptions are driven by the exsolution of dissolved gas. As the gas forms bubbles, it expands in volume and forces the magma out of the vent/chamber system onto the surface. The combination of magma viscosity and gas content can produce a range of eruptive styles, from gentle, effusive eruptions to violent explosions. see also: hot spot, magma, mantle, plate tectonics
water table	the upper surface of groundwater, that is, the underground level at which groundwater is accessible.

Glossary

watt	a unit of power measuring the rate of energy conversion or transfer designated by the International System of Units as one joule per second. See also: energy, joule, power
weather	the measure of short-term conditions of the atmosphere such as temperature, wind speed, and humidity. These conditions vary with the time of day, the season, and yearly or multi-year cycles.
weathering	the breakdown of rocks by physical or chemical means. Rocks are constantly being worn down and broken apart into finer and finer grains by wind, rivers, wave action, freezing and thawing, and chemical breakdown. Over millions of years, weathering and erosion can reduce a mighty mountain range to low rolling hills. Some rocks wear down relatively quickly, while others can withstand the power of erosion for much longer. Softer, weaker rocks such as shale and poorly cemented sandstone and limestone are much more easily worn away than hard, crystalline igneous and metamorphic rocks, or well-cemented sandstone and limestone. Harder rocks are often left standing alone as ridges because surrounding softer, less resistant rocks were more quickly worn away. See also: erosion, igneous rock, metamorphic rock, sedimentary rock
wind	the movement of air from areas of high pressure to areas of low pressure. The greater the temperature difference, the greater the air pressure difference and, consequently, the greater the speed at which the air will move.

wind shear	when wind speed and/or direction changes with increasing height in the atmosphere. Wind shear can happen when a cold front moves rapidly into an area with very warm air. There, the condensing water droplets mix with the cooler, drier air in the upper atmosphere to cause a downdraft. See also: wind
Wisconsinian glaciation	the most recent interval of glaciation, which occurred during the Pleistocene, 85,000 to 11,000 years ago. See also: glacier, Pleistocene
zinc	a metallic chemical element (Zn, atomic number 30). Zinc is typically used in metal alloys and galvanized steel.

General Resources

On the Earth System Science of North America

Books

Bally, A.W., and Palmer, A.R., eds., 1989, *The geology of North America—An overview, v. A of The geology of North America*. Geological Society of America: Boulder, CO, 619 p.

Maps (printed)

Thelin, G.P. and Pike, R.J., 1991, *Landforms of the Conterminous United States—A Digital Shaded-Relief Portrayal*. USGS Miscellaneous Investigations Series Map I-2206, http://pubs.usgs.gov/imap/i2206/.

Muehlberger, W.R., compiler, 1992, *Tectonic map of North America, scale 1:5,000,000*. American Association of Petroleum Geologists: Tulsa, OK.

Reed, J.C., and Bush, C.A., 2007, *Geology: The National Atlas of the United States* 32 x 28", http://pubs.usgs.gov/circ/1300/.

Reed, J.C., and Bush, C.A., 2007, About the geologic map in the National Atlas of the United States of America. *US Geological Survey Circular* 1300, 52 p., http://pubs.usgs.gov/circ/1300/pdf/Cir1300_508.pdf.

USGS, 2005, *Resources for the Geologic Map of North America*. http://ngmdb.usgs.gov/gmna/.

Vigil, J.F., Pike, R.J., and Howell, D.G., 2000, A tapestry of time and terrain. *US Geological Survey Geologic Investigations Series* 2720, 1 plate scale 1:2,500,000, 1 pamphlet, http://pubs.usgs.gov/imap/i2720/.

Maps (online)

American Geological Institute's *Earth Comm* 2nd edition, Map Resources. http://www.agiweb.org/education/earthcomm2/maps.html (a compilation of online map resources).

Google Earth. http://www.google.com/earth/.

The National Atlas of the United States. http://nationalatlas.gov/mapmaker (custom-make maps).

The National Map. http://nationalmap.gov.

The National Map: Historical Topographic Map Collection. http://nationalmap.gov/historical/index.html (on-line historic topographic maps).

US Topo Quadrangles—Maps for America. http://nationalmap.gov/ustopo/index.html (on-line topographic maps).

Geologic time resources online

Correlated History of the Earth Chart, v 8, 2013 (Laminated).

International Commission on Stratigraphy, http://www.stratigraphy.org/.

The Paleontology Portal, www.paleoportal.org.

Dictionaries

Allaby, M.,2013, *A dictionary of geology and Earth sciences*. Oxford University Press: Oxford, UK.

Bates, R. Latimer, & Jackson, J. A.,1984, *Dictionary of geological terms* (3rd ed.), Anchor Press: Garden City, NY.

McGraw-Hill Education, 2003, *McGraw-Hill dictionary of geology and mineralogy*. McGraw-Hill: New York.

Earth system science organizations

American Association of State Geologists, http://www.stategeologists.org/.

American Geological Institute (AGI is an umbrella organization representing over 40 other geological organizations), http://agiweb.org.

American Geophysical Union, http://agu.org.

Association for Women Geoscientists, http://awg.org.

Geological Society of America, http://geosociety.org.

Natural Resources Conservation Service, http://www.nrcs.usda.gov/wps/portal/nrcs/site/national/home/ (NRCS helps US farmers, ranchers and forest landowners conserve soil, water, air and other natural resources).

Paleontological Research Institution, http://priweb.org (publisher of this volume).

Paleontological Society, http://paleosoc.org.

US Geological Survey, http://usgs.gov.

General Earth Science Education Resources

Websites

Digital Library for Earth System Education (DLESE), http://dlese.org.

Resources for Earth science and geography instruction, by Mike Francek, Central Michigan University, http://webs.cmich.edu/resgi/.

SERC (The Science Education Resource Center) K-12 resources, http://serc.carleton.edu/k12/index.html. (Hundreds of classroom activities organized by grade level and topic as well as guidance on effective teaching.)

SERC Earth Exploration Toolbook, http://serc.carleton.edu/eet/index.html. (Collection of online Earth system science activities introducing scientific data sets and analysis tools.)

Science education organizations

National Association of Geoscience Teachers, http://nagt.org. (Focuses on undergraduate geoscience education, but includes active secondary school educators.)

National Earth Science Teacher Association, http://nestanet.org. (Focused on secondary school Earth science education.)

National Science Teacher Association, http://nsta.org.

Resources by State

Geologic maps of individual US states. (Digital geologic maps of US states with consistent lithology, age, GIS database structure, and format.) http://mrdata.usgs.gov/geology/state.

Illinois

Frankie, W., 2004, *Guide to Rocks and Minerals of Illinois*. Geoscience Education Series 16. 69 p.

Illinois Geological Survey, https://www.isgs.illinois.edu.

Illinois Department of Natural Resources, http://www.dnr.illinois.gov/Pages/default.aspx.

Indiana

Camp, M. J., & Richardson, G. T., 1999, *Roadside geology of Indiana*. Mountain Press Publ.: Missoula, MT.

Bedrock Geology of Indiana, Indiana Geological Survey, http://igs.indiana.edu/Bedrock.

Indiana Geological Survey, http://igs.indiana.edu.

Indiana Department of Natural Resources, http://www.in.gov/dnr/.

Iowa

Anderson, W.I., 1998, *Iowa's geological past: Three billion years of change*. University of Iowa Press, Iowa City, 440 p.

Iowa Geological Survey, http://www.iihr.uiowa.edu.

Iowa Department of Natural resources, Environment, http://www.iowadnr.gov/Environment.aspx.

Michigan

Barker, C. F.,2005, *Under Michigan the story of Michigan's rocks and fossils*. Wayne State University Press: Detroit.

Mueller, B., & Gauthier, K.,2010, *Lake Huron rock picker's guide*. University of Michigan Press: Ann Arbor.

Michigan Geological Survey, http://wmich.edu/geologysurvey.

Michigan Department of Natural Resources, http://www.michigan.gov/dnr.

Minnesota

Gauthier, K., & Mueller, B., 2007, *Lake Superior rock picker's guide*. University of Michigan Press: Ann Arbor.

Ojakangas, R. W., 2009, *Roadside geology of Minnesota*. Mountain Press Publ.: Missoula, MT.

Ojakangas, R. W., & Matsch, C. L., 1982, *Minnesota's geology*. Minneapolis: University of Minnesota Press.

Sansome, C. J., & Sansome, K. N., 1983, *Minnesota underfoot: a field guide to the state's outstanding geologic features*. Boyageur Press: Bloomington, MN.

Natural History: Minnesota's Geology, Minnesota Department of Natural Resources. http://www.dnr.state.mn.us/snas/naturalhistory.html.

Minnesota Geological Survey, http://www.mngs.umn.edu.

Minnesota Department of Natural Resources, http://www.dnr.state.mn.us/index.html.

Ohio

Camp, M. J., 2006, *Roadside geology of Ohio*. Mountain Press Publ.: Missoula, MT.

Ohio Department of Natural Resources, Division of Geological Survey. http://www2.ohiodnr.com/geosurvey/.

Ohio Department of Natural Resources, Soil and Water Resources. http://soilandwater.ohiodnr.gov/.

Wisconsin

Dott, R. H., & Attig, J. W., 2004, *Roadside geology of Wisconsin*. Mountain Press Publ.: Missoula, MT.

LeBerge, G.L.,1994, *Geology of the Lake Superior Region*, Geoscience Press, 309 p.

Wisconsin Geology, Wisconsin Geological & Natural History Survey, http://wgnhs.uwex.edu/wisconsin-geology/

Wisconsin Geological Survey and Natural History, http://wgnhs.uwex.edu.

Wisconsin Department of Natural Resources, http://dnr.wi.gov.

Acknowledgments

We are grateful to the following reviewers, each of whom edited one or more chapters of the *The Teacher-Friendly Guide™ to the Earth Science of the Midwestern US*: Don Duggan-Haas, Rod Feldmann, Bryan Isacks, William Kean, Russell Martin, Judith Parrish, and Debra Zolynsky.

Richard Kissel managed early content development of the Guide, and was aided in content research by Sara Auer Perry. The glossary was developed by Paula Mikkelsen and Andrielle Swaby.

Funding for this Guide came from National Science Foundation DR K-12 grant DRL-0733303 to the Paleontological Research Institution. Funding to start *The Teacher-Friendly Guide™* series was provided by the Arthur Vining Davis Foundations. Jane (Ansley) Picconi did page layout for the first Guide in the series, *The Teacher-Friendly Guide™ to the Geology of the Northeastern US* (Paleontological Research Institution special publication 24, 2000), many features of which have been adopted for this Guide.

Figure Credits

Chapter 1: Geologic History

1.1: Jane Picconi
1.2: Jim Houghton
1.3: Adapted from figure in: *Iowa's Geological Past: Three Billion Years of Change*, by Wayne I. Anderson
1.4: Adapted from figure in: Tectonic model for the Proterozoic growth of North America, by Steven J. Whitmeyer and Karl Karlstrom, *Geosphere*, August 2007, 3(4): 220–259
1.5: Adapted from figure in: Direct measurement of timing: Underpinning a reliable petroleum system model for the Mid-Continent rift system, by Kerry Hegarty *et al., AAPG Bulletin*, July 2007, 91(7) 959–979
1.6: Jane Picconi
1.7: Jim Houghton
1.8: Jim Houghton
1.9: Jane Picconi
1.10: Jane Picconi
1.11: Adapted from USGS
1.12: Adapted from figure by William A. Cobban and Kevin C. McKinney, USGS
1.13: Jim Houghton
1.14: Jim Houghton
1.15: Jim Houghton
1.16: Adapted from US Army Corps of Engineers
Crust box: Jim Houghton

Chapter 2: Rocks

2.1: Jane Picconi
2.2: Jim Houghton
2.3: Jim Houghton
2.4: Adapted from USGS
2.5: Adapted from figure in: Direct measurement of timing: Underpinning a reliable petroleum system model for the Mid-Continent rift system, by Kerry Hegarty *et al., AAPG Bulletin*, July 2007, 91(7) 959–979
2.6: Don Duggan-Haas
2.7: Adapted from Niagara Escarpment map, Wikimedia Commons
2.8: Adapted from figure by Illinois State Geological Survey
2.9: Adapted from *The Earth Through Time* (8th edition), by Harold L. Levin
Surface Rocks box: Jim Houghton
Metamorphism box: Jim Houghton
Stromatolite box: James St. John [CC-BY-2.0 (http://creativecommons.org/licenses/by/2.0)], via Wikimedia Commons
Sedimentary Structures box: Jim Houghton
Sedimentary Environments box: Jim Houghton

Chapter 3: Fossils

3.1: Alex Wall
3.2 - 3.5: © Christie Sobel
3.6: A) From E.L. Palmer, 1965, *Fossils*. D.C. Heath, Boston; B) © Christie Sobel
3.7: © Christie Sobel
3.8: A) © Christie Sobel; B) from E.L. Palmer, 1965, *Fossils*. D.C. Heath, Boston
3.9: A) and B) Sloan (2005); C) and D) from E.L. Palmer, 1965, *Fossils*, D.C. Heath, Boston
3.10: A) from Palmer, E.L., 1965, *Fossils*. D.C. Heath, Boston; B) from W. Twenhofel and R. Shrock, 1935, *Invertebrate Paleontology*, McGraw-Hill, New York
3.11–3.15: © Christie Sobel
3.16: From E.L. Palmer, 1965, *Fossils*. D.C. Heath, Boston
3.17–3.30: © Christie Sobel
Krukowski Quarry box: © Christie Sobel
Tully Monster box: © Christie Sobel
Mammoth/Mastodon box: © Christie Sobel

Chapter 4: Topography

4.1: Adapted from USGS
4.2: Transect from Google Earth
4.3: Altered from map by David C. Wilson
4.4: Transect from Google Earth
Elevation map: Andrielle Swaby
Karst box: Adapted from figures by American Geological Institute

Chapter 5: Mineral Resources

5.1: Jane Picconi
5.2: Adapted from 2009 USGS State Mineral Info
5.3: Adapted from 2009 USGS State Mineral Info
5.4: Adapted from figure by Swinsto101 [CC-BY-SA-3.0 (http://creativecommons.org/licenses/by-sa/3.0)] via Wikimedia Commons
5.5: Adapted from figure by the Salt Association
5.6: Adapted from 2009 USGS State Mineral Info
Hydrothermal box: Jim Houghton

Chapter 6: Glaciers

6.1: Adapted from figure by USGS
6.2: Jim Houghton
6.3: Wade Greenberg-Brand
6.4: Jim Houghton
6.5: Wade Greenberg-Brand
6.6: Jim Houghton
6.7: Wade Greenberg-Brand
6.8: Adapted from data by NOAA
6.9: Adapted from figures by C.L. Matsch and USGS
6.10: Adapted from figure by Michigan Geological Survey
6.11: Jim Houghton
6.12: Adapted from US Army Corps of Engineers
6.13: Adapted from figure by USGS
6.14: Photo by Jeff Dlouhy [CC-BY-2.0 (https://creativecommons.org/licenses/by/2.0/)] via Flickr
Snail box: Adapted from photo by US Fish and Wildlife Service

Chapter 7: Energy

7.1: Jim Houghton
7.2: Adapted from figure by US Energy Information Administration
7.3: Adapted from figure by the National Renewable Energy Laboratory
7.4: Adapted from figure by USGS
7.5: Peter Nester
Coal box: Jim Houghton
Oil/Gas box: Jim Houghton

Chapter 8: Soils

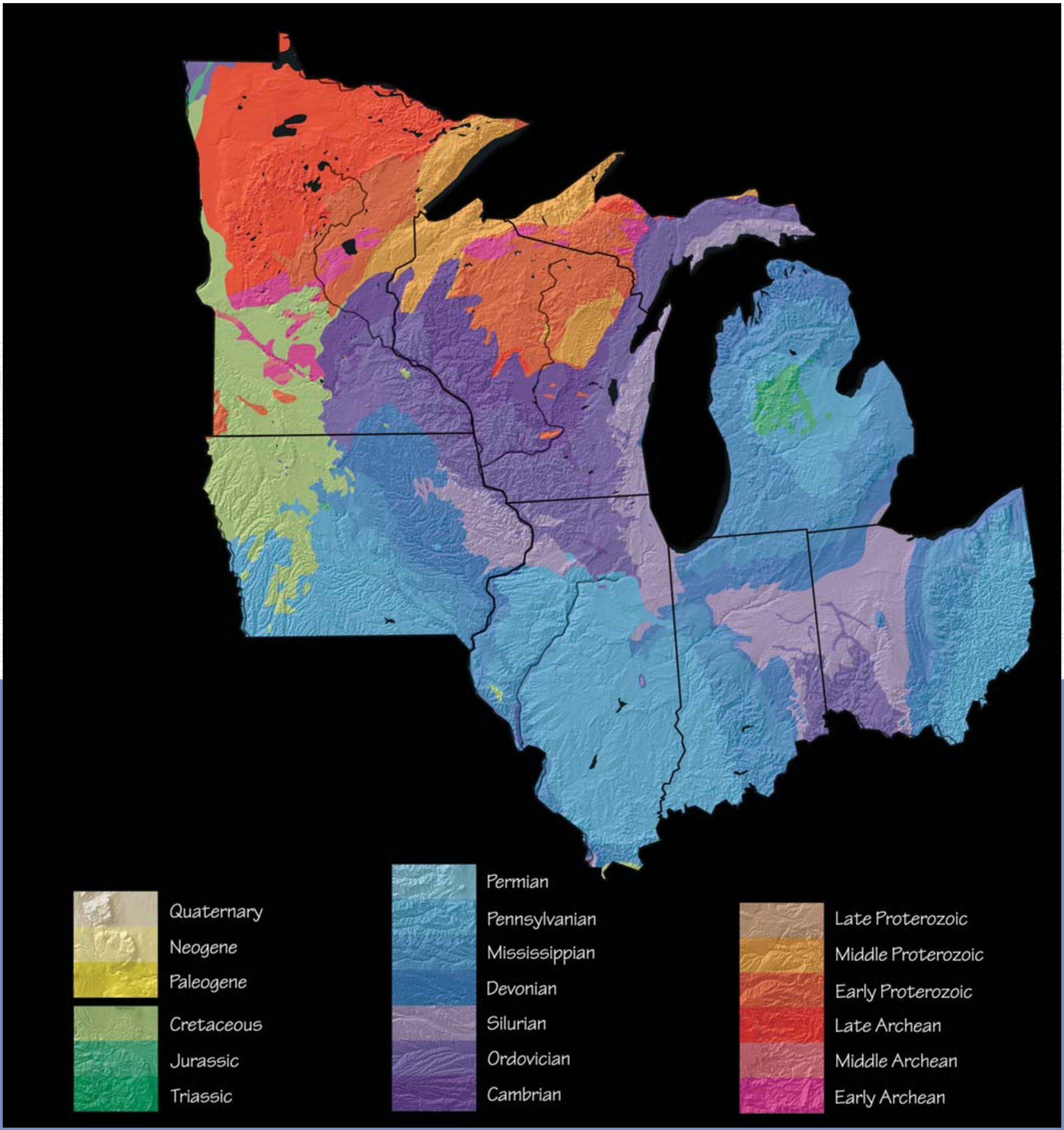
8.1: Adapted from figure by USDA NRCS
8.2: Adapted from figure by USDA NRCS
8.3: Wade Greenberg-Brand
8.4: Adapted from USDA National Soil Survey Center, 1995
8.5: Adapted from figure by USDA NRCS
8.6: Adapted from figure in Bradly and Weil, *The Nature and Properties of Soils* (11th ed.), 1996, Prentice Hall
8.7: Adapted from figure by University of Iowa/Iowa Geological Survey
8.8: Adapted from figure in Bradly and Weil, *The Nature and Properties of Soils* (11th ed.), 1996, Prentice Hall
8.9: Jim Houghton
8.10: Photo by Ilona L [CC-BY-NC-SA 2.0 (https://creativecommons.org/licenses/by-nc-sa/2.0)] via Flickr

Chapter 9: Climate

9.1: Jim Houghton
9.2: Adapted from Wikipedia
9.3: Photo by Ryan Somma [CC-BY-SA-2.0 (https://creativecommons.org/licenses/by-sa/2.0/)] via Flickr
9.4: Nyttend
9.5: Adapted from figure by William A. Cobban and Kevin C. McKinney, USGS
9.6: Pearson Scott Foresman
9.7: Jim Houghton
Koppen box: Adapted from figures by NOAA and Grieser *et al.*, 2006, World Map of the Köppen-Geiger climate classification updated, *Meteorologische Zeitschrift*, 15: 259–263
Tornado box: Adapted from figure by FEMA

Chapter 10: Earth Hazards

10.1: NOAA
10.2: US. Global Change Research Program
10.3: US. Global Change Research Program
10.4: Union of Concerned Scientists
10.5: USGS
10.6: Adapted from figure by Tobin and Weary, 2004, USGS
10.7: EPA
10.8: US Army Corps of Engineers



PALEONTOLOGICAL RESEARCH INSTITUTION
1259 Trumansburg Road
Ithaca, New York 14850 U.S.A.
www.priweb.org

ISBN: 978-0-87710-507-7

9 780877 105077 53000

US $30.00