The *Teacher-Friendly* Guide™

to the Earth Science of the Northwest Central US

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

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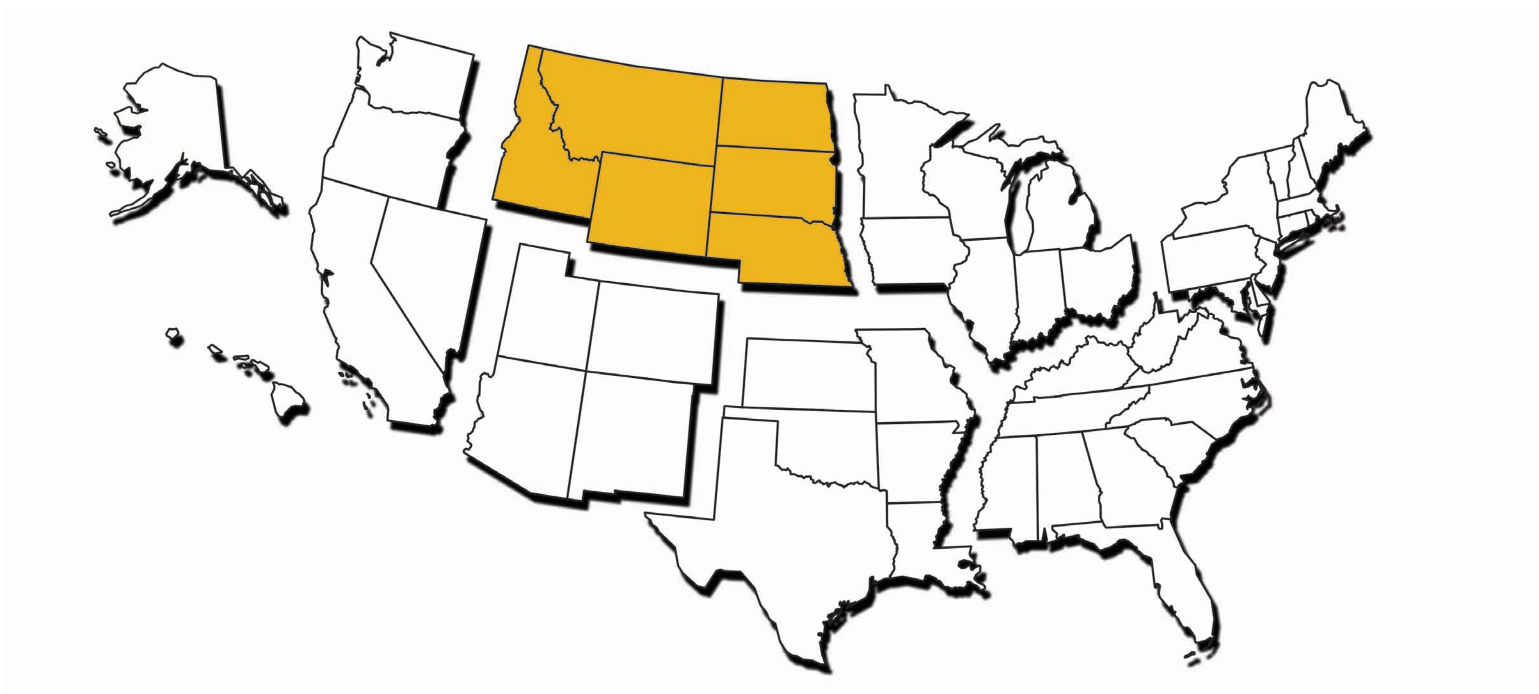

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On the back cover: Blended geologic and digital elevation map of the Northwest Central US. Each color represents the age of the bedrock at the surface. Adapted from Barton, K.E., Howell, D.G., Vigil, J.F., *The North America Tapestry of Time and Terrain*, 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 evolution of the Rocky Mountains and the sedimentary basins overlying the more stable continental interior. 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 Northwest Central United States in terms of a basic sequence of historical events and processes. Nationally distributed textbooks make references specifically to the Northwest Central area of the country. While a number of reasonably good resources exist for individual states, these do not take enough geographic scope into account to show why, say, geothermal energy and volcanic deposits are abundant in Idaho, but fossil fuel resources and sedimentary rocks are abundant in North Dakota and Wyoming, and what that has to do with the formation of the Rocky Mountains and the distribution of ancient crystalline igneous and metamorphic rocks at the surface. 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 Northwest Central US (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 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 Northwest Central US 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 five natural regions of the Northwest Central. 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
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September 2015

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How to Use this Guide

General philosophy of the Teacher-Friendly Guides™

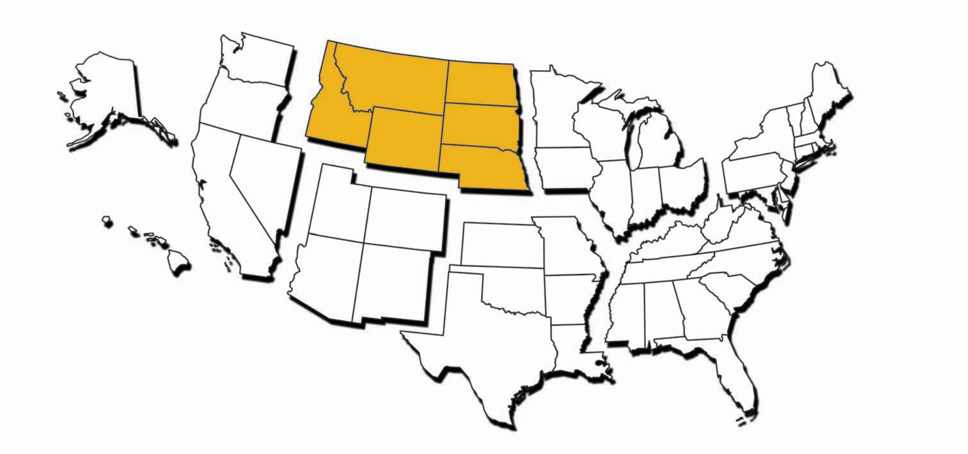
This Guide is organized by regional geologic history because it helps make sense of local Earth science—*Why does this place look the way it does? Why is this particular set of rocks, soil, landforms, water bodies, and local climate here?* We recommend introducing geologic history into your curriculum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



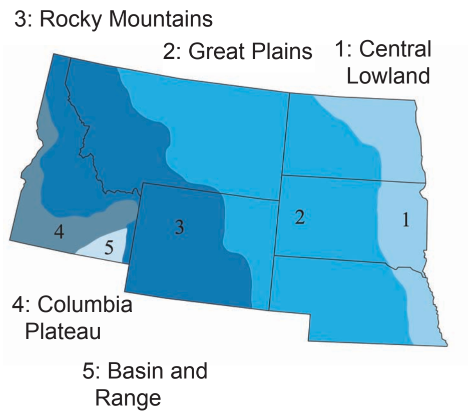
This Guide is one of seven covering the United States. There are also two *Teacher-Friendly Guides™* to evolution, one focused upon bivalves and another focused on maize genetics. To learn more, visit www.teacherfriendlyguide.org, a website of the Paleontological Research Institution.

For the interactive website version of this Guide, visit www.teacherfriendlyguide.org. To download individual chapters for printing, visit the website for the Northwest Central 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 Northwest Central US into five 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 five 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.

system • *a set of connected things or parts forming a complex whole.*

energy • *the power derived from the use of physical or chemical resources.*

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Big Ideas

Big Idea 1: The Earth is a system of systems

plate tectonics • *the process 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.*

delta • *a typically wedge-shaped deposit formed as sediment is eroded from mountains and transported by streams across lower elevations.*

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

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

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 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 from the north during the **ice age**, they cut into river valleys. This glacial system shaped the landscape of upper North America, deepening and widening existing rivers and damming huge lakes that later emptied in great torrents. For example, Glacial Lake Missoula emptied in a catastrophic flood that carved out the Channeled Scablands in northern Idaho and eastern Washington while also leaving behind huge sediment deposits. Had glaciers never advanced this far south, the erosional forces that led to the formation and draining of these lakes would have never been set in motion. The interaction of **climate**, rock, and water has shaped every natural landscape on the planet. Humans and other living things build upon (or tear down) the foundations laid down by these systems, furthering their interplay.

See Chapter 6: Glaciers to learn more about glacial lakes, including Lake Missoula and Lake Agassiz.

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.
>
> The landscape we see today in the Northwest Central has been shaped by the geologic forces of the past, and these forces are still active. 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. Evidence throughout the Northwest Central's terrain tells a story that began billions of years ago with the formation of tectonic plates, and this story continues today. Plate tectonics played a significant role in the formation of the Rocky Mountains when upwelling **mantle** heat pushed the **crust** upwards around 68 million years ago. Today, thanks to a swath of **fault** zones in the Rockies and tectonic activity at the Yellowstone **hot spot,** the Rocky Mountains and Columbia Plateau regions comprise one of the most seismically active areas in the United States, with as many as 3,000 earthquakes occurring each year.
>
> During the most recent ice age, glaciers advanced and retreated many times throughout 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.

See Chapter 10: Earth Hazards for more information about seismic activity in the Northwest Central.

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.*

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.*

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 • *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).*

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

Big Ideas

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

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._

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.

The Great Plains and Central Lowland regions, which make up the eastern portion of the Northwest Central, support extensive ranching and agriculture. The overwhelming majority of these regions are either under cultivation, used for grazing livestock, or developed for residential and commercial use. When we ask, "Why does this place look the way it does?" the role of humans must be central to our answer.

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.
>
> Tectonic processes have been at work in the same way for billions of years, opening and closing oceans and building up and tearing down landscapes. The Yellowstone hot spot, currently located in Yellowstone National Park in northwestern Wyoming, is a mantle plume that has melted the crust (and induced **volcanic** eruptions) as the North American plate has passed over it. The trail of volcanic rock from these eruptions crosses southern Idaho, forming the Snake River Plain and ending at Yellowstone National Park. Major explosive **caldera** eruptions have occurred on a cycle of around 600,000 years—this recent geological history of volcanism has led the Yellowstone area to be classified as a **supervolcano**.

See Chapter 1: Geologic History for more about the tectonic processes that led to the formation of North America as we know it today.

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).*

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

caldera • *a collapsed, cauldron-like volcanic crater formed by the collapse of land following a volcanic eruption.*

supervolcano • *an explosive volcano capable of producing more than 1000 cubic kilometers (240 cubic miles) of ejecta.*

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

compression • *flattening or squeezing as a result of forces acting on an object from all or most directions.*

The use of models is fundamental to all of the Earth sciences. Maps and models 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. They also 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 that occurs 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 riverbed, 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 Rocky Mountains 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 sheer weight of such an object depresses the continental mass. Understanding this **compression**—and the rebound that occurs upon the glacier's 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

Books

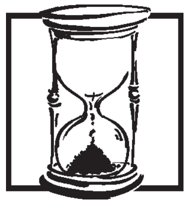
Donovan, S., & J. Bransford, 2005, *How Students Learn: Science in the Classroom*, National Academies Press, Washington, DC, http://books.nap.edu/catalog.php?record_id=10126.

Wiggins, G. P., & J. McTighe, 2005, *Understanding by Design, 2nd edition*, Association for Supervision and Curriculum Development, Alexandria, VA, 382 pp.

Wiske, M. S., ed., 1998, *Teaching for Understanding: Linking Research with Practice*, Jossey-Bass, San Francisco, CA, 379 pp.

Websites

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



Chapter 1: Geologic History of the Northwest Central US: Reconstructing the Geologic Past

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

The shape and position of North America has changed dramatically over the last billion years, and geologic processes continue these changes today. The Earth's outer layer—the **crust**—is dynamic, consisting of constantly moving **plates** that are made of a rigid continental and oceanic **lithosphere** overlying a churning, plastically flowing **asthenosphere**—part of the Earth's **mantle** (*Figure 1.1*). 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 the land, but also affects the distribution of rocks and **minerals**, natural resources, **climate**, and life.

Reconstructing the past is a lot like solving a mystery. Geologists use scraps of evidence to piece together events they have not personally observed, but to do so they must contend with two major complications. First, the overwhelming majority of geologic history occurred long before there were any human witnesses. Second, much of the evidence for the older events is highly fragmented. By studying rocks, **fossils**, and other geologic features, however, scientists can still reconstruct a great deal of what the ancient Earth might have looked like.

Rocks and sediments are indicators of past geologic processes and the environments in which those processes took place. In general, **igneous rocks**, created through tectonic activity, reflect the history of molten rock, both below the surface (**plutonism**) and at the surface (**volcanism)**. Likewise, **metamorphic rocks**, created when sediment is subjected to intense **heat** and pressure, provide important clues about past mountain-building events, and geologists often use them to map the extent of now-vanished mountain ranges. **Sedimentary rocks** tell perhaps the most comprehensive story of the Earth's history, as they record

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.*

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

volcanic island • *one of a string of islands created when molten rock rises upward 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.*

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1

Geologic History

Reconstructing

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

ultramafic rocks • *igneous rocks with very low silica content (< 45%), which are composed of usually greater than 90% mafic minerals.*

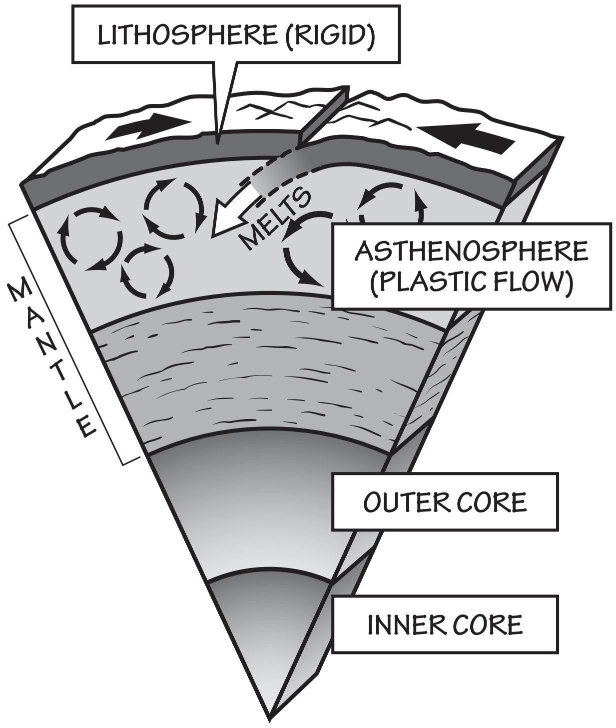


Figure 1.1: The layers of the Earth include the rigid crust of the lithosphere, which is constantly moving over the plastically flowing asthenosphere.

Lithosphere and Asthenosphere: What's the difference?

The difference between crust and mantle is mainly chemical: the lithosphere's composition typically varies between basalt in oceanic crust and diorite or *gabbro* in continental crust, while the mantle is composed of homogenous *ultramafic* material. The boundary between rigid lithosphere and flowing asthenosphere is usually found *within* the mantle, and is largely a result of temperature increase with depth beneath the surface. In tectonically active regions of extension such as the Basin and Range, where temperature rises rapidly with depth compared to in more tectonically stable regions, the asthenosphere begins nearly at the base of the crust.

Reconstructing

characteristics of far-away mountain ranges, river **systems** that transported the sediments, and the final environment in which the sediments accumulated and **lithified**. The size and shape of sediments in sedimentary rocks, as well as the presence of fossils and the architecture of sedimentary rock layers (sedimentary structures), can help us infer how the sediments were transported and where they were finally deposited. However, because rocks are often reformed into different rock types, ancient information is lost as the rocks cycle through the igneous, metamorphic, and sedimentary stages.

See Chapter 2: Rocks to learn more about different rocks found in the Northwest Central.

Fossils indicate both the type of life that once flourished in an area and the kind of climate in which that life existed. Paleontologists use groups of fossils found in the same place to construct pictures of ancient ecosystems. These ecosystems of the past are matched to similar present-day ecosystems, whose climate conditions are then used to infer what sort of climate the fossilized organisms lived in. Unfortunately, few organisms can be easily preserved as fossils, and many environments do not lend themselves to preserving organisms as fossils. As a result, the clues that fossils give us provide only incomplete glimpses of the ancient world, with many important details missing.

See Chapter 3: Fossils for more information about the Northwest Central's prehistoric life.

Landscapes and geologic structures are also indicators of past geologic processes and the environments in which they occurred. For instance, the shape of a valley reflects the forces that carved it. Valleys with V-shaped profiles tend to be the products of stream **erosion**, whereas U-shaped valleys are more likely to have been carved by **glaciers**. Layers of intensely folded rock indicate a violent past of tectonic plate collisions and mountain building. Sedimentary structures, such as **ripple marks** or **cross-bedding**, can demonstrate the direction and energy level of the water that transported the sediment. Although landscapes tell us much about the geologic processes that created them, they inevitably change over time, and information from the distant past is overwhelmed by the forces of the more recent past.

See Chapter 4: Topography for more detail about the landscape of the Northwest Central States.

Ultimately, geologists rely upon the preserved clues of ancient geologic processes to understand Earth's history. Because younger environments retain more evidence than older environments do, the Earth's recent history is better known than its ancient past. Although preserved geologic clues are indeed fragmentary, geologists have become increasingly skilled at interpreting them and constructing ever more detailed pictures of the Earth's past.

system *• a set of connected things or parts forming a complex whole.*

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

erosion *• the transport of weathered materials.*

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

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

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

1

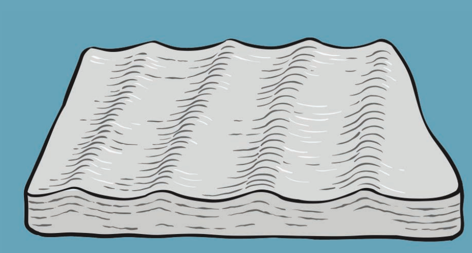
Geologic History

Reconstructing

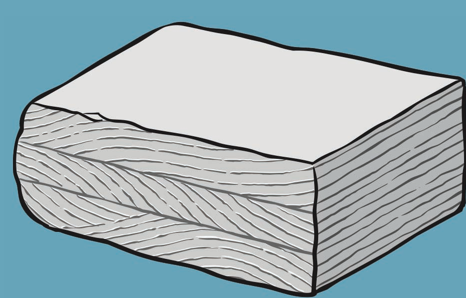
geologic time scale *• a standard timeline used to describe the age of rocks and fossils, and the events that formed them.*

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.

The **geologic time scale** (*Figure 1.2*) 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.

The first of these four divisions, the **Precambrian**, extends from the beginning of the Earth, around 4.6 billion years ago, to the beginning of the **Cambrian** period, around 541 million years ago. The Precambrian is subdivided into two sections: the **Archean** (before 2.5 billion years ago) and the **Proterozoic** (2.5 billion to 541 million years ago). Less is known about the Earth during the Precambrian than during later parts of its history, since relatively few fossils

Geologic History

1

Reconstructing

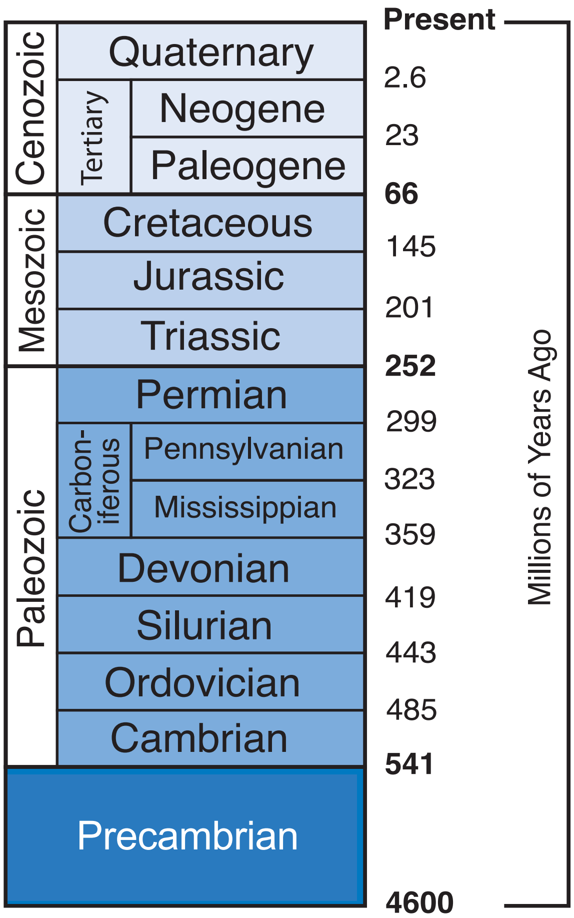


Figure 1.2: The Geologic Time Scale (spacing of units not to scale).

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 found 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.*

Geologic Time

How did geologists come up with the timeline for the history of the Earth? The geologic time scale was developed over the course of many years and through the combined work of geologists around the world. 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, evolutionary successions of fossils were discovered that helped geologists 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.

1

Geologic History

or unaltered rocks have survived. Nevertheless, the evidence that has been preserved and discovered reveals much about the planet's first several billion years, including clear evidence 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. Geological evidence shows that during this time period, continents moved, mountains formed, and 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.

Pangaea, meaning "all Earth," began to assemble over 300 million years ago and lasted for almost 150 million years. All of the Earth's continents were joined as one to form a giant supercontinent.

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 much more diverse and abundant. We humans didn't come into the picture until the last two 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 two seconds before midnight!

The Northwest Central States

The Big Picture

The geologic history of the Northwest Central United States is a story of the repeated assembly and disassembly of a large continental mass. By around 600 million years ago, the core of what would eventually become most of North America was a separate continental block. Over the next several hundred million years this continent was mostly tectonically stable and flat, and was repeatedly flooded and exposed by rising and falling sea level. Around 300 million years ago, episodes of tectonic activity and volcanism added land to the continent along what would become the West Coast. Major mountain building did not begin until around 100 million years ago, and reached its peak around 65 million years ago, at the very end of the Mesozoic era. These episodes of **orogenic** activity formed the Rocky Mountains, which have dominated the geology and landscape of western North America ever since. At the same time that the Rockies were rising, globally high sea level caused an enormous shallow sea – the Western Interior Seaway – to form across what is today the Great Plains, from Texas to Alaska. This seaway disappeared in the early Cenozoic era, and was replaced by a changing landscape of forest and grasslands filled with

Big Picture

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

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

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

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

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

natural hazards *• events that result from natural processes and that have significant impacts on human beings.*

meteorite *• a stony or metallic mass of matter that has fallen to the Earth's surface from outer space.*

an amazing diversity of life, especially mammals, which replaced dinosaurs in most of the ecological niches for large terrestrial vertebrates.

In this volume, the Northwest Central States are divided up into five different geologic provinces or regions (*Figure 1.3*): the Central Lowland (1), Great Plains (2), Rocky Mountains (3), Columbia Plateau (4), and the Basin and Range (5). Each of these regions has a different geological history and thus varies in rocks, fossils, **topography**, mineral resources, **soils**, and **natural hazards**.

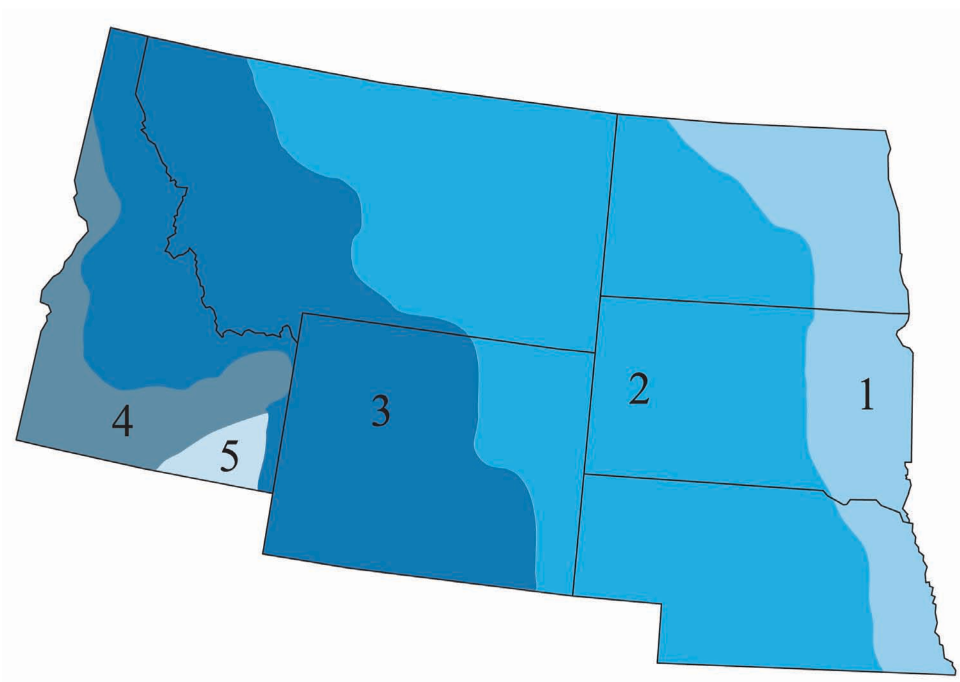


Figure 1.3: Geologic regions of the Northwest Central.

Precambrian Beginnings

Roots of the Northwest Central

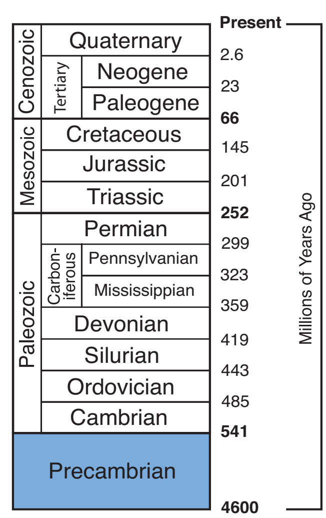
The Earth is estimated to be approximately 4.6 billion years old—an age obtained by dating **meteorites**. Rocks dating to around four billion years old are found on almost every continent, but the oldest rocks known on Earth are 4.3 billion-year-old rocks found along the eastern shore of Hudson Bay in northern Quebec. These are part of the **Canadian Shield**, the ancient core of the North American continental landmass, which has experienced very little tectonic activity (**faulting** and folding) for millions of years. Shields, or **cratons**, are the stable cores of all continents and are often covered by layers of younger sediments. They formed and grew during pulses of **magmatic** activity, as bodies of molten rock deep in the Earth's crust contributed to form new crust. In the Northwest Central US, the main cratonic elements are referred to as the Wyoming Province (Wyoming

Precambrian

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

***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.*

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



1 Geologic History

Precambrian

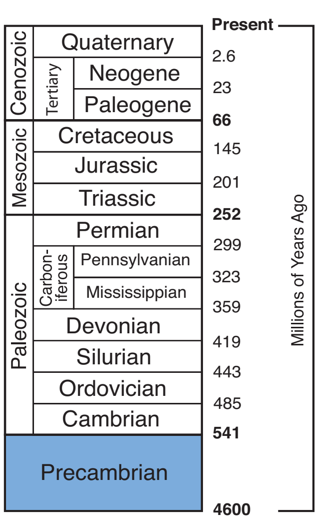
uplift *• upward movement of the crust due to compression, subduction, or mountain building.*

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

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

compression *• flattening or squeezing as a result of forces acting on an object from all or most directions.*

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



and eastern Montana), the Medicine Hat Block (northwestern Montana), and the Superior Province (Dakotas, Minnesota, Wisconsin, and Michigan) (*Figure 1.4*). Outcrops of these rocks are exposed mainly as **uplifted** blocks in mountain ranges throughout Wyoming, Montana, and South Dakota. The oldest rocks identified so far in the Northwest Central US are 3.6– to 3.8-billion-year-old **granitic gneisses** found in Wyoming's Wind River Mountains.

The oldest known materials in the world are 4.4-billion-year-old zircons from rocks in Western Australia.

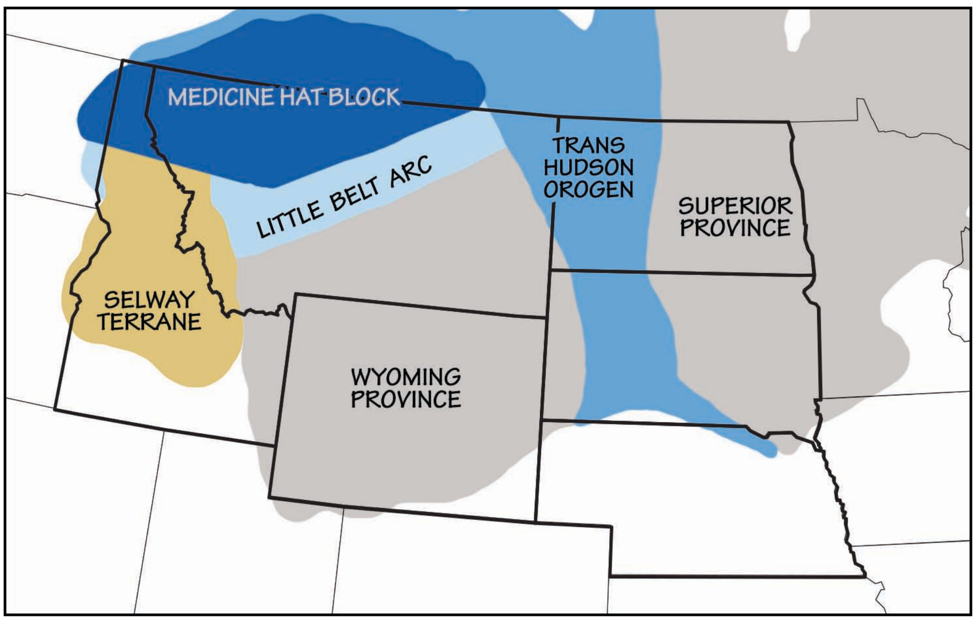


Figure 1.4: Cratonic elements and belts of deformation. (See TFG website for full-color version.)

The shape and position of North America has changed dramatically over the last billion years, and geologic processes continue these changes today. **Compression** from colliding plates, tension from plates pulling apart, the addition of land to North America, **weathering**, uplift, and erosion have combined to slowly sculpt the form of the continent. As such, it is very difficult to reconstruct the size, shape, and position of continents during the Precambrian. Fewer rocks are preserved from this time, and those that remain have been highly altered. Nevertheless, available evidence suggests that the proto-North American continent, also called Laurentia, had its Precambrian beginnings in a supercontinent that existed around 2.6 billion years ago. From this proto-North America, sediment was eroded and transported by rivers and streams across the ancient continental margins and then into the adjacent oceans. The sediment deposited in the ocean waters on the western margin of Laurentia can be found today in southern Wyoming's 2.2– to 2.4-billion-year-old Snowy Range Supergroup, where thick sequences of **sandstone**, **conglomerate**, and **limestone** were deposited near what is now the southern margin of Wyoming.

These sediments contain 2.3-billion-year-old **stromatolites** (mounds of sediment formed by mats of photosynthetic **cyanobacteria**), indicating that they were deposited in a continental shelf environment. During this time period, at least two episodes of glaciation occurred, represented by rocks formed from glacially derived sediments (**tillites**) found in Idaho and Montana.

See Chapter 2: Rocks to learn more about stromatolites.

Around two billion years ago, a second supercontinent, often called columbia or Nuna, began to assemble from major cratons and other fragments of land. In the Northwest Central, the zones of collision between the cratons and fragments are preserved as deformed metamorphic rocks in the Little Belt Arc of northern Idaho and Montana, the Selway Terrane of southern Idaho, and the Trans-Hudson Orogen of the Dakotas and Canada (*see Figure 1.4*). The breakup of this supercontinent began around 1.5 billion years ago.

The remainder of the Precambrian period saw the formation of a third supercontinent, which geologists call **Rodinia,** about 1.1 billion years ago (*Figure 1.5*), and its eventual breakup about 750 million years ago. Preserved remnants of the continental collisions that formed this supercontinent are found widely across modern North America, but very few of these elements are recognizable in the Northwest Central US.

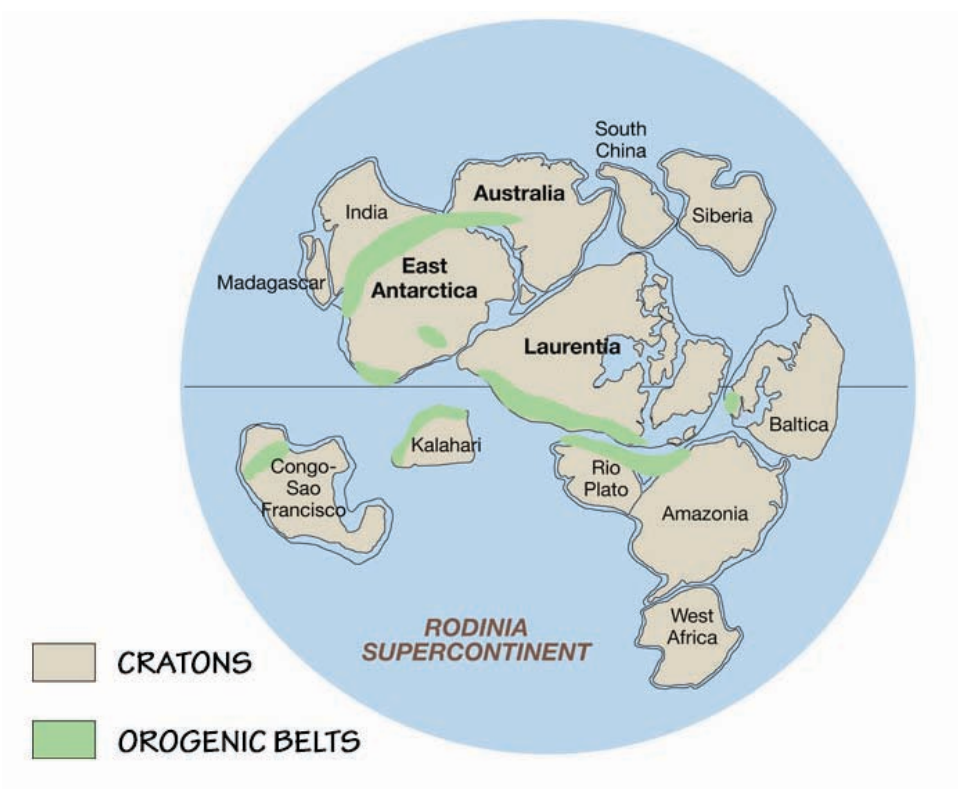


Figure 1.5: The supercontinent Rodinia, circa 1.1 billion years ago. Laurentia represents proto-North America. (See TFG website for full-color version.)

Precambrian

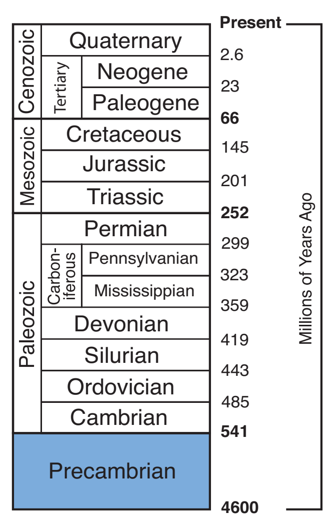
sandstone • *sedimentary rock formed by cementing together grains of sand.*

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

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

tillite • *glacial till that has been compacted and lithified into solid rock.*

Rodinia • *a supercontinent that contained most or all of Earth's landmass, between 1.1 billion and 750 million years ago, during the Precambrian.*



1 Geologic History

Paleozoic

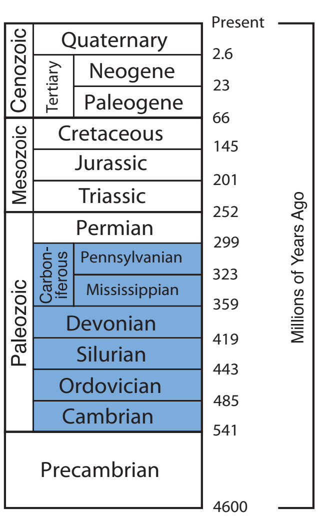
__rift__ • a break or crack in the crust that can be caused by tensional stress as a landmass breaks apart into separate plates.

__passive margin__ • a tectonically quiet continental edge where crustal collision or rifting is not occurring.

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

__accretion__ • the process by which a body of rock increases in size due to the addition of further sedimentary particles or of large chunks of land.

__plate tectonics__ • the process by which the plates of the Earth's crust move and interact with one another at their boundaries.



The breakup of Rodinia was associated with the formation of **rifts** throughout North America, with igneous activity occurring in rifted zones and continuing slowly and irregularly until about 600 million years ago. North America's rifted edges formed **passive margins**, where sediments were deposited on continental shelves into the early Paleozoic era.

A rift occurs when tectonic plates move away from each other. Magma rises up into the margin, cooling to produce new oceanic crust. The resulting action is similar to two conveyor belts moving away from each other. A failed rift occurs when the existing crust is stretched thin and magma begins to well up, but the plate is never completely broken.

The Paleozoic:
Formation of a Continent

At the beginning of the Paleozoic, during the Cambrian, the area that is now the states of California, Oregon, Washington, Idaho, and Nevada did not yet exist as part of the North American continent. The edge of North America's continental shelf was located at approximately the Arizona-Utah-Nevada-Idaho line (*Figure 1.6*). In the late **Devonian** (370 million years ago), a portion of the continental shelf adjacent to present-day Idaho and Nevada transitioned from quiet passive margin to an active **subduction** zone, where oceanic crust plunged beneath the continent. Here, as oceanic crust descended deep into the upper mantle, the rock above the descending crust melted to form a line of volcanoes on the surface. Subduction also led to **accretion**—sediment, sedimentary rock, and even bits of the oceanic crust itself were scraped off the descending crustal plate and pushed onto the overlying plate (*Figure 1.7*). Just as a rug develops folds when pushed from the side, these rocks were wrinkled up into mountains. Volcanic islands carried along by the subducting plate also accreted to the edge of the continent. The landmass began to rotate, moving the North American plate into a more modern orientation.

During the **Carboniferous**, **plate tectonics** led to the initial stages of Pangaea's assembly. As North America began to collide with **Gondwana**, forces from the collision began to affect the continent's topography. During the **Mississippian** (340 million years ago), most of the West Coast had transformed into a subduction zone. A series of exotic **terranes**, consisting of sedimentary rock made from former seafloor sediment, slabs of volcanic and granitic rock, and the remains of volcanic islands, collided with and accreted to western North America. These collisions deformed and elevated the continent's topography, generating two major mountain-building events: the **Antler Orogeny** (340 million years ago) and the **Sonoman Orogeny** (245 million years ago).

During the **Pennsylvanian** (300 million years ago), compressional forces from the collision and tension from coastal subduction combined to deform the continent's interior, buckling

Geologic History 1

Paleozoic

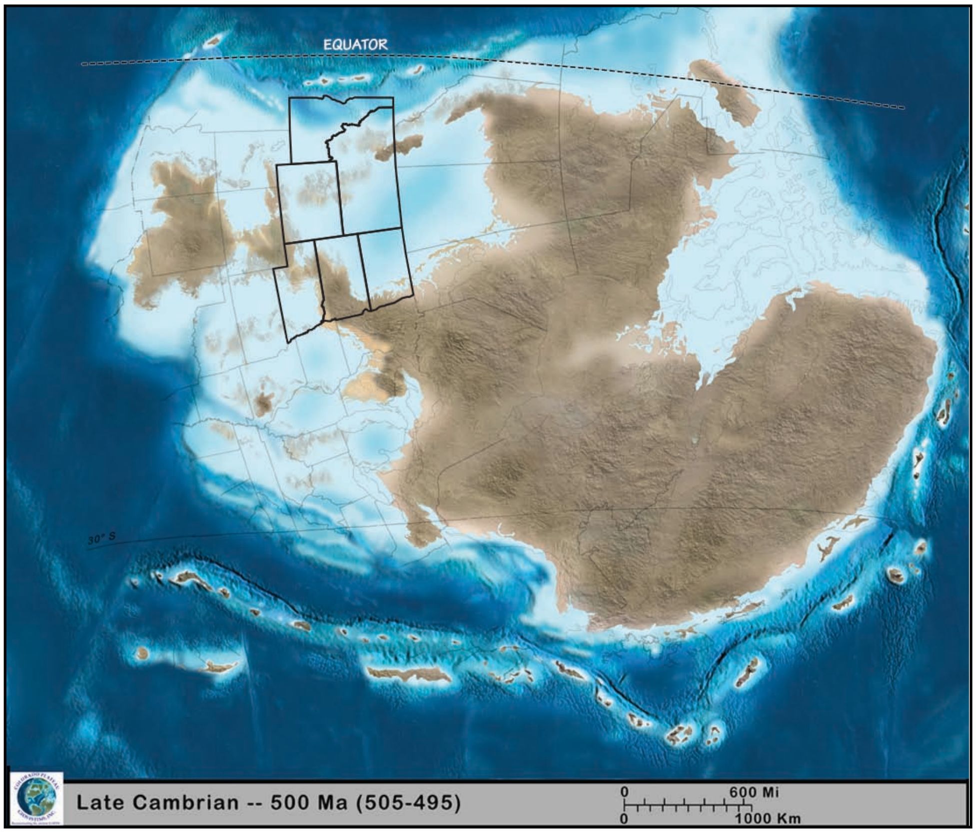


Figure 1.6: The Northwest Central US during the late Cambrian, approximately 500 million years ago. The entire region is located in the southern hemisphere—note the position of the equator.

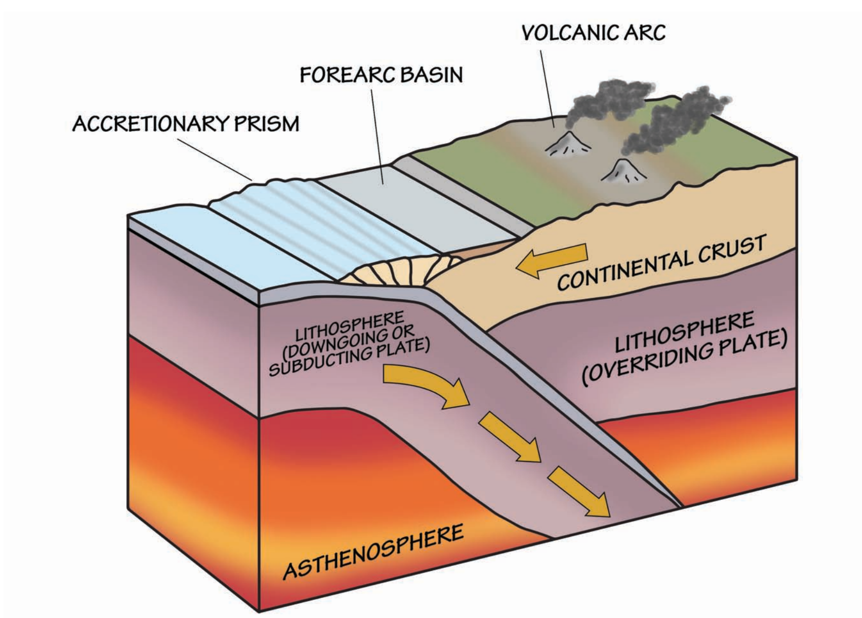


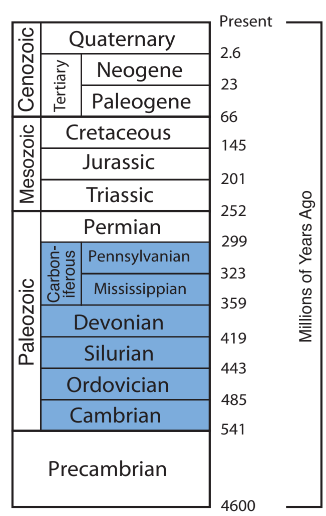
Figure 1.7: Subduction along the western edge of the North American plate.

Gondwana *• the super-continent of the Southern Hemisphere, composed of Africa, Australia, India, and South America.*

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

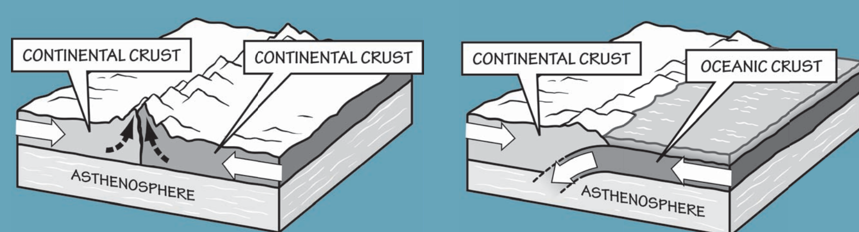
Antler Orogeny *• a period of mountain building that deformed rocks in a belt extending from the California–Nevada border northward into Idaho.*

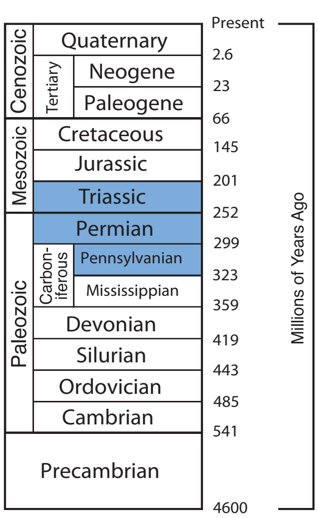
Sonoman Orogeny *• a period of mountain building along the western edge of North America, in what is now Nevada and eastern Oregon.*



Continental and Oceanic Crust

The lithosphere includes 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 denser 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.





the crust and creating deep basins between uplifted blocks. Shallow **inland seas** spread across the interior of the continent, covering parts of North America's Precambrian shield (*Figure 1.8*). Uplift formed a mountain range, known as the Ancestral Rocky Mountains, in Wyoming, Colorado, and New Mexico, and land was also raised above sea level in Canada, Montana, and the Dakotas. Sediments that eroded from this range and other uplifted areas were transported to the inland sea and the continental margins, forming deposits of conglomerates, sandstones, **shales**, limestones, and **evaporite** minerals. Although the Ancestral Rocky Mountains has long since eroded away, remnants of its core remain, and can be seen today in Colorado and Utah. As accretion continued over time, the coastline moved farther seaward (*Figure 1.9*). Sea level fell in the late Paleozoic, during the Pennsylvanian and **Permian**, as continental collisions progressed to form the supercontinent Pangaea.

Paleozoic

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

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

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

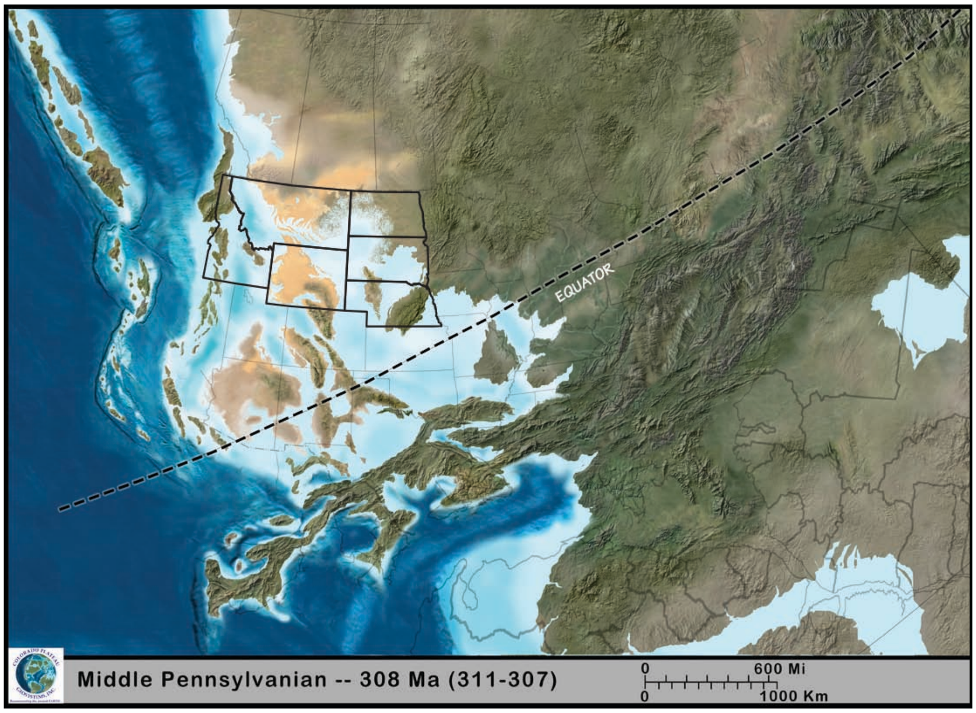


Figure 1.8: The Northwest Central US during the Pennsylvanian, approximately 208 million years ago.

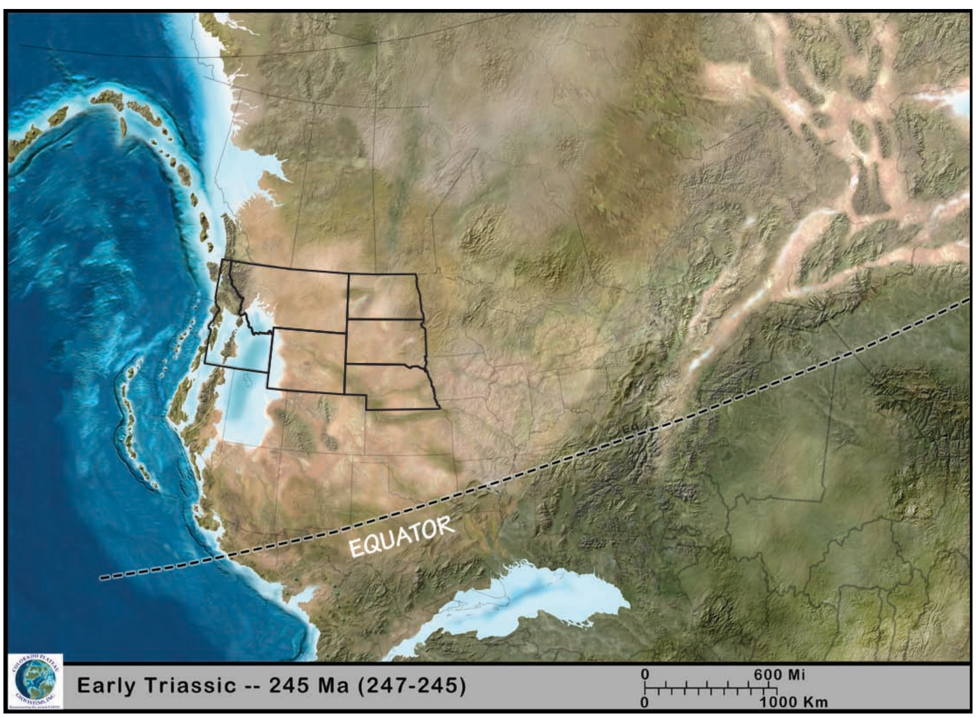
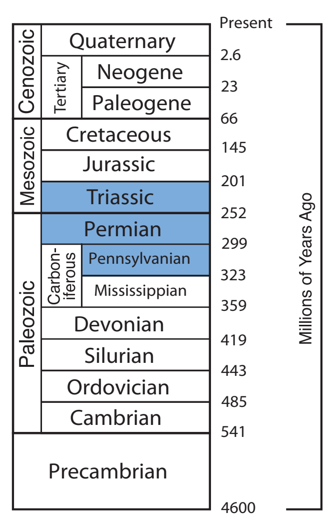


Figure 1.9: The Northwest Central US during the early Triassic, approximately 245 million years ago.



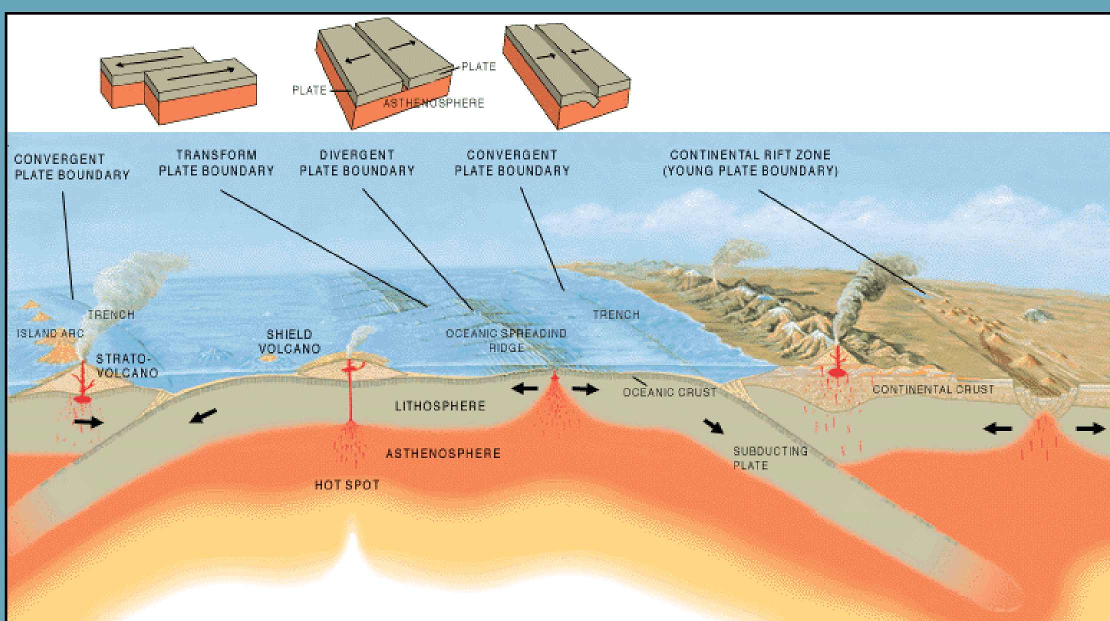
1 Geologic History

Paleozoic

Understanding Plate Boundaries

Active plate margins are the boundaries between two plates of the Earth's crust that are colliding, pulling apart, or moving past each other as they move over the mantle.

When one plate slides beneath another, it is called a *convergent boundary* or subduction zone. When two plates pull apart from each other, it is known as a *divergent boundary* or rift margin. When the plates slip past each other in opposite directions, it is called a *transform boundary*.



(See TFG website for full-color version.)

The Mesozoic:
A Story of Mountains and Seas

The Mesozoic era is frequently known as the Age of the Dinosaurs or Age of Reptiles, but many other life forms evolved and thrived during this time, including marine invertebrates, flowering plants, birds, and mammals. The Mesozoic was also a time of major geologic change during which great thicknesses of rocks were deposited across the western US.

The supercontinent Pangaea was in place by the end of the Permian period, and global sea level was probably at its lowest of any time during the past 600 million years. During the **Triassic** and **Jurassic**, sea levels rose, and a shallow arm of the sea reached from Canada through Montana and parts of Wyoming (*Figure 1.10*). **Iron**-rich limestones, sandstones, and mudstones laid down in this sea were **oxidized**, giving a distinctive and characteristic red color to the rocks, which are appropriately called "red beds." During the Jurassic, mudstone and sandstones were also deposited in lowland areas and river channels throughout the Rocky Mountains and **Colorado Plateau**; these formed the Morrison Formation, which is famous for its abundant dinosaur fossils.

See Chapter 3: Fossils to learn about the Morrison Formation and other fossil-rich rock formations.

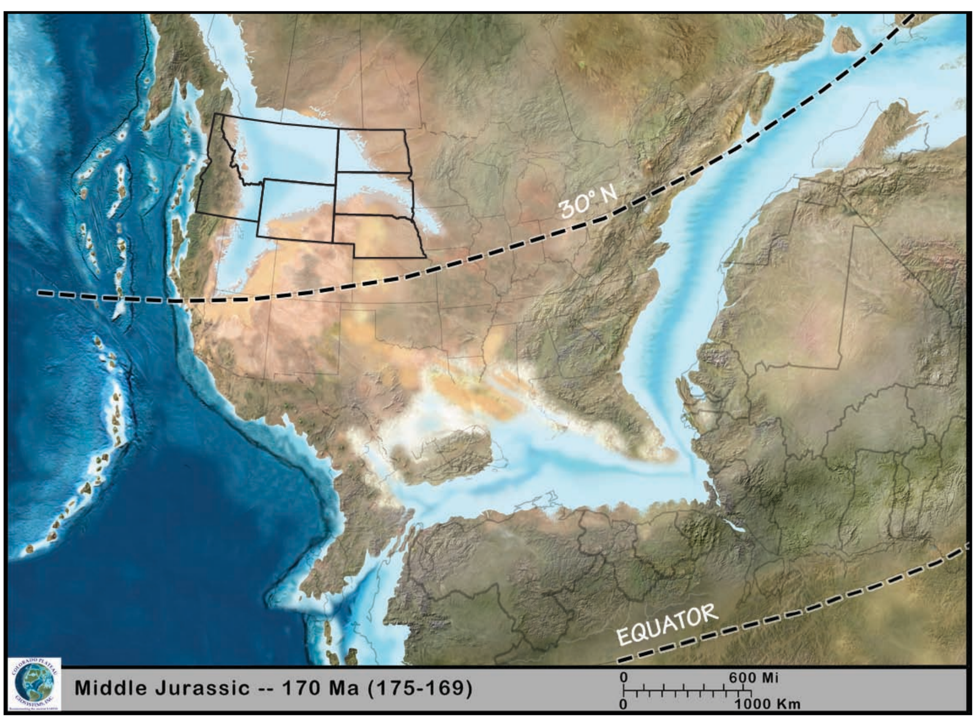


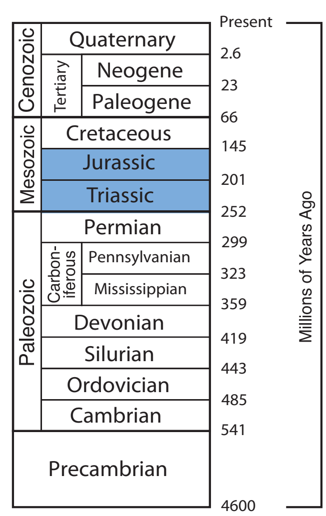
Figure 1.10: The Northwest Central US during the Jurassic, approximately 170 million years ago.

Mesozoic

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

oxidation • *a chemical reaction involving the loss of at least one electron when two substances interact.*

Colorado Plateau • *a physiographic region that covers an area of 337,000 square kilometers (130,000 square miles) of desert and forest within Colorado, New Mexico, Arizona, and Utah.*



Mesozoic

downwarp *• a segment of the Earth's crust that is broadly bent downward.*

Sevier Orogeny *• a mountain-building event resulting from subduction along the western edge of North America, occurring mainly during the Cretaceous.*

During the early **Cretaceous**, Pangaea entered its final stages of breakup (*Figure 1.11*). Far to the west, oceanic crust (the Farallon plate) had been subducting under western North America for tens of millions of years, causing a series of volcanic island complexes to collide with and become accreted to that margin of the continent, forming the Sierra Nevada of California. As the new Atlantic Ocean widened, sea levels began to rise. Around 85 million years ago, when the Farallon plate began to subduct at an unusually shallow angle, it slid farther inland beneath western North America before finally sinking into the asthenosphere. This **downwarped** the center of the continent and created a basin that allowed the waters of the Gulf of Mexico to meet with those in the north, forming the Western Interior Seaway (*Figure 1.12*), which inundated a 1000-kilometer (620-mile) wide swath from Mexico to Alaska. During the very latest stages of the Cretaceous period, around 70 million years ago, the Western Interior Seaway was displaced by slow uplift of the continent.

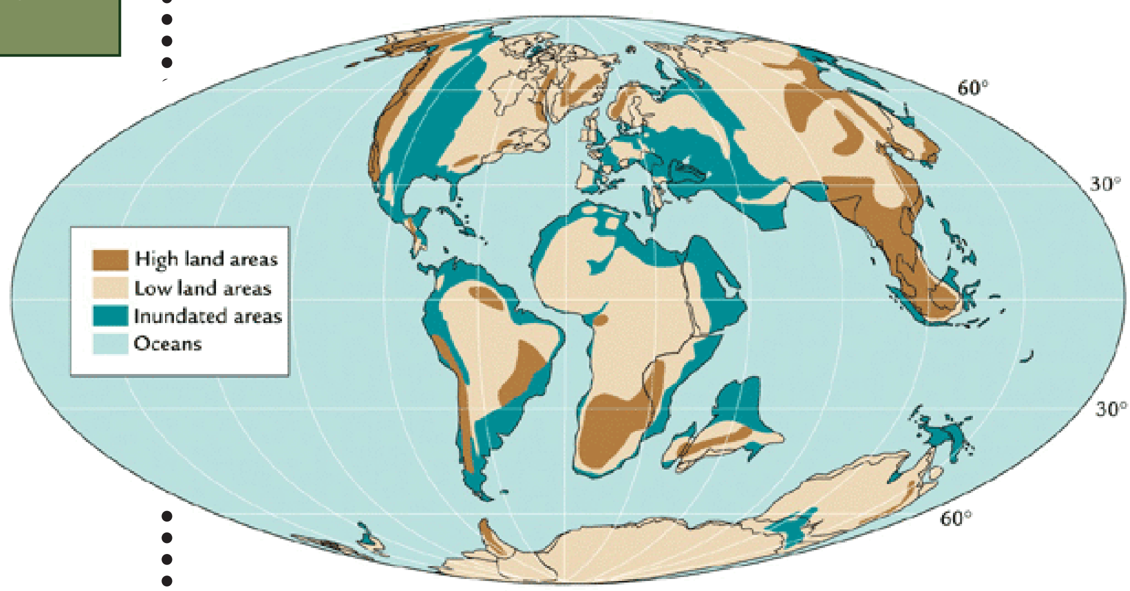
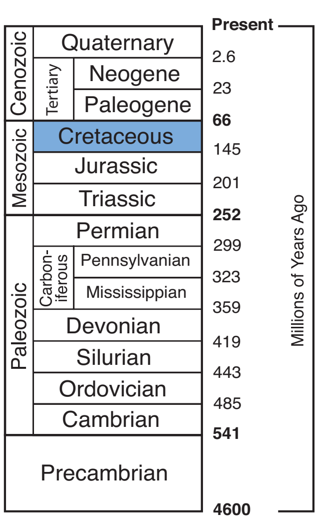


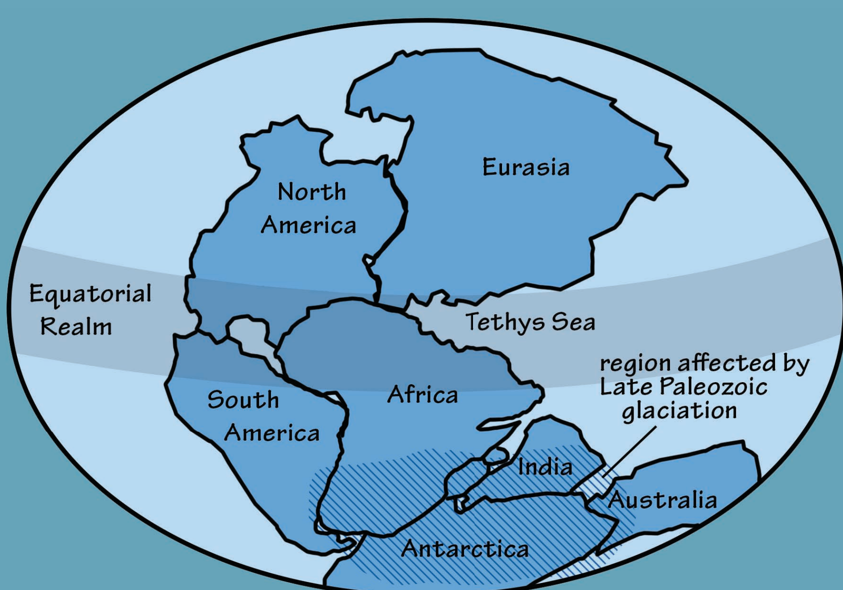
Figure 1.11: Landmasses following the breakup of Pangaea. (See TFG website for full-color version.)



The Farallon plate continued to collide with western North America, thrusting layers of rock up over each other and causing increasing volcanism to the west of the Western Interior Seaway. The compressional forces of subduction faulted the crustal rocks of western North America and uplifted the Rocky Mountains in two major pulses. The **Sevier Orogeny** (100–72 million years ago) raised the portion of the Rocky Mountains in Montana, Wyoming, and Utah known as the "Overthrust Belt." The second event, the **Laramide Orogeny**, peaked around 68–65 million years ago, when the angle of the subducting plate became shallower, uplifting the Rocky Mountains in Colorado and New Mexico. While most of the magmatic activity at this time occurred on the western edge of the continent in the volcanic arc of the Sierra Nevada, some did take place farther inland. The largest and most important evidence of this is the Idaho Batholith—three major lobes of granitic material **intruded** beneath large areas of Idaho

Evidence for Pangaea

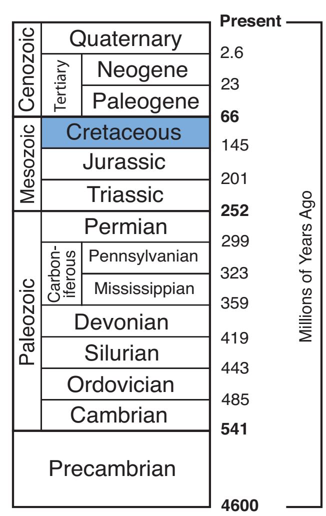
How do we know that Pangaea existed 250 million years ago? Fossil evidence and mountain belts provide some of the clues. For example, the Permian-age fossil plant *Glossopteris* had seeds too heavy to be blown across an ocean. Yet *Glossopteris* fossils are found in South America, Africa, Australia, 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, which slowly moved toward their present-day positions over the following 150 million years.



Pangaea during the late Paleozoic era

Laramide Orogeny • *a period of mountain building that began in the Late Cretaceous, and is responsible for the formation of the Rocky Mountains.*

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



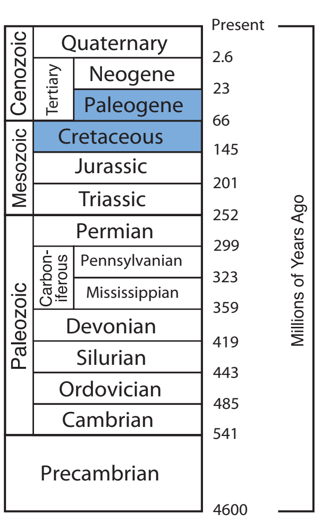
Mesozoic

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

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.*

fluvial *• see outwash plain: large sandy flats created by sediment-laden water deposited when a glacier melts.*

volcanic ash *• fine, unconsolidated pyroclastic grains under 2 millimeters (0.08 inches) in diameter.*



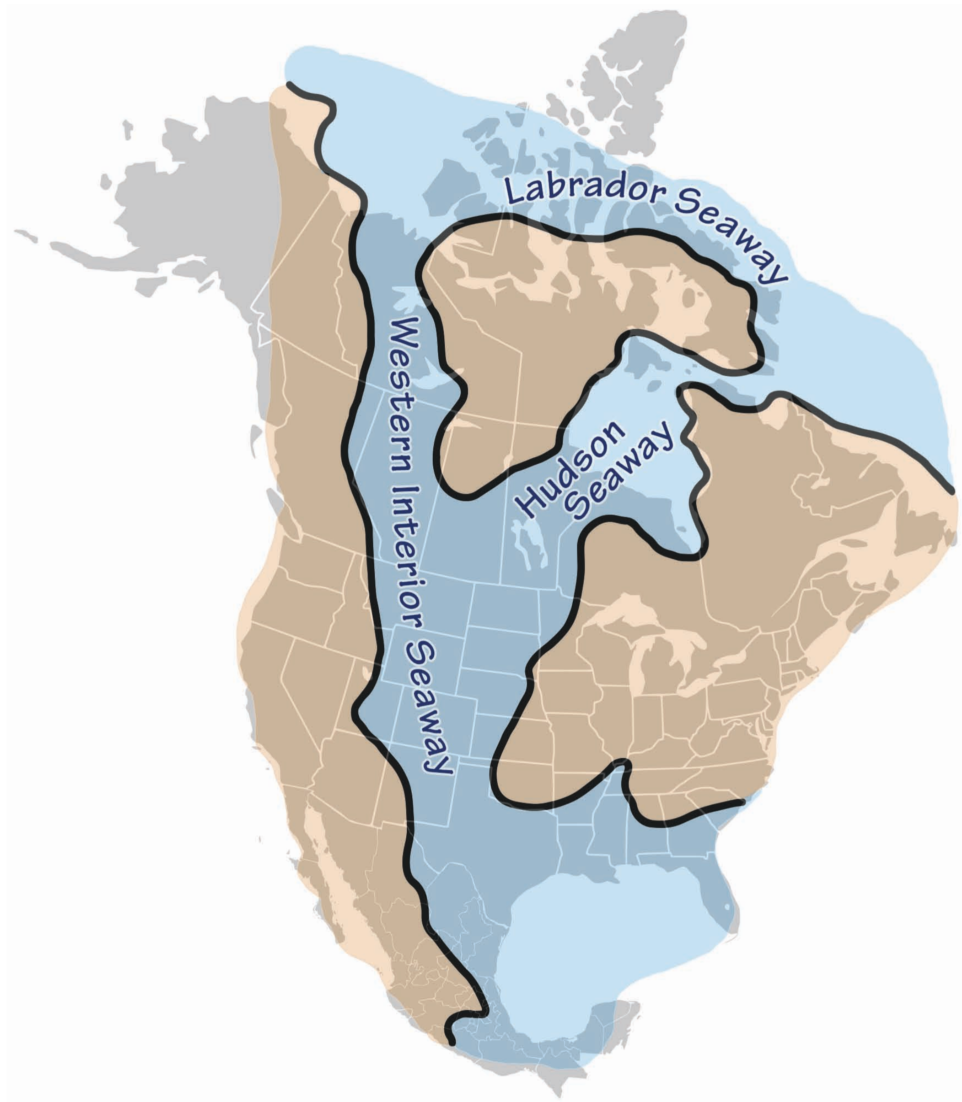


Figure 1.12: The Western Interior Seaway.

between 100 and 65 million years ago. The rising ancestral Rocky Mountains provided sediment that filled the seaway, and uplift from the ongoing orogeny finally caused the water to split in the Dakotas and retreat south.

Because the crust flexes or breaks under compression, several **inland basins** formed between the mountain ranges, and the eroding mountains shed thick layers of sediment into these basins, forming conglomerates, sandstones, and mudstones. The Colorado Plateau remained stable during this time of compression, and persisted during the subsequent episode of extension that followed from the **Paleogene** period to the present day.

Geologic History 1

Cenozoic

The Cenozoic

Volcanism and Tectonism

The Cenozoic era (consisting of the Paleogene and **Neogene** periods, 66 million years ago to present) was an age of diversification and evolution of mammals, birds, insects, flowering plants, and coral **reefs**. The continents continued to spread apart to reach their present day positions. Sea levels rose and fell, affecting the coastline, but the interior of North America remained relatively high. Sediment deposition, for the most part, occurred as **fluvial** and lake deposits. This was also a time of active volcanism in western North America. The Cenozoic geology of western North America is dominated by three large-scale processes: erosion, subduction and extension, and volcanic activity.

Erosion of the mountains and highlands that had formed during the Mesozoic produced thick layers of conglomerates, sandstones, and mudstones across much of the Northwest Central. **Volcanic ash** is commonly interlayered with these sediments. Many of these sedimentary layers were deposited by rivers, or in **alluvial** fans coming from the mountain systems. Several such layers are now important **aquifers**, including the enormous Ogallala Aquifer (*Figure 1.13*) which today supplies water for farming and communities across much of the Great Plains. Due to crustal deformation during the Mesozoic, several basins formed inland lakes or depressions into which sediments were deposited. The best-known example is the Green River Basin of western Wyoming, which is famous for its well-preserved fossils found in lakebed shales and mudstones.

See Chapter 3: Fossils for more information about the Green River fauna.

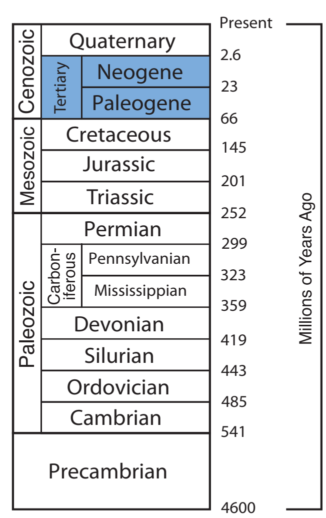
Subduction at the West Coast ceased with the development of the San Andreas Fault System. Due to the complex interplay of plate motions, the portion of the subducting plate beneath the Southwest US overrode hot, upwelling mantle. This, in turn, caused a number of major changes. In the early Paleogene, melting of the lower crust resulted in the emplacement of numerous granitic bodies and volcanic eruptions across the western US, including the Absaroka Range in Wyoming and Montana and the Challis Volcanic Field in Idaho. These large packages of volcanic rocks also host important mineral deposits. Ash from these eruptions fell long distances from its source, and is a major component of terrestrial sediment on the Great Plains, much of which is abundantly fossiliferous.

By the Neogene, the Farallon plate lay shallowly under the North American plate for hundreds of kilometers eastward of the West Coast. Now situated more fully beneath what are now the South Central, Southwestern, and Northwest Central States, this extra layer of crust caused uplift and extension of the region, as the added thickness of buoyant rock (relative to the mantle) caused the entire area to rise **isostatically**. The Farallon plate was subjected to increasing temperatures as it subducted, causing it to expand. As heat dissipated to the overlying North

alluvial *• a thick layer of river-deposited sediment.*

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

isostasy *• an equilibrium between the weight of the crust and the buoyancy of the mantle.*



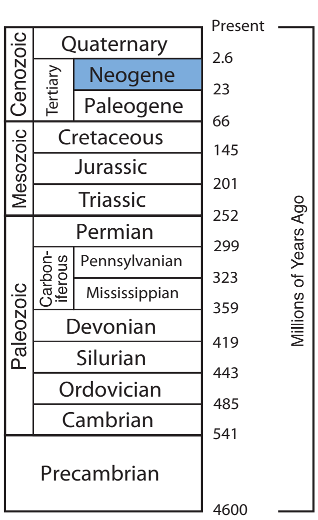
Cenozoic

badlands *• a type of eroded topography that forms in semi-arid areas experiencing occasional periods of heavy rainfall.*

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

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

caldera *• a collapsed, cauldron-like volcanic crater formed by the collapse of land following a volcanic eruption.*



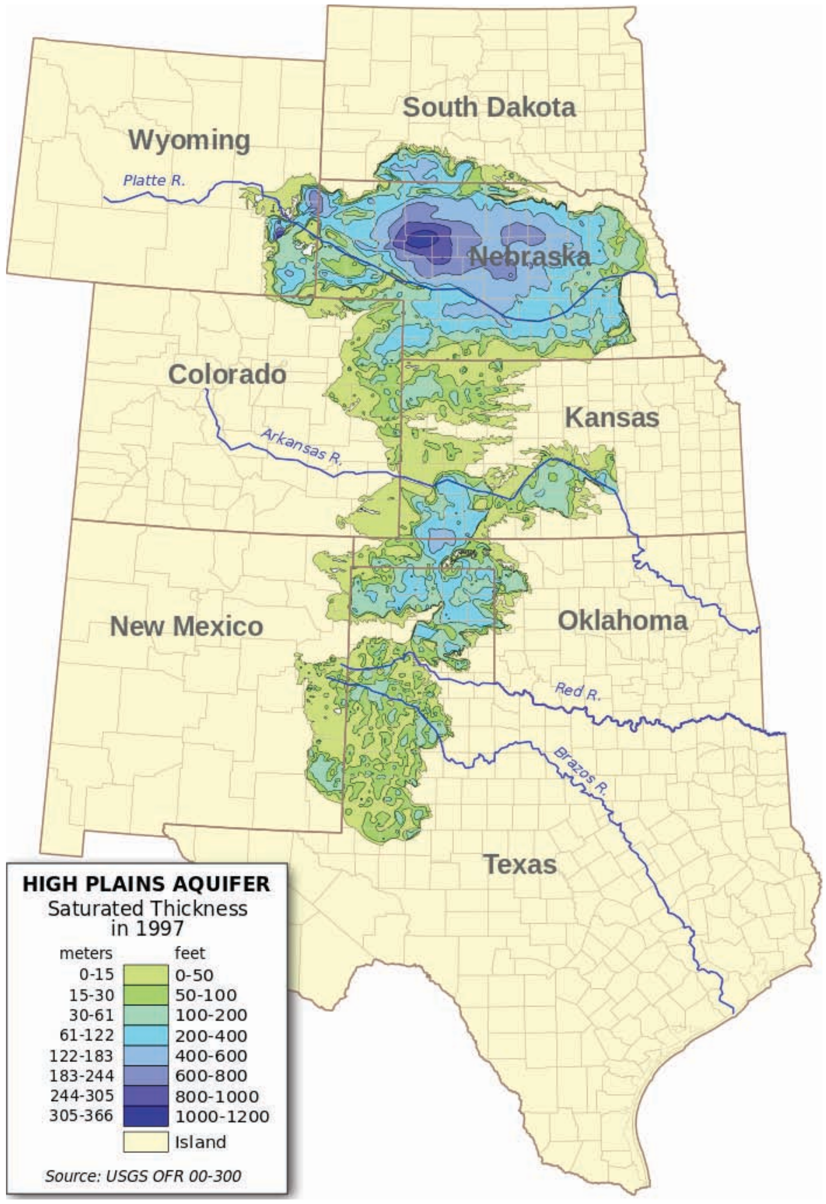


Figure 1.13: Extent and saturated thickness of the Ogalalla Aquifer. (See TFG website for full-color version.)

American plate, that rock expanded as well. Finally, the high temperatures in the upper mantle caused the Farallon plate to melt, and the resulting magma was injected into the North American plate, destabilizing it. These processes caused the surface of the North American plate to pull apart and fault into the mountainous blocks of the huge Basin and Range province that stretches from Idaho, Nevada and Utah into California, Arizona, New Mexico, and Texas.

See Chapter 4: Topography to learn more about the Basin and Range.

At the end of the Neogene, around eight million years ago, epeirogenic uplift (resulting from upwelling mantle heat pushing the crust upwards) began, raising the Rocky Mountains and Colorado Plateau to its current "mile-high" elevation and initiating the downcutting of the Grand Canyon in Arizona. Another example of downcutting is the more recent development, 500,000 years ago, of the Badlands in South Dakota, where Cretaceous and Cenozoic sedimentary rocks are eroded into **badland** topography.

The development of the Yellowstone **hot spot** appears to have begun with the eruption of the voluminous Columbia Plateau flood **basalts** in present-day Washington and Oregon around 14 million years ago. As the North American plate traveled over this mantle plume, the crust melted and produced a trail of volcanic rock that crosses southern Idaho, forming the Snake River Plain and ending at Yellowstone National Park in northwestern Wyoming (*Figure 1.14*). The trail of volcanic eruptions from the hot spot works its way east along this path, with major explosive **caldera** eruptions occurring on a cycle of around 600,000 years. Multiple minor eruptions occur between the larger explosions; for example, Craters of the Moon National Mounment in southern Idaho is a recent (15,000 to 2000 years old) volcanic flow associated with rift zones formed by the Yellowstone hot spot. The latest caldera at Yellowstone National Park is 630,000 years old, and contains many younger minor volcanic flows and domes. The recent geological history of volcanism at Yellowstone has led the area to be classified as a **supervolcano**. While there is concern that the hot spot could generate another violent eruption, researchers using **seismic tomography** have not observed large volumes of melt below the area that could result in a large eruption. The hot spot has now reached a boundary of thicker overlying crust, which will significantly affect the amount and timing of the melt it produces, and the odds of an explosive eruption occurring during the next several thousand years are very low.

See Chapter 2: Rocks for more about the products of past and present volcanism at the Yellowstone hot spot.

The Quaternary
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 that originated in northern Canada (*Figure 1.15*). The Quaternary period is divided into two epochs: the **Pleistocene** and **Holocene**. During the Pleistocene, ice sheets advanced south and retreated north several dozen times, reaching their maximum extent most recently 25,000–18,000 years ago. The Holocene epoch is the most recent (and current) period of retreat, and is referred to as an **interglacial** interval. The beginning of the Holocene is considered to be 11,700 years ago, or about 9700 BCE.

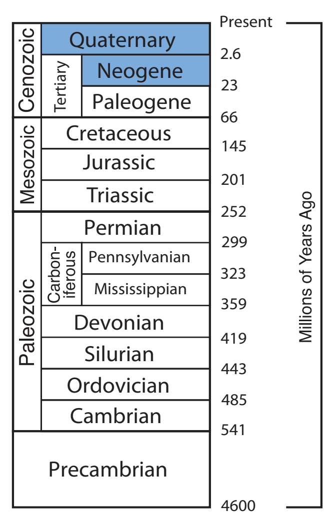
Quaternary

supervolcano • *an explosive volcano capable of producing more than 1000 cubic kilometers (240 cubic miles) of ejecta.*

seismic tomography • *a technique for imaging Earth's sub-surface characteristics, in which the velocity of seismic waves is analyzed in an effort to understand deep geologic structure.*

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).*

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



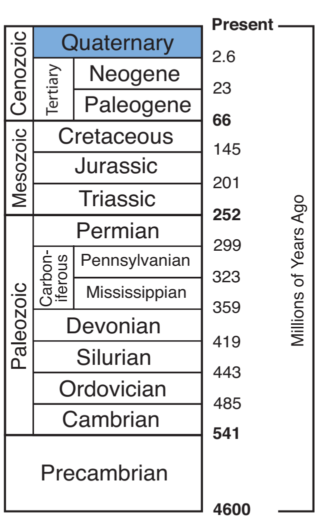
Quaternary

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.*

Laurentide Ice Sheet *• an ice sheet that covered most of Canada during the last major glaciation.*

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

Cordilleran Ice Sheet *• one of two continental glaciers that covered Canada and parts of the Western US during the last major Pleistocene ice age.*



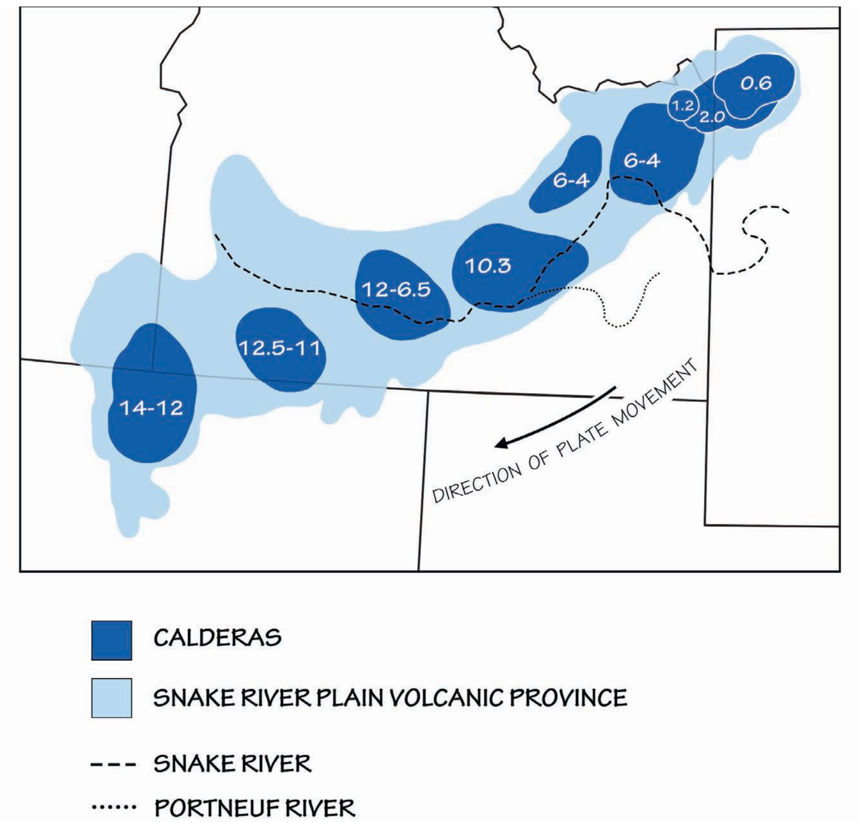


Figure 1.14: The path of the Yellowstone hot spot over the past 16 million years, including the Snake River Plain (part of the Columbia Plateau region) and Yellowstone National Park.

The entire United States was affected by the cooling climate during the most recent **ice age**. A cooling climate contributes to the growth of continental glaciers: as more snow falls in the winter than melts in the summer, the snow packs into dense glacial ice. In this case, as snow and ice continued to accumulate on the glacier, the ice began to move under its own weight and pressure. The older ice on the bottom was pushed out horizontally by the weight of the overlying younger ice and snow. Glacial ice then radiated out from a central point, flowing laterally in every direction away from the origin (*Figure 1.16*). As a result, the continental glacier that originated in Canada migrated southwards toward the United States. During this time, the **Laurentide Ice Sheet** reached into Montana, the Dakotas, Nebraska, Kansas, and east into the **Great Lakes**. The **Cordilleran Ice Sheet** reached into Washington, Idaho, and western Montana. Alpine glaciers covered the mountain heights in Idaho, Montana, Wyoming, Utah, Colorado, and New Mexico, as well as the Cascades and Sierra Nevada in the western states.

Glacial lakes formed in low areas between or in front of glaciers, and also during times between glacial advances. These lakes included Lake Missoula in Montana and Lake Agassiz in south-central Canada, Minnesota, and North Dakota. The catastrophic release of an ice dam on Lake Missoula carved the Channeled Scablands in northern Idaho and eastern Washington. (*Figure 1.17*)

Quaternary

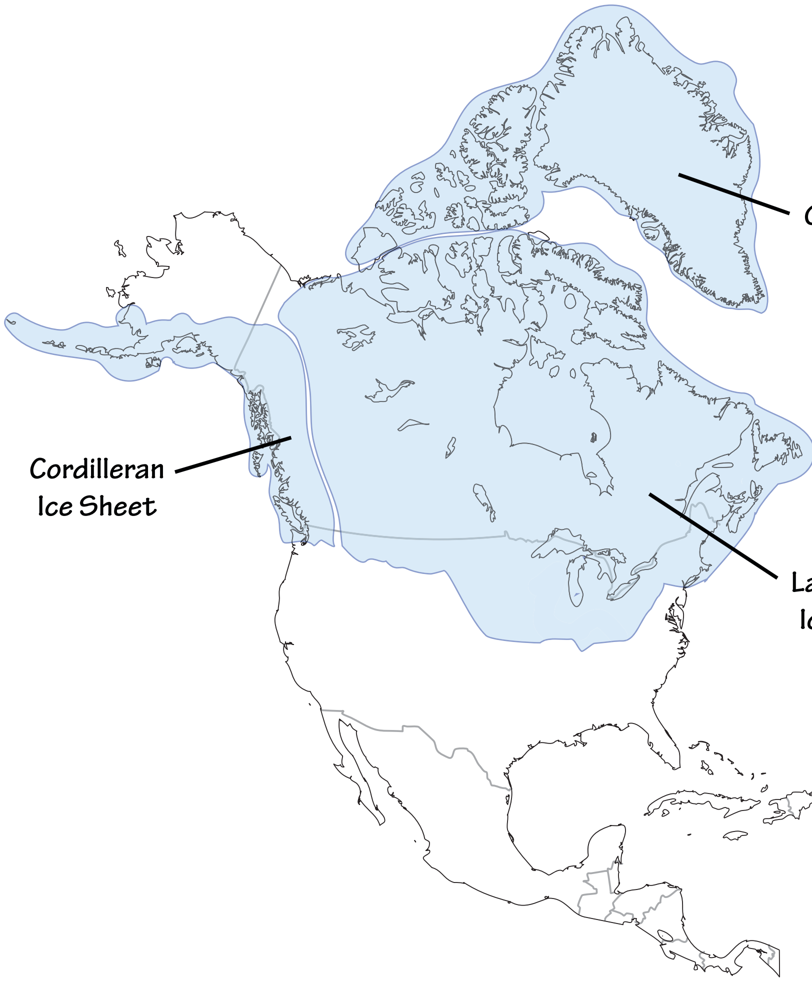
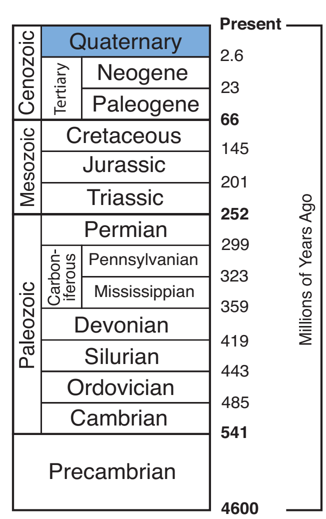


Figure 1.15: Extent of glaciation over North America during the Quaternary.

Figure 1.16: Continental glaciers originating in Canada spread across North America, including the northern portion of the Northwest Central, during the Quaternary period.



Quaternary

cirque *• a large bowl-shaped depression carved by glacial erosion and located in mountainous regions.*

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

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

outwash plain *• large sandy flats created by sediment-laden water deposited when a glacier melts.*

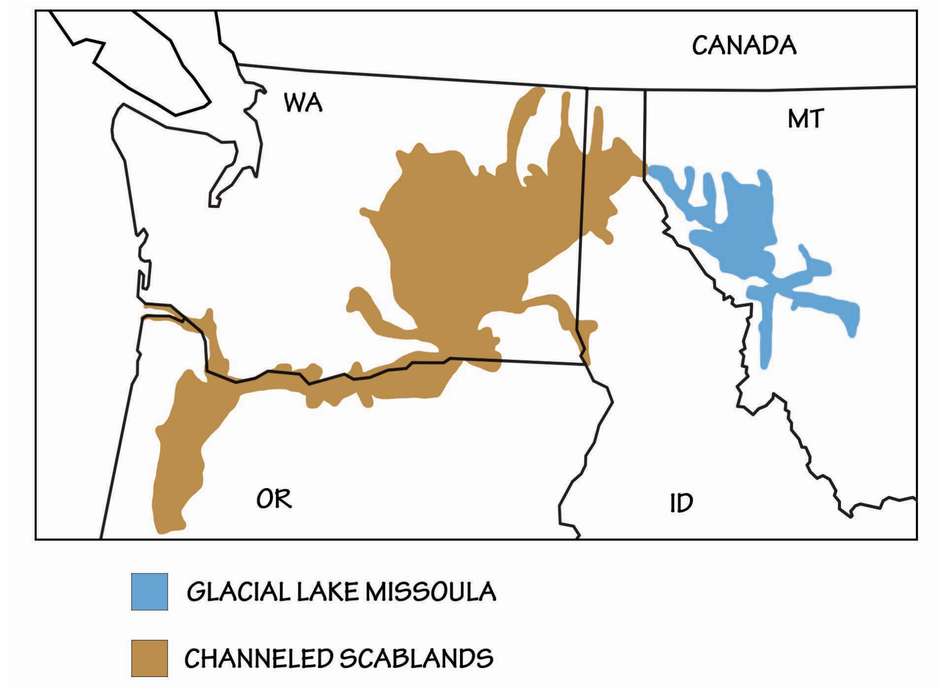


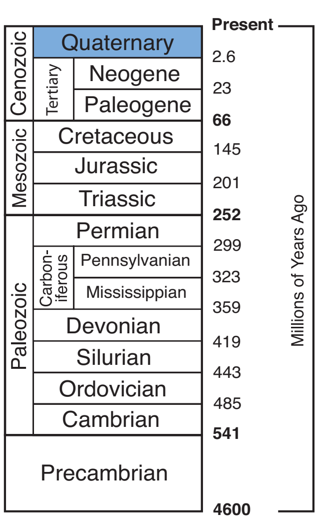
Figure 1.17: The extent of ancient Lake Missoula between 15,000 and 13,000 years ago, and the modern Channeled Scablands, carved by the lake's outburst flood. (See TFG website for full-color version.)

Effects of glaciation on the Northwest Central's landscape include carved glacial **cirques** and valleys, and deposits of glacial **till** in **moraines** and **outwash plains**. Glacier National Park in Montana contains many good examples of these features. Fine **silt** from glacier-ground rock was picked up from the glacial outwash by wind and deposited in thick layers of **loess** across large areas of the midcontinental US. **Sand** dunes, formed where a supply of outwash sand was picked up and blown by the wind, include the Sandhills of Nebraska and Killpecker Sand Dunes in Wyoming.

See Chapter 4: Topography for more on sand dunes in the Northwest Central.

The ice age continues today, but the Earth is in an interglacial stage, since the ice sheets have retreated for now. The current interglacial period has slowed both erosional and depositional processes in the South Central—this and a higher, more stable sea level allowed coastal features such as barrier islands and lagoons to form, resulting in the landscape we know today. The glacial-interglacial cycling of ice ages indicates that the world will return to a glacial stage in the future, that is unless the impacts of human-induced **climate change** radically shift these natural cycles.

See Chapter 9: Climate to learn more about how climate change affects the environment.



Geologic History 1

Quaternary

Why was there an ice age?

What led to the formation of large continental glaciers in the Northern Hemisphere between 3.5 and 2.5 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, and altering ocean currents that transported heat from the equator to the poles. Sufficient precipitation in northern Asia and North America also enabled continental glaciers to grow and flow outward. The rise of the Himalayas exposed new rock that trapped carbon dioxide through chemical weathering; in turn, the decreased levels of carbon dioxide led to a global cooling. Finally, and surprisingly, the formation of the Central American Isthmus, which connects North and South America in what is now Panama, likely had a major effect on climate. Ocean currents than had once flowed east to west through the Central American Seaway were now diverted northward into the Gulf of Mexico and ultimately into the Gulf Stream in the western Atlantic. This strengthened Gulf Stream transported more moisture to high northern latitudes, causing more snow, which eventually formed glaciers.

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

loess *• very fine grained, wind-blown sediment, usually rock flour left behind by the grinding action of flowing glaciers.*

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

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

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**

1 Geologic History

Resources

Resources

General Books on Geologic History

Bjornerud, M., 2005, *Reading the Rocks: The Autobiography of the Earth*, Westview Press, Cambridge, MA, 237 pp.

Fortey, R. A., 2004, *The Earth, An Intimate History*, HarperCollins, London, 509 pp.

Hazen, R. M., 2012, *The Story of Earth: The First 4.5 Billion Years, from Stardust to Living Planet*, Viking, New York, 306 pp.

Kious, J., and R. I. Tilling, 1996, *The Dynamic Earth: The Story of Plate Tectonics*, US Geological Survey, Washington, DC, 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, 266 pp.

Morton, J. L., 2004, *Strata: The Remarkable Life Story of William Smith, the Father of English Geology, new edition*, Brocken Spectre, Horsham, UK, 171 pp.

Powell, J., 2001, *Mysteries of Terra Firma: The Age and Evolution of the Earth*, Free Press, New York, 256 pp.

Winchester, S., and S. Vannithone, 2001, *The Map That Changed the World: William Smith and the Birth of Modern Geology*, HarperCollins, New York, 329 pp.

General Websites on Geologic History

Color-coded Continents!, US Geological Survey, http://geomaps.wr.usgs.gov/parks/pltec/ scplseqai.html. (Reconstructions of color-coded continental motions from 620 million years ago through the present; maps from C. Scotese.)

Earth Viewer, by BioInteractive at Howard Hughes Medical Institute, http://www.hhmi.org/ biointeractive/earthviewer. (Free iPad app; an interactive paleogeographic atlas of the world; state and country overlays allows tracking the development of the Western States.)

Geologic Maps of the 50 United States, by Andrew Alden, http://geology.about.com/od/maps/ig/stategeomaps/.

North America During the Last 150,000 Years, compiled by J. Adams, http://www.esd.ornl.gov/projects/qen/nercNORTHAMERICA.html.

The Paleomap Project, by C. R. Scotese, http://www.scotese.com.

Paleogeography, by R. Blakey, https://www2.nau.edu/rcb7/RCB.html. (The older, but free, version of the site.)

Reconstructing the Ancient Earth, Colorado Plateau Geosystems, http://cpgeosystems.com/index.html. (R. Blakey, updated site.)

Tour of Geologic Time, University of California Museum of Paleontology, http://www.ucmp.berkeley.edu/help/timeform.php. (Online interactive geologic calendar exhibit.)

Geologic History of the Northwest Central

Love, D., J. C. Reed Jr., and K. L. Pierce, 2003, *Creation of the Teton Landscape, 2nd revised and enlarged edition*, Grand Teton Association, Moose, WY, 135 pp. [1971 edition, by Love and Reed, is online in full, http://www.nps.gov/parkhistory/online_books/grte/grte_geology/index.htm]

Roehler, H. W., 1992, Introduction to greater Green River basin geology, physiography, and history of investigations, *US Geological Survey Professional Paper* 1506-A, 14 pp., http://pubs.usgs.gov/pp/1506a/report.pdf.

Trimble, D. E., 1980, The geologic story of the Great Plains: a nontechnical description of the origin and evolution of the landscape of the Great Plains, *US Geological Survey Bulletin* 1493, http://library.ndsu.edu/exhibits/text/greatplains/text.html. (Also paperback edition, 2000, published by Theodore Roosevelt Nature & History Association, 64 pp.)

Activities

Okland, L., 1991, Paleogeographic mapping, in: R. H. Macdonald, and S. G. Stover, eds., *Hands-on Geology: K-12 Activities and Resources*, Society for Sedimentary Geology (SEPM), Tula, OK, https://www.beloit.edu/sepm/Fossil_Explorations/Paleogeographic_Mapping.html. (Constructing paleogeographic maps for elementary and middle school students.)

Toilet Paper Analogy for Geologic Time, by J. Wenner, in: *Teaching Quantitative Skills in the Geosciences*, at Resources for Undergraduate Students and Faculty, SERC, http:// serc. carleton.edu/quantskills/activities/TPGeoTime.html. (Demonstration of geological time using a 1000-sheet roll of toilet paper.)

Understanding Geologic Time, Texas Memorial Museum at the University of Texas at Austin, http://www.jsg.utexas.edu/glow/files/Understanding-Geologic-Time-6-8.pdf. (Timeline activity for middle school students.)

Chapter 2: Rocks of the Northwest Central US

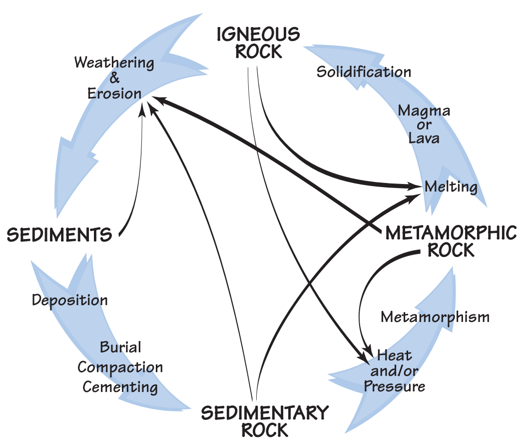
The amazing diversity of rocks in the Northwest Central records several billion years of history—from 3.8-billion-year-old **Precambrian** granites to sedimentary deposits from the most recent **ice age**. Colliding **plates**, **rifting**, **inland seas**, deposition, **erosion**, igneous and metamorphic activity, and recent **glacial** processes are all part of this story. The Northwest Central's different rock types influence its **topography** and tell us where to look for certain **fossils** or natural resources. Each type of rock forms in a particular environment under particular conditions (*Figure 2.1*).

Igneous Rocks of the Northwest Central

andesite	granite	obsidian	rhyolite
basalt	komatiite	phonolite	syenite
dacite	lamproite	pyroclastic rocks	tuff

Unconsolidated Sediments of the Northwest Central

clay
gravel
loess
sand
silt



Metamorphic Rocks of the Northwest Central

gneiss
greenstone
marble
novaculite
quartzite
schist

Sedimentary Rocks of the Northwest Central

chalcedony	mudstone
chert	shale
conglomerate	siltstone
halite (rock salt)	sandstone
gypsum	tillite
limestone	travertine

Figure 2.1: The rock cycle shows the relationships among the three basic types of rock.

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.*

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

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

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

CHAPTER AUTHORS

Lisa R. Fisher
Bryan Isaacs

2 Rocks

Review

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

__system__ • a set of connected things or parts forming a complex whole.

__plate tectonics__ • the process 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.

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

__cementation__ • the precipi-tation of minerals that binds together particles of rock, bones, etc., to form a solid mass of sedimentary rock.

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 differences between the 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**, such as **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, such as 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

Mineral Content	Sedimentary Rock	Environment of Deposition
calcium carbonate skeletons of marine organisms	limestone	tropical reefs, beaches, warm shallow seas
precipitated calcium carbonate	travertine, tufa	hot spings, playas (dry lake beds), drying seas
gypsum	rock gypsum	playas, dryng seas
halite	rock salt	playas, drying seas

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) such as **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**.

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**. When magma comes to the surface (as lava), it cools quickly so that individual crystals are not visible, resulting in a **volcanic** rock such as **basalt**. In some circumstances, lava may cool so quickly that crystals do not form at all, creating a **glassy rock** such as **obsidian**. Smaller fragmental rocks that cool quickly at the surface form during explosive eruptions; these are called pyroclastic rocks, and they are composed of a variety of different volcanic ejecta.

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	--

Review

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.*

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

calcium carbonate • *a chemical compound with the formula $CaCO_3$, commonly found in rocks in the mineral forms calcite and aragonite, as well as the shells and skeletons of marine organisms.*

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

dolostone • *a rock primarily composed of dolomite, a carbonate mineral.*

2

Rocks

Review

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

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

compression • *flattening or squeezing as a result of forces acting on an object from all or most directions.*

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

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

Every rock is capable of being melted, weathered, or changed by **heat** and pressure. Any rock that has been subjected to intense heat and pressure can **recrystallize** into a **metamorphic rock**. This process destroys features in the rock that would have revealed its previous history, transforming it into an entirely new form as the minerals within realign. The pressure to transform a rock may come from burial by sediment or from **compression** due to plate movements, while the heat may come from very deep burial or from contact with magma.

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.

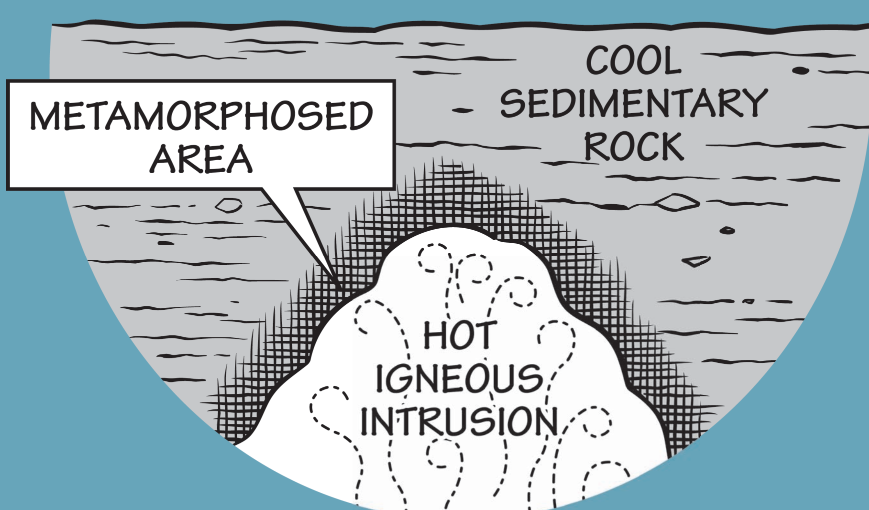
Parent rock	Metamorphic rocks
shale	slate, phyllite, schist, gneiss (in order of increasing heat and pressure)
granite	gneiss
sandstone	quartzite
limestone	marble
peridotite	serpentinite

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. For example, when plates collide, compression and friction melt the **crust**. The rising magma forms igneous **intrusions** that crystallize below the surface, producing large-grained igneous rocks such as granite. The rising magma may break through the surface in the form of volcanoes, creating volcanic rocks such as basalt. Tectonic collision also leads to increased heat and pressure, creating metamorphic rocks. Basins adjacent to mountains fill with transported sediment, producing thick sequences of sedimentary rock.

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 farther 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.

Review

foliation • *the arrangement of the constituents of a rock in leaflike layers.*

contact metamorphism • *the process by which a metamorphic rock is formed through direct contact with magma.*

regional (dynamic) metamorphism • *a metamorphic rock that has been altered due to deep burial and great pressure.*

2 Rocks

Review

physiography • *a subfield of geography that studies the Earth's physical processes and patterns.*

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 deposited by glaciers as they recede.*

outwash plain • *large sandy flats created by sediment-laden water deposited when a glacier melts.*

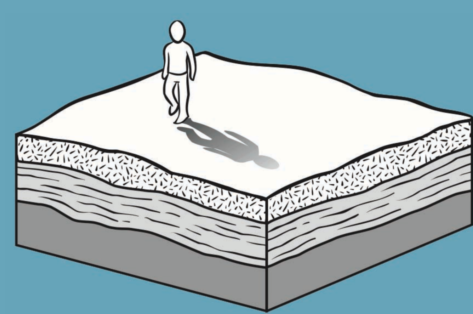
Mesozoic • *a geologic time period that spans from 252 to 66 million years ago.*

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

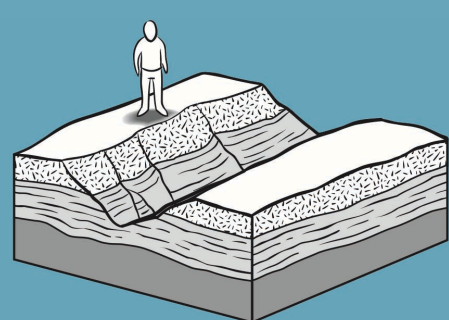
basement rocks • *the foundation that underlies the surface geology of an area, generally composed of igneous or metamorphic crystalline rock.*

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

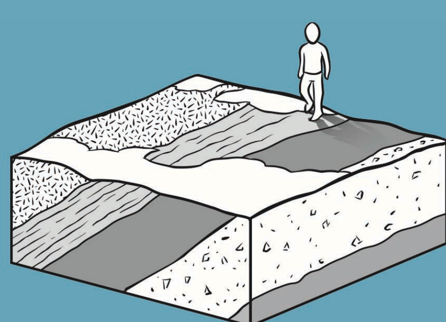
As you walk across the surface of the Earth, you will observe an amazing variety of rock types. If all rocks were flat-lying layers and there was no erosion, then we would only see one type of rock exposed on the surface. Often, however, rocks have been worn away (eroded), and the underlying layers are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

Rocks of the Central Lowland and Great Plains

Regions 1 and 2

The two **physiographic** regions of the Central Lowland and Great Plains are combined in this section due to their geological continuity. The Central Lowland, an area of low terrain that extends like a saucer with gently rising rims, stretches to meet the Great Plains on its western border in the eastern Dakotas and eastern Nebraska. In general, surface deposits in these two regions are composed of **Quaternary** glacial **tills** and **outwash** in the northernmost and easternmost plains, and **Mesozoic-Cenozoic** sediments in the western plains. Outcrops of older material are usually exposed by stream erosion, dissected terrain, or quarries. Erosional processes from the Missouri, Yellowstone, Little Missouri, Cheyenne, Niobrara, and Platte river systems dominate the area's active geology.

See Chapter 1: Geologic History for a geologic time scale on which you can reference the time periods described throughout this chapter.

The Great Plains and Central Lowland are underlain by a **basement** of igneous and metamorphic Precambrian rocks, some of which are up to 2.6 billion years old. These rocks are, for the most part, buried and inaccessible, with the exception of the Black Hills in southwestern South Dakota and the Sioux Arch in southeastern South Dakota.

The Sioux Arch area contains **Proterozoic** Sioux Quartzite, a formation of pink and red **orthoquartzite** with **cross-bedding**, ripples, and mudcracks. It consists largely of conglomerates formed from stream deposits, sandstones from **braided streams** and **alluvial** plains, and red to purple mudstones from tidal and lagoonal deposits. These materials, eroded from **Archean** granites, sandstones, and **iron** formations, were deposited between 1.8 and 1.6 billion years ago before being subjected to mild metamorphism.

Although the Sioux Quartzite is largely overlain by **Cretaceous** rocks and **Pleistocene** glacial materials, it appears in small outcrops in southeastern South Dakota and adjacent Minnesota, and is exposed in abundance at Sioux Falls Park along the Big Sioux River (*Figure 2.2*). The **quartzite** is quarried for building and decorative material (*Figure 2.3*), and the mudstones are also known as "pipestone" since Native Americans quarried them for pipes and carvings (*Figure 2.4*).

The most dramatic outcrops of Precambrian rocks within the Great Plains and Central Lowland are located in South Dakota's Black Hills. The Black Hills are the easternmost outlier of the Cordilleran system, **uplifted** during the **Laramide Orogeny** between 68 and 65 million years ago. The range is cored by a complex set of 3.5- to 2.5-billion-year-old Archean rocks that

Regions 1–2

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

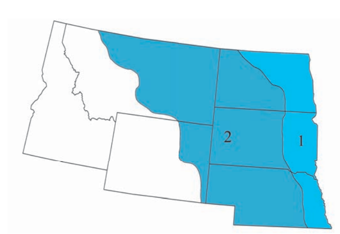
orthoquartzite • *a sandstone composed nearly entirely of well-rounded quartz grains cemented by silica.*

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

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

alluvial • *a thick layer of river-deposited sediment.*

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



2 Rocks

Regions 1–2

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

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

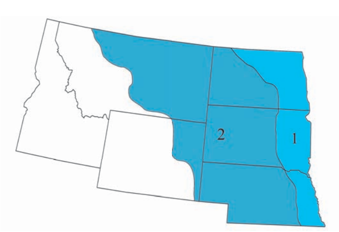
batholith • *a large exposed structure of intrusive igneous rock that solidified at depth, and covers an area of over 100 square kilometers (40 square miles).*

pegmatite • *a very coarse-grained igneous rock that formed below the surface.*

Figure 2.2: Sioux Falls Park, Sioux Falls, South Dakota.

Figure 2.3: Sioux Quartzite was used to construct the Federal Building in Sioux Falls, South Dakota.

were later deformed and metamorphosed into various **schists** and **gneisses** accompanied by the intrusion of granitic rocks. At the very center of the uplift is the notable 1.7-billion-year-old Harney Peak granite **batholith** from which Mt. Rushmore is carved (*Figure 2.5*). Related **pegmatites** known for a great variety of spectacular minerals and crystals are also found here.



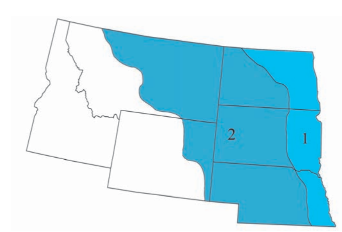
Regions 1–2

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

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

Figure 2.4: Native American pipe bowl, carved from pipestone into the shape of an owl.

Figure 2.5: Mt. Rushmore, carved from the Harney Peak granite.



Thick sequences of **Paleozoic** and Cenozoic sedimentary rocks cover the basement beneath the Great Plains. Layers of limestone and shale were deposited when shallow seas repeatedly flooded the area, while sandstones accumulated from **sandy** beaches were left behind as the seas retreated. These sedimentary layers are largely undeformed except where they have been pushed up and exposed by uplift in the Black Hills. Here, extensive cave

Regions 1–2

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

speleothem • *an often-delicate mineral deposit in limestone or dolostone caves, formed through the dissolution of carbonate minerals.*

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.*

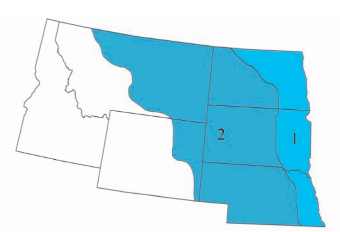
systems formed in the **Mississippian**-aged Madison limestone (locally known as Pahasapa limestone) after the layers were uplifted and subjected to surface erosion (*Figure 2.6*). The delicate formations found in these caves today, called **speleothems**, are mineral deposits that formed in more recent times.

Unless rock layers are over-turned, 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*.

Figure 2.6: Jewel Cave in the Black Hills of South Dakota. The cave was formed as acid-rich water gradually dissolved layers of limestone that had been cracked by the uplift of the Black Hills around 60 million years ago.

In easternmost Nebraska, a small area of **Carboniferous** strata is exposed at the surface thanks to erosion from the Mississippi River. The dark shales and **coal** beds in this area originate from a swampy shoreline and oxygen-poor continental shelf. Here, rivers flowing from the east deposited sediments eroded from the Appalachian Mountains. A band of **Permian** bedrock is also exposed in the southeastern portion of Nebraska, deposited there as sea levels moved back and forth across the state during the late Paleozoic.

See Chapter 3: Fossils to learn about the diverse fossils found in Nebraska's Carboniferous rocks.



Throughout the Mesozoic, shallow seas periodically covered much of North America's interior. The sedimentary deposits resulting from the water's advance and retreat became the limestones, shales, and sandstones that are now near the surface and actually outcrop in many areas of the Great Plains. For example, **Triassic** and **Jurassic** deposits of red **silts** and **clays** surround the Black Hills in a ring, providing evidence of an ancient arid coastal plain and **intertidal** mudflats. These red stones and interbedded layers of **gypsum** are part of a geological formation called the Spearfish Formation, which extends from the Dakotas into Montana, Wyoming, and Nebraska. The Belle Fourche River, which flows from Wyoming to South Dakota, cuts through and exposes these layers (*Figure 2.7*).

Figure 2.7: The Spearfish Formation is cut by the Bell Fourche River near Devils Tower National Monument, Wyoming.

During the Cretaceous period, the interior of North America was **downwarped** by tectonic processes associated with the **subduction** of oceanic **lithosphere** along the western edge of North America. As the Laramide and **Sevier orogenies** occurred to the west, the North American interior was flooded by a particularly vast inland sea called the Western Interior Seaway (*Figure 2.8*). Episodes of **transgression** and **regression** deposited thousands of feet of marine and terrestrial sedimentary rock across the Great Plains and Central Lowland. As the Cretaceous drew to a close, mountain building progressed eastward, and the vast inland sea receded for the final time. The pattern of sedimentation transitioned from marine, to near shore, and finally to on-land **gravels**, sands, and muds deposited by the action of streams and rivers flowing eastward from the elevated Rockies. These continental deposits covered the entire Great Plains progressively from north to south.

Triassic • *a geologic time period that spans from 252 to 201 million years ago.*

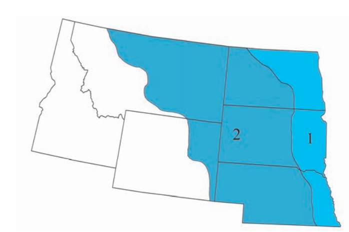
Jurassic • *the geologic time period lasting from 201 to 145 million years ago.*

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.*

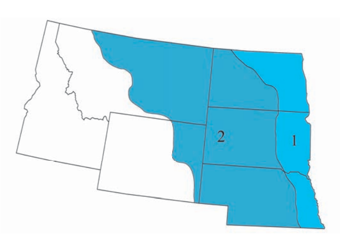
intertidal • *areas that are above water during low tide and below water during high tide.*

gravel • *unconsolidated, semi-rounded rock fragments larger than 2 millimeters (0.08 inches) and smaller than 75 millimeters (3 inches).*



Regions 1–2

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



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 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.**

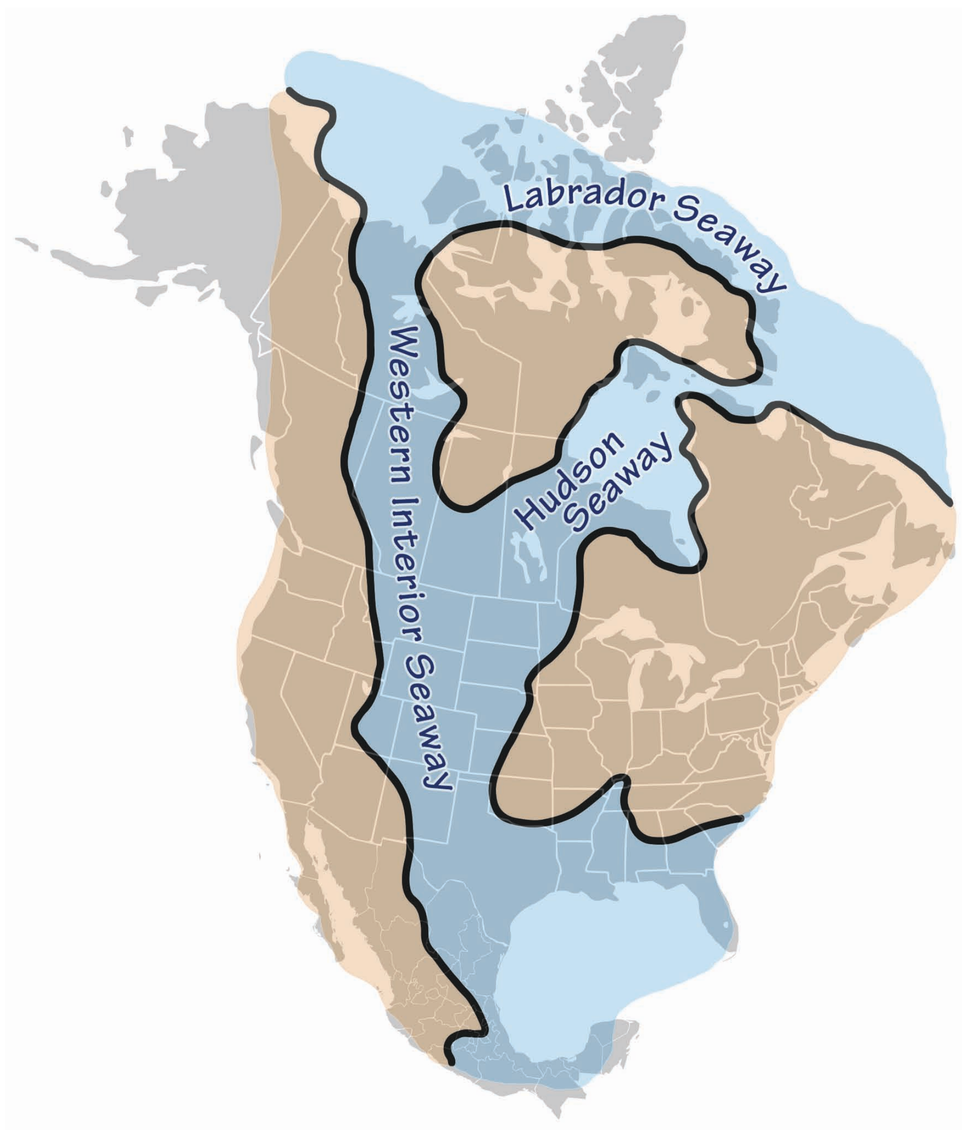


Figure 2.8: The Western Interior Seaway.

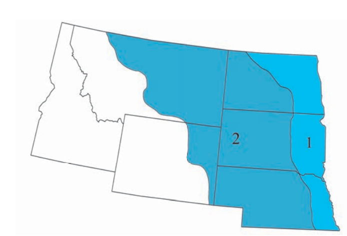
Why are there different sedimentary rocks in different environments?

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 darker, carbon-rich 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. These shelled creatures tend to fare better in clear water, so limestone usually forms far from other sources of sediment. While this process happens over much of the seafloor, if more than 50% of the sediment being deposited is from another source, the rock that forms is, by definition, not limestone.

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

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



Regions 1–2

phonolite • *an extrusive igneous rock of intermediate composition, which forms from magma with a relatively low silica content.*

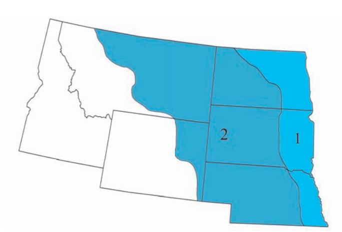
feldspar • *an extremely common, rock-forming mineral found in igneous, metamorphic and sedimentary rocks.*

columnar joint • *five- or six-sided columns that form as cooling lava contracts and cracks.*

joint • *a surface or plane of fracture within a rock.*

syenite • *a durable, coarse-grained intrusive igneous rock, which is similar to granite but contains less quartz.*

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



Tectonic activity associated with the Laramide Orogeny also generated volcanism and igneous intrusions near the area of mountain building. The famous Devils Tower, an exposed igneous intrusion that rises 386 meters (1267 feet) above the surrounding terrain, lies in Wyoming just west of the Black Hills (*Figure 2.9*). Devils Tower is composed of **phonolite**, a gray or greenish gray igneous rock containing conspicuous crystals of white **feldspar**. This igneous rock exhibits spectacular **columnar jointing**, indicating that it cooled quickly at a shallow depth. A popular interpretation for the formation of this landmark classifies it as a solidified volcanic neck, but alternate interpretations peg it as a laccolith or other shallow intrusive body. Just 6 kilometers (3.5 miles) to the northwest of Devils Tower lies a set of four summits, the Missouri Buttes, which are also composed of **jointed** phonolite of the same age (*Figure 2.10*). A similar landform in Montana, Snake Butte, is also the result of an igneous intrusion; it is composed of a coarse-grained igneous rock called **syenite**, and it also exhibits columnar jointing (*Figure 2.11*). Syenite is particularly durable, and was an important source of material used to build the Ft. Peck Dam in the 1930s.

Figure 2.9: Devils Tower, a large intrusive igneous rock formation with well-developed columnar jointing, in Crook County, Wyoming.

Volcanic eruptions in the Rockies during the **Neogene** and **Paleogene** generated ash that was carried eastward by the prevailing winds, and often fell across the Great Plains in thick layers. The Ashfall Fossil Beds in northeastern Nebraska are an example of one such location, formed after a dense **volcanic ash** fall that occurred in the late

See Chapter 3: Fossils for more about mammal fossils preserved in ash.

Columnar Jointing

As a lava flow cools, it contracts, and the resulting force may cause the rock to crack. These cracks continue down to the bottom of the flow, resulting in five- or six-sided columns. Columnar joints are not restricted to basalt flows and can form in ashflow tuffs as well as shallow intrusions. The columns are generally vertical, but may also be slightly curved.

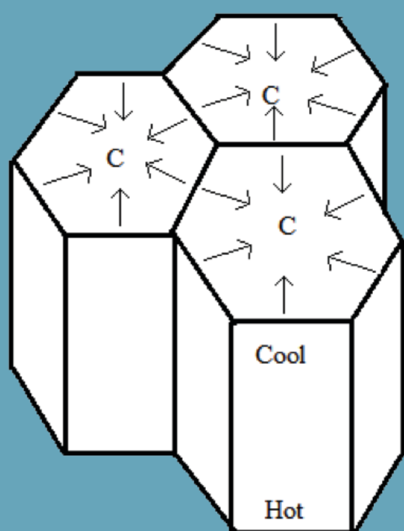
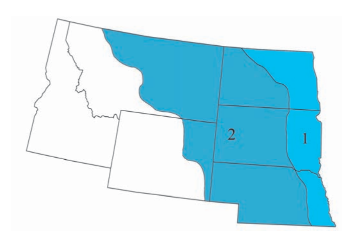


Figure 2.10: Devils Tower and the Missouri Buttes at sunrise.

Paleogene • *the geologic time period extending from 66 to 23 million years ago.*

volcanic ash • *fine, unconsolidated pyroclastic grains under 2 millimeters (0.08 inches) in diameter.*



Regions 1–2

Miocene *• a geological time unit extending from 23 to 5 million years ago.*

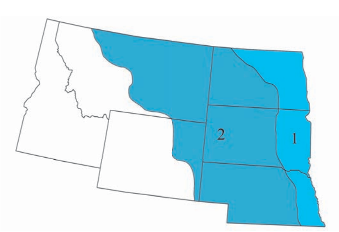
bentonite *• a clay, formed from decomposed volcanic ash, with a high content of the mineral montmorillonite.*

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

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).*

ice cap *• an ice field that lies over the tops of mountains.*

badlands *• a type of eroded topography that forms in semi-arid areas experiencing occasional periods of heavy rainfall.*



Miocene. Sentinel Butte in North Dakota also contains a widespread ash and **bentonite** deposit that is up to 8 meters (25 feet) thick in some areas (*Figure 2.12*).

Figure 2.11: Columnar jointing at Snake Butte, an exposed igneous sill located on the Ft. Belknap Reservation in Montana.

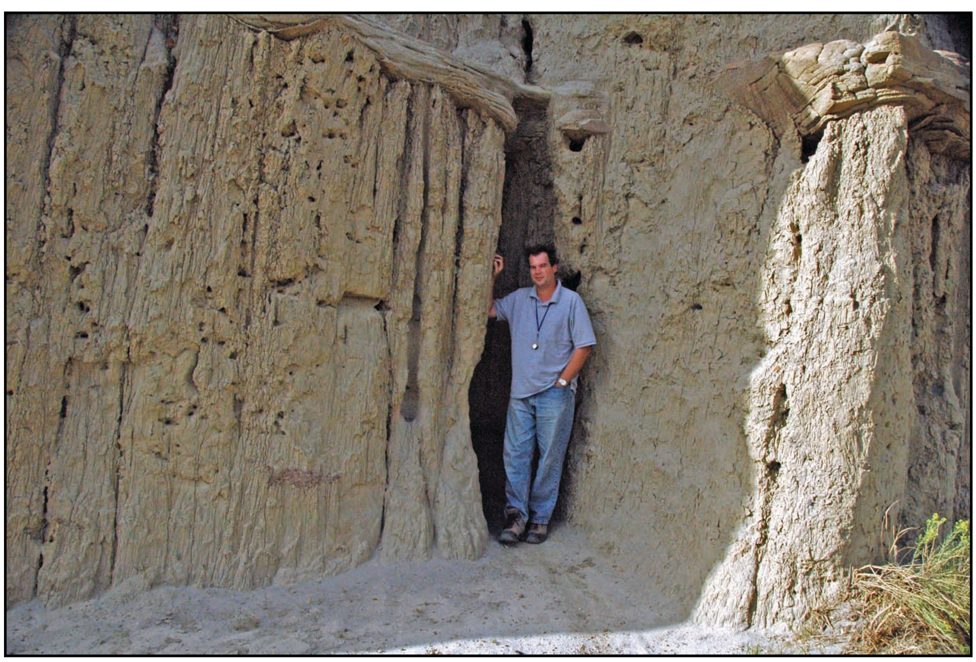


Figure 2.12: The Sentinel Butte Formation, a Paleocene ash deposit in the Little Missouri Badlands of North Dakota.

Regions 1–2

During the Cenozoic, many sediments were deposited in terrestrial environments such as lakes, rivers, and **floodplains**. These deposits cover the region's Cretaceous rocks in two large areas. The first, comprising mostly **Paleocene** sediments, is located in the northern Great Plains of Montana, Wyoming, and the Dakotas. The other area includes a large tract of late Paleocene to Neogene strata that has escaped much erosional loss, and constitutes the High Plains subdivision of the Great Plains between Nebraska and Texas. The sandstones in the High Plains Ogallala Formation house the famous Ogallala or High Plains Aquifer. Water in the Ogallala Aquifer, stored since Quaternary times, is now being withdrawn by extensive agricultural development at rates exceeding recharge in the modern **climate** regime.

See Chapter 10: Earth Hazards to learn about the effects of drought and agriculture on the Ogalalla Aquifer.

Rivers flowing eastward out of the Rocky Mountains since the early Cenozoic have eroded and carried sediment towards the plains. The process was intensified by the successive accumulation and melting of mountain glaciers and **ice caps** over many of the mountain ranges in the Rockies. These rivers, continually cutting into and removing earlier sedimentary cover, have thereby created much of the scenery and spectacular rock outcrops found in the Great Plains. Some examples include the Upper Missouri Breaks National Monument in central Montana (*Figure 2.13*), Badlands National Park in southwestern South Dakota (*Figure 2.14*), and the Scotts Bluff National Monument in western Nebraska (*Figure 2.15*). Many of these sculpted **badland** areas also contain abundant **concretions** and **nodules**, hard rounded bodies of rock formed by the precipitation of dissolved minerals, and later exposed by erosion. For example, large spherical sandstone concretions called "cannonballs" are common in the Sentinel Butte Formation of western North Dakota (*Figure 2.16*).

See Chapter 4: Topography for more on badland landscapes.

The Quaternary deposits of the Great Plains and Central Lowland are primarily related to glacial processes. During the ice age, the **Laurentide Ice Sheet** advanced several times in four main pulses and covered northern Montana and most of the Dakotas, and also penetrated into Nebraska and Kansas. The advancing **ice sheet scoured** and abraded the bedrock beneath it, breaking it down from huge boulders into fine dust, called **rock flour**. When the glaciers retreated, till and outwash were carried in meltwater and deposited in lakes or by streams. Rock flour and sand was picked up by the wind and blown for many kilometers (miles) until it settled into thick layers of **loess** (*Figure 2.17*). The Sandhills of Nebraska are perhaps the best-known example of wind-transported glacial sediments in the Great Plains.

See Chapter 6: Glaciers for more information about how glaciation altered the Northwest Central's landscape.

Paleocene • *a geologic time interval spanning from about 66 to 56 million years ago.*

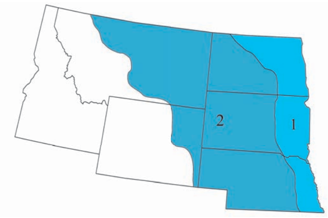
concretion • *a hard, compact mass, usually of spherical or oval shape, found in sedimentary rock or soil.*

nodule • *a small, irregular or rounded mineral deposit that has a different composition from the sedimentary rock that encloses it.*

Laurentide Ice Sheet • *an ice sheet that covered most of Canada during the last major glaciation.*

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).*

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



Rocks

Figure 2.13: The Upper Missouri Breaks in central Montana are composed of Mesozoic and Cenozoic shales, sandstones, and volcanic materials.

Figure 2.14: The Brule Formation, exposed in Badlands National Park, is a sequence of fine-grained mudstones, claystones, and siltstones interbedded with freshwater carbonate rock, volcanic ash, and sandstone. These sediments were deposited during the Oligocene, 34-30 million years ago.

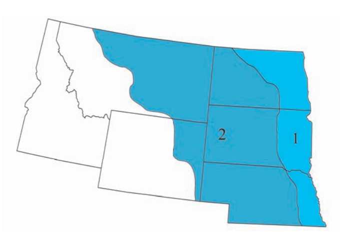


Figure 2.15: Scotts Bluff exposes 225 meters (740 feet) of Paleogene-Neogene terrestrial sediments, including sandstone, limestone, and volcanic material.

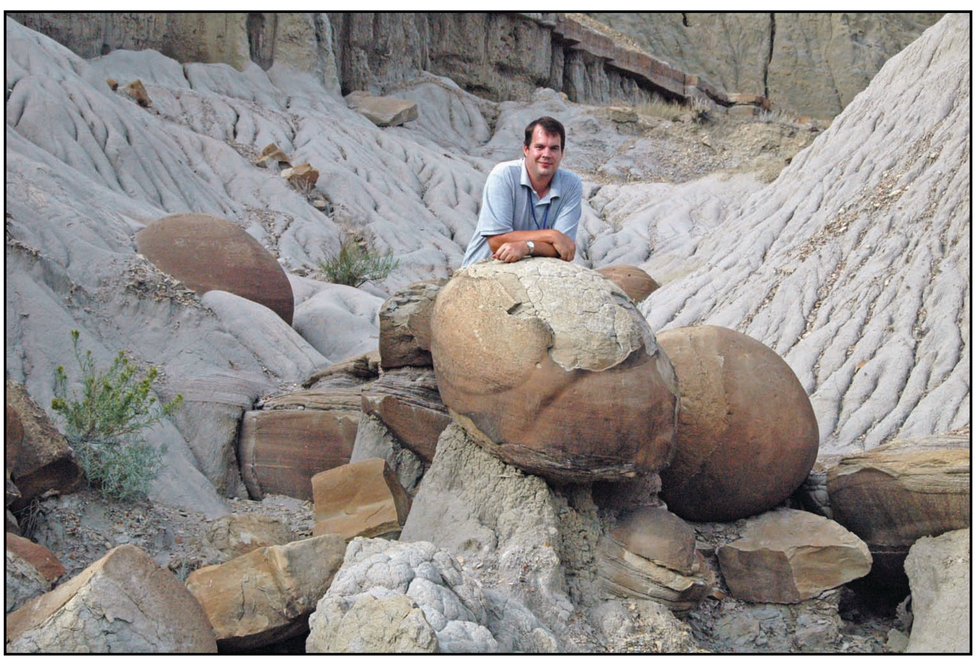
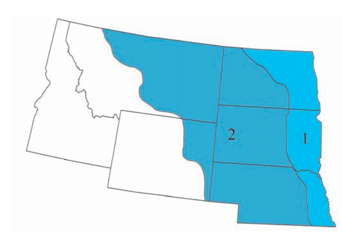


Figure 2.16: Cannonball concretions in the Sentinel Butte Formation, Theodore Roosevelt National Park, North Dakota.



2 Rocks

Regions 1–3

__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.

__oil__ • See petroleum: a naturally occurring, flammable liquid found in geologic formations beneath the Earth's surface and consisting primarily of hydrocarbons

__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.

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

__craton__ • the old, underlying portion of a continent that is geologically stable relative to surrounding areas.

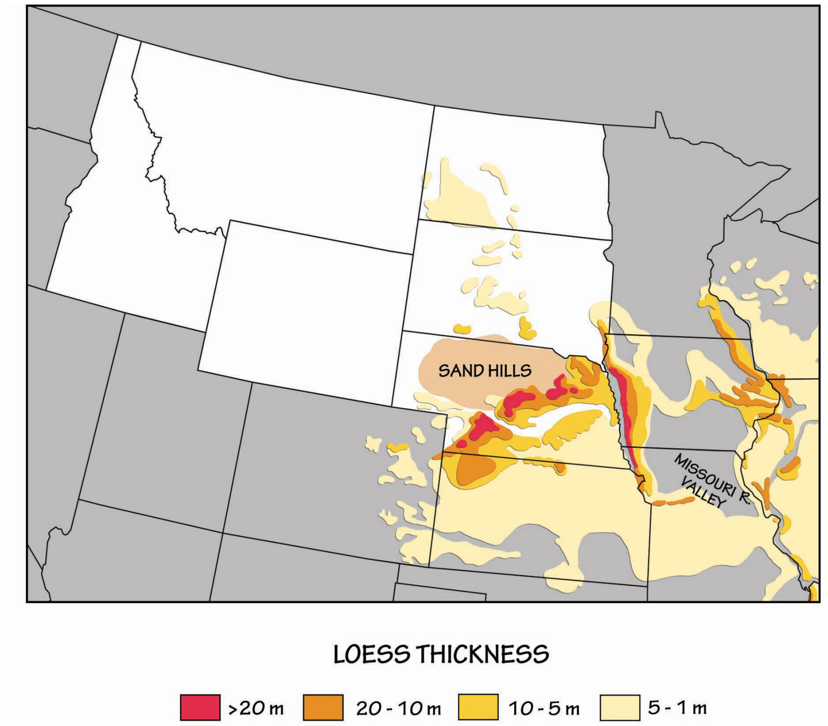


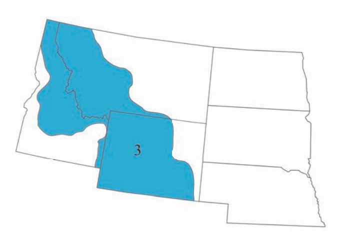
Figure 2.17: Loess deposits in the central US. (See TFG website for full-color version.)

Rocks of the Rocky Mountains
Region 3

The rocks of the Rocky Mountain region are the most varied in the Northwest Central, ranging from Archean gneisses—some of the oldest rocks found in the US—to Paleozoic **reefs**, **oil** shales, volcanic fields, and glacial till. This great variety of rock types is mainly a result of the Laramide and Sevier orogenies, which uplifted numerous discrete blocks of terrain along thrust **faults** that accommodated compressional shortening and thickening of the crust. The overlying sediments were subsequently eroded to expose deeper Precambrian rock as well as Mesozoic and Paleozoic sedimentary formations. The thrust-faulted uplift also produced adjacent basins, which subsequently accumulated sediments eroded from the surrounding mountains.

See Chapter 1: Geologic History to learn more about mountain building during the Laramide and Sevier orogenies.

The oldest rock found so far in the Rocky Mountain region is a 3.65- to 3.8-billion-year-old granitic gneiss found in the Wind River Range. Other Archean-aged rocks, including gneisses, **amphibolites**, schists, and iron formations, are found throughout the uplifted ranges of Wyoming, Montana, and Idaho, including



the Teton, Bighorn, Beartooth, and Wind River mountains (*Figure 2.18*). These rocks were formed when **cratons** collided between 3.6 and 3 billion years ago, producing belts of metamorphosed and deformed rock. In southwest Montana, the mountains contain excellent examples of metamorphosed sedimentary rocks with interesting occurrences of minerals (blue **calcite**, rubies, and more), schists, **marble**, quartzite, iron formations, and greenstone. At the southern end of the Wind River Mountains, a **greenstone belt** hosts **gold** deposits, and the Granite Mountains host a thick iron formation with metamorphosed sediments, greenstone, gold deposits, and good examples of **komatiites**.

A gneiss is a very highly metamorphosed rock with alternating bands of dark and light minerals. The dark bands are mafic and higher in magnesium and iron, while the lighter bands are felsic and higher in silicates. These bands may form because extreme temperature and pressure cause a *chemical reaction* that forces the different elements into separate layers. Banding may also occur when a set of varied protoliths are subjected to extreme *shearing* and sliding forces, causing them to stretch into stacked sheets.

Figure 2.18: Cathedral Peak in the Wind River Range, Wyoming, is composed of Archean-aged granitic gneiss.

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

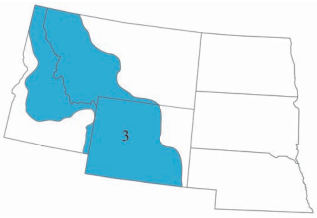
marble • *a metamorphic rock composed of recrystallized carbonate minerals, most commonly calcite or dolomite.*

greenstone belt • *a series of interlayered volcanic and sedimentary rocks that have been metamorphosed into meta-sedimentary rocks and amphibolite.*

gold • *a soft, yellow, corrosion-resistant element (Au), which is the most malleable and ductile metal on Earth.*

komatiite • *mafic volcanic rocks richer in magnesium and erupted at a higher temperature than basalts.*

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



Rocks

Region 3

Snowy Pass Supergroup *• a 2.4–2.5 billion year old series of sedimentary rocks, located in the Medicine Bow Range in southern Wyoming.*

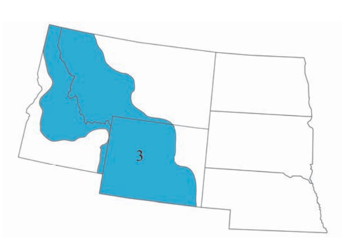
Belt Supergroup *• a 1.45-billion-year-old series of sedimentary rocks, found in the Northern Rocky Mountains, that contain sandstones and mudstones.*

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

Greenstones

A greenstone belt is a term used to describe a series of interlayered volcanic and sedimentary rocks that have been metamorphosed into meta-sedimentary rocks and amphibolite. The rocks are called "greenstones" due to the presence of metamorphic minerals that give the rock a greenish-grey color. Many geologists believe these belts are the result of deposition in volcanic arc environments. An unusual volcanic rock type—komatiite—is often found in Archean greenstone belts. Komatiites are mafic volcanic rocks richer in magnesium and erupted at a higher temperature than basalts. They are restricted to the Archean, when the mantle temperatures were higher at the depths where magma is generated. Komatiites often exhibit "spinifex texture," which is an unusual crystallization-cooling texture that produces large, long crystals.

Spinifex texture in a komatiite from the Komati Formation greenstone in South Africa. Similar rocks are common in the Archean greenstones of Wyoming.



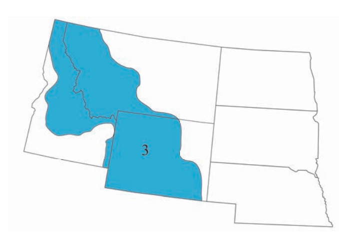
Two main groups of Proterozoic rocks record the early formation of the North American continent: the **Snowy Pass Supergroup** and the **Belt Supergroup**. The Snowy Pass Supergroup, 2.4–2.5 billion years old, is located in the Medicine Bow Range in southern Wyoming. These strata—thick sequences of sandstone, conglomerate, and limestone—were deposited in a continental shelf environment on the passive margin of proto-North America. The sediments were later metamorphosed by an **orogenic** episode accompanied by volcanic activity. Today, the Medicine Peak quartzite forms high cliffs along the ridge of the Medicine Bow Range (*Figure 2.19*). Metamorphosed limestones in the Snowy Range also host 2.3-billion-year-old **stromatolites**, or mats of colonial **cyanobacteria** (*Figure 2.20*).

Figure 2.19: Medicine Bow Peak, a ridge of 2.4-billion-year-old quartzite (metamorphosed sandstone) in the Medicine Bow Range, Wyoming.

Figure 2.20: Stromatolite in metamorphosed Proterozoic dolostone from the Nash Formation, Medicine Bow Range, Wyoming.

stromatolite • *regularly banded accumulations of sediment created by the trapping and cementation of sediment grains in bacterial mats.*

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

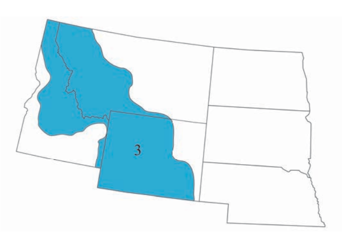


Stromatolites

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 that leads 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.

A stromatolite from the Green River Formation (Eocene) of southwestern Wyoming.



The Belt Supergroup is located in northwestern Montana and adjacent Idaho, and is composed of a sequence of low-grade metamorphic sandstones, siltstones, mudstones, shales, and limestones over 10 kilometers (6 miles) thick. These rocks come in many **colors**—orange, yellow, rusty, red, purple, and green with white quartzite. They were deposited in a large sedimentary basin between 1.4 and 1.1 billion years ago, and they preserve many fossils as well as sedimentary structures including **ripple marks**, mudcracks, and raindrops. Rocks from the Belt Supergroup are best seen in Glacier National Park, Montana, where they have been exposed by an extensive system of thrust faults and folds related to the subduction of the Farallon plate beneath western North America in the late Cretaceous. The Belt Supergroup is of particular note due to its age and excellent preservation. It is extremely rare for sedimentary rocks of over a billion years in age to not have been warped, tilted, metamorphosed, or otherwise altered. The Belt Supergroup is also famous for its abundant and well-preserved stromatolites. In addition, ancient **tillites** (glacial deposits) found in Idaho represent major glaciation events that occurred during the Proterozoic (*Figure 2.21*).

See Chapter 4: Topography for more about the Lewis Overthrust, which exposes rocks of the Belt Supergroup.

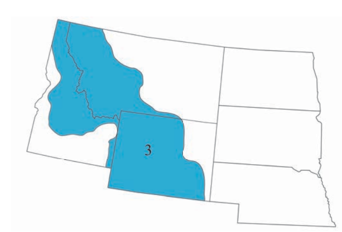
See Chapter 6: Glaciers to learn about Proterozoic glacial periods.

color (mineral) *• a physical property determined by the presence and intensity of certain elements within the mineral.*

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

tillite *• glacial till that has been compacted and lithified into solid rock.*

Figure 2.21: Diamictite, a type of tillite from the Pocatello Formation near Pocatello, Idaho. This rock is thought to have been deposited during the "Snowball Earth" Proterozoic glacial period.



Region 3

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

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

phosphate • *an inorganic salt of phosphoric acid, and a nutrient vital to biological life.*

aeolian • *pertaining to, caused by, or carried by the wind.*

While most of the ranges and uplifts in the Rocky Mountains are cored by Archean rocks, two major areas are not. The Snake and Salt River Ranges of western Wyoming and adjacent Idaho, and the range just west of Choteau, Montana, consist of Paleozoic and Mesozoic units faulted and uplifted during the Sevier Orogeny. The ranges of central Idaho are primarily made up of the three major lobes of the Idaho Batholith, a set of late Cretaceous granitic intrusions (*Figure 2.22*).

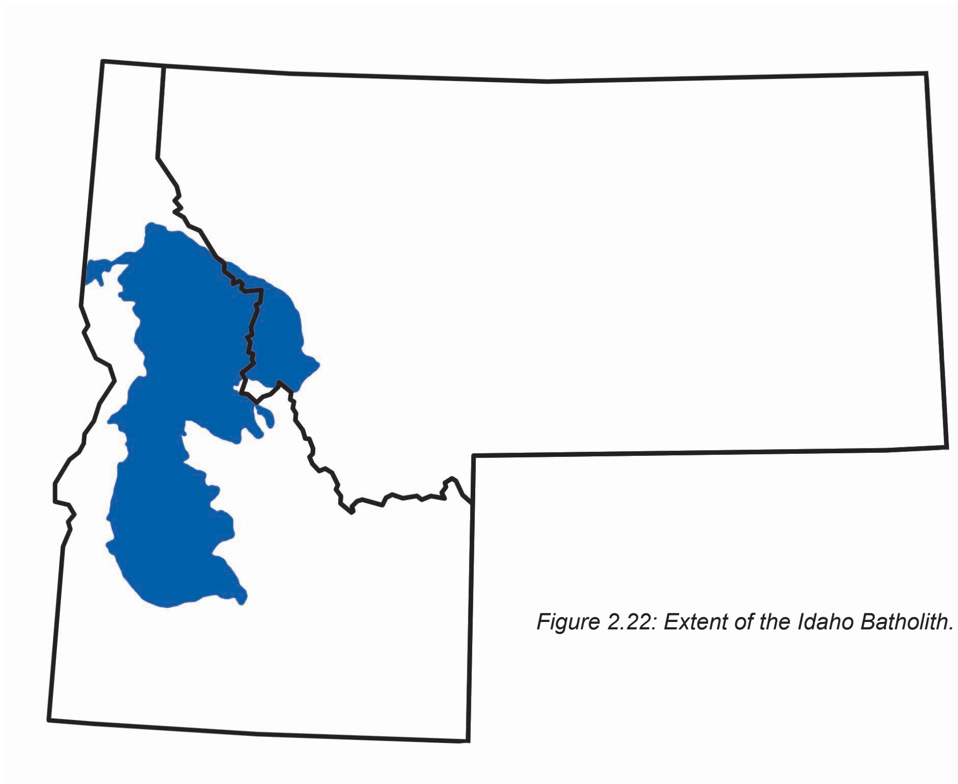
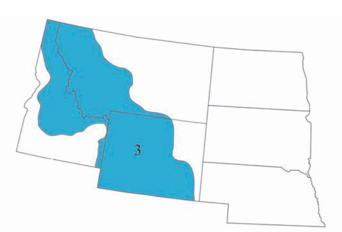


Figure 2.22: Extent of the Idaho Batholith.

The **Cambrian** to Mississippian rocks of the Rocky Mountain region are a succession of sandstones, limestones, and shales that were deposited on the continental shelf of what was then the western shore of North America (*Figure 2.23*). From the **Pennsylvanian** through the Permian, a transition to shallow and evaporating seas deposited sandstones, mudstones, limestones, and **phosphate**-rich rocks. During the Triassic, a hot and arid landscape stretched across the region, as the shallow seas of the previous era retreated. This led to the deposition of continental rocks on nearshore marine environments and vast floodplains: red beds, sandstones, mudstones, and limestones. Others were deposited by **aeolian** processes; the Nugget Sandstone, found in parts of southwest Wyoming, exhibits cross-bedding and was deposited by wind on a Jurassic shoreline or desert.

See Chapter 3: Fossils for more information about Wyoming's Mesozoic fossils.

The bright red and orange colors of many Mesozoic siltstones and sandstones are caused by the presence



of iron **oxides** (*Figure 2.24*). During the Cretaceous, shales, sandstones, and coals formed when the epicontinental Western Interior Seaway covered the area (*see Figure 2.8*).

Figure 2.23: Ridges of the Mississippian-aged Madison Limestone, exposed by thrust faulting along the Rocky Mountain Front in Montana.

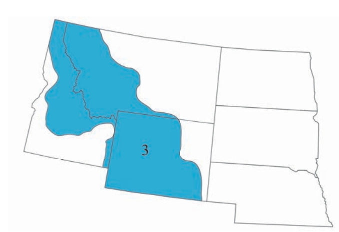
Between the main ranges of the Rockies, there are a series of **intermontane** basins and mesas (*Figure 2.25*); surface rocks here are predominantly of Cretaceous and early Cenozoic age. Most of the rocks were formed when eroded sediment from the uplifted mountains was deposited by rivers into alluvial fans in lakes, basins, and swamps. These deposits eventually formed conglomerates, sandstones, mudstones, shales, **evaporites**, coal, and limestone. Thick blankets or wedges of Paleogene and Neogene sediments were deposited on the flanks of uplifted mountains. Paleozoic, Triassic, and Jurassic rocks crop out where they are uplifted at the margins of uplifts and ranges, but are typically buried within the basins.

The most important intermontane basins in the Rocky Mountain region are the Green River, Bighorn, Wind River, and Red Desert basins. These areas were centers for the deposition of thick layers of shale and mudstone into lakes, later forming evaporite beds as the lakes dried. The best known of these basin deposits are the sediments of the Green River Basin, which include well known fossil beds, oil shales, and large coal deposits. It is also the world's largest source of trona, a non-marine evaporate mineral, along with related minerals including sodium bicarbonate (baking soda). Because of the basins' isolated

oxidation *• a chemical reaction involving the loss of at least one electron when two substances interact.*

intermontane *• between or among mountains.*

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



butte *• an isolated hill with steep, often vertical sides and a small, relatively flat top.*

lamproite *• an ultramafic volcanic (extrusive) rock with high levels of potassium and magnesium that contains coarse crystals.*

Figure 2.24: An outcrop of Triassic sandstone near Thermopolis, Wyoming.

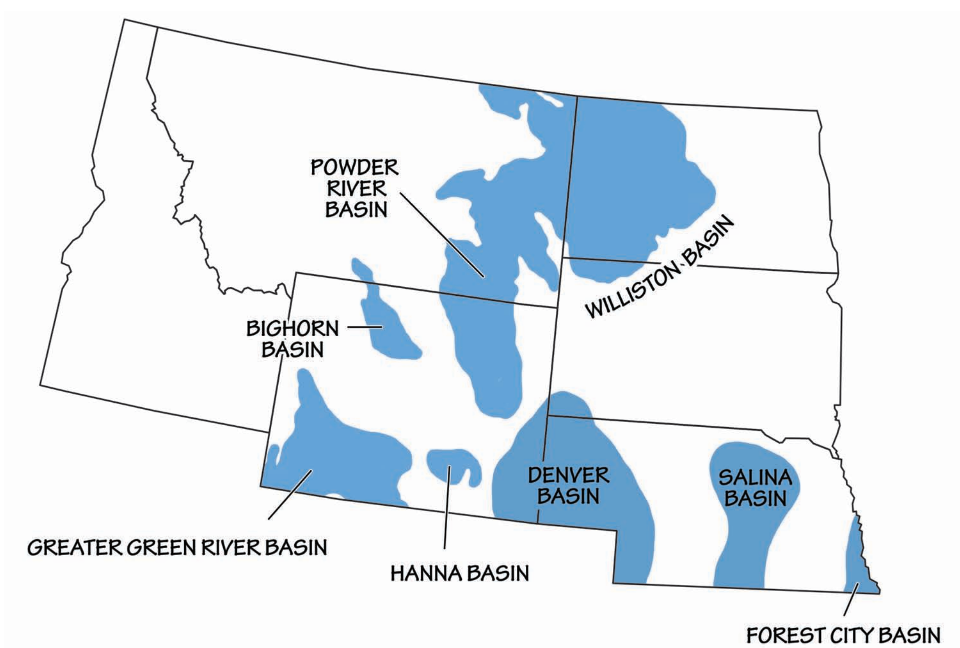
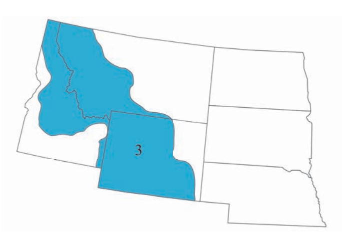


Figure 2.25: Geologic basins of the Northwest Central US.

nature, early Cenozoic deposits are mainly basin-specific, with individual units often restricted to a particular basin or set of related basins. Some basins also contain igneous outcroppings—for example, Boars Tusk, an isolated **butte** within the Green River Basin, is the heavily eroded **lamproite** core of a 2.5-million-year-old volcano (*Figure 2.26*).



Region 3

Figure 2.26: Boars Tusk, located within Sweetwater County, Wyoming, is the core of an extinct volcano.

During the Neogene, large volcanic eruptions related to the Yellowstone **hot spot** periodically buried parts of the region in thick layers of ash, forming **tuff** (*Figure 2.27*). Active **Eocene** volcanism and plutonism produced the Absaroka Volcanic Field in northwestern Wyoming, as well as smaller fields and intrusive bodies in Montana and Idaho. The Absaroka volcanics are up to 1500 meters (5000 feet) thick, and are composed of **andesites**, **dacites**, basalts, tuffs, and mudflows with minor related igneous intrusions (*Figure 2.28*).

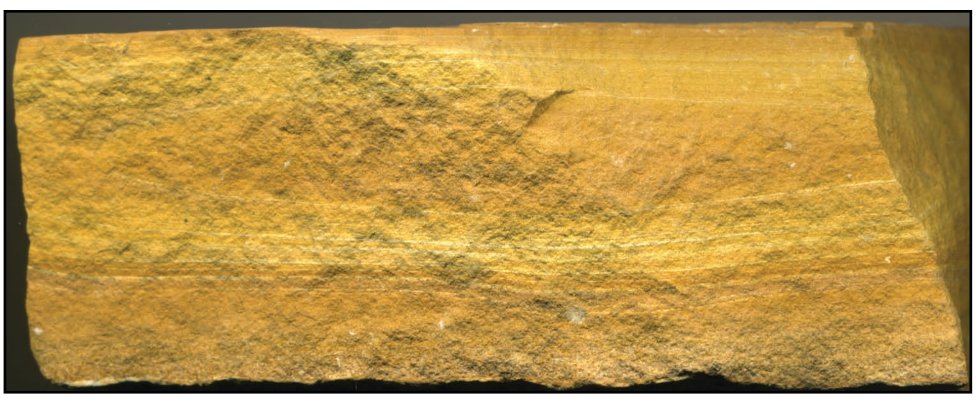


Figure 2.27: Volcanic ashfall tuff from the Eocene, Green River Formation, Wyoming.

A *pluton* is a large body of igneous rock that formed under the Earth's surface through the slow crystallization of magma. The term comes from Pluto, the Roman god of the underworld.

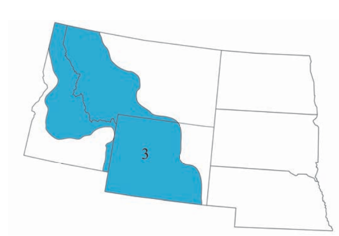
hot spot • *a volcanic region thought to be fed by underlying mantle that is anomalously hot compared with the mantle elsewhere.*

tuff • *a pyroclastic rock made of consolidated volcanic ash.*

Eocene • *a geologic time period extending from 56 to 33 million years ago.*

andesite • *a fine-grained extrusive volcanic rock, with a silica content intermediate between that of basalt and dacite.*

dacite • *a fine-grained extrusive igneous rock, with a silica content intermediate between that of andesite and rhyolite.*



Region 3

cirque • *a large bowl-shaped depression carved by glacial erosion and located in mountainous regions.*

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

caldera • *a collapsed, cauldron-like volcanic crater formed by the collapse of land following a volcanic eruption.*

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

geyser • *a hot spring characterized by the intermittent explosive discharge of water and steam.*

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

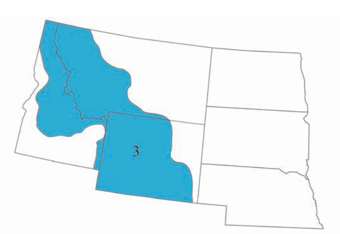


Figure 2.28: An andesite dike intrudes through a volcanic debris flow conglomerate exposed by a roadcut in the Absaroka Range, Wyoming.

Pleistocene glaciation produced glacial till and outwash materials in the region's mountains and basins. Alpine glaciers, rather than continental ice sheets, carved **cirques** and deposited **moraines** in mountain valleys.

Greater Yellowstone Area

Yellowstone National Park and its surrounding area are the latest and current manifestation of the Yellowstone hot spot, whose trail from Oregon to Wyoming produced the Snake River Plain in Idaho. The most recent **caldera** eruption associated with this hot spot occurred 640,000 years ago, and more recent minor eruptive activity produced **rhyolitic** domes and basalt flows. The Yellowstone area is rich with volcanic features, such as calderas, resurgent domes, lava flows, and hydrothermal explosion craters. Yellowstone also has the world's greatest number of **geysers**, along with hot springs, fumaroles, and mudpots. **Earthquakes** are common here, and many are related to faults connected with the movement of magma, groundwater, thermal expansion, or contraction of the ground.

See Chapter 10: Earth Hazards to learn more about natural hazards associated with the Yellowstone hot spot and supervolcano.

Due to the Yellowstone area's history of volcanism, rocks in the park are primarily volcanic. Major explosive caldera eruptions in the Yellowstone area occurred 2.1, 1.3, and 0.63 million years ago, with multiple minor eruptions occurring between the major caldera-forming eruptions. The volume of material ejected during these major eruptions has led to Yellowstone's classification as a **supervolcano** (*Figure 2.29*). A wide range of volcanic rock types and textures are present in the park, including basalts, rhyolites, obsidian (volcanic glass), agglomerates (volcanic flows that picked up cobbles or fragments of other volcanic rocks), and ashflows. In some areas, volcanic ashflows are mixed with sedimentary conglomerates, sandstones, and mudstones from stream and mudflow deposits.

The rocks formed during Yellowstone's past eruptive events can be seen in exposures throughout the park. The Huckleberry Ridge ash bed, laid down during the caldera explosion of 2.1 million years ago, is exposed in the walls of Golden Gate Canyon (*Figure 2.30*). An eruption around 590,000 years ago produced the Canyon Rhyolite flow, which can be seen in the Grand Canyon of the Yellowstone River on the eastern side of the park (*Figure 2.31*). Here, the rhyolites in the canyon walls have been altered by oxidation and acidic groundwater, resulting in striking yellows, pinks, and lavenders. Obsidian Cliff formed from a rhyolite lava flow that occurred 180,000 years ago (*Figure 2.32*); it contains abundant obsidian and was an important source of tool-making material for prehistoric peoples in the area.

Rhyolite and Basalt

Both rhyolite and basalt are lavas, but they behave differently due to their different densities and melt structures. Rhyolite is composed of felsic minerals including quartz, orthoclase, and biotite, and is high in silica and *aluminum*. This composition results in a very viscous magma. The lavas in volcanoes with felsic (rhyolitic) compositions are too viscous to flow easily; pressure builds up beneath them until they erupt explosively. The most explosive volcanoes form calderas, and the ash from such an explosion can travel many miles. The eruptions that occurred at the Yellowstone hot spot were rhyolitic in nature.

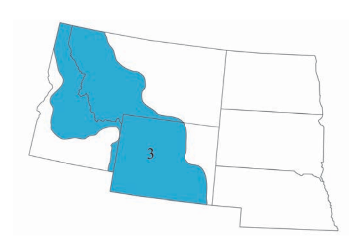
Basalt is composed of the mafic minerals plagioclase and *pyroxene*, and may contain *olivine*. These minerals are high in iron and magnesium, and produce a very fluid magma. Volcanoes with mafic or basaltic compositions tend to produce fluid lava flows comparable to those associated with the eruptions presently seen in Hawai'i. The voluminous Columbia Flood Basalts (see Region 4: the Columbia Plateau) are the result of a basaltic eruption.

supervolcano *• an explosive volcano capable of producing more than 1000 cubic kilometers (240 cubic miles) of ejecta.*

aluminum *• a metallic chemical element (Al), and the most abundant metal in the Earth's crust.*

pyroxene *• dark-colored rock-forming silicate minerals containing iron and magnesium.*

olivine *• an iron-magnesium silicate mineral ((Mg,Fe)2SiO4) that is a common constituent of magnesium-rich, silica-poor igneous rocks.*



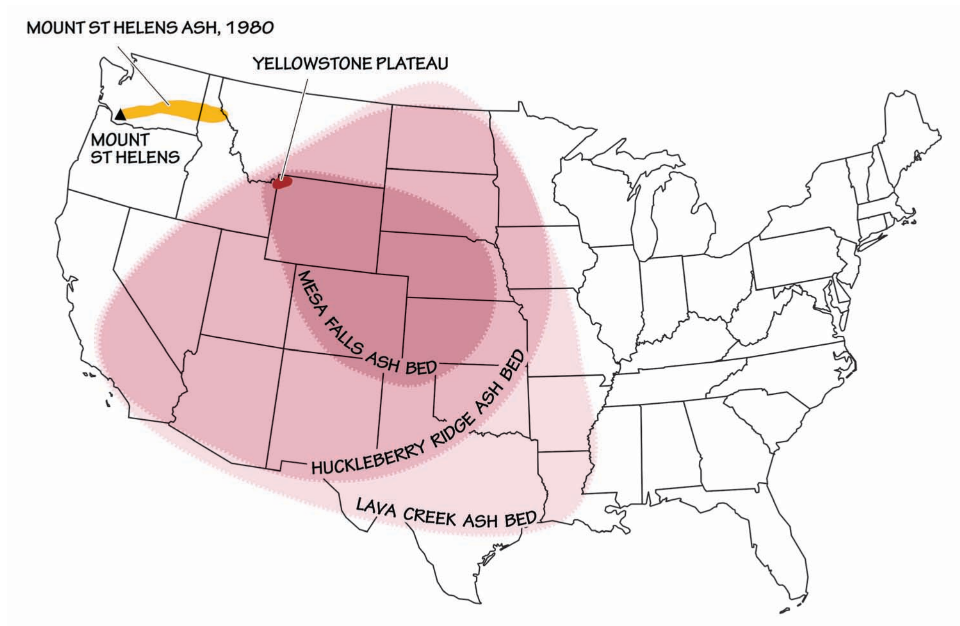


Figure 2.29: The extent of the three most recent ashfalls from Yellowstone supervolcano eruptions, as compared to the eruption of Mt. St. Helens in 1980.

Figure 2.30: The pink- and yellow-hued rocks exposed in Golden Gate Canyon are composed of Huckleberry Ridge Tuff, formed from an ashfall after a Yellowstone supervolcano eruption 2.1 million years ago.

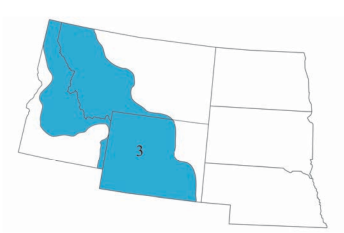
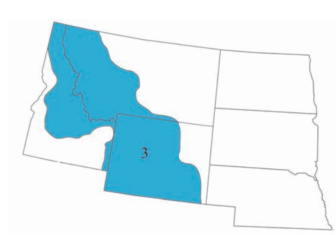


Figure 2.31: Brightly colored rhyolites are exposed in the Grand Canyon of the Yellowstone.

Figure 2.32: Thick veins of obsidian run through the rhyolite of Obsidian Cliff. Note the sunglasses used for scale.



Region 3

hydrothermal solution *• hot, salty water moving through rocks.*

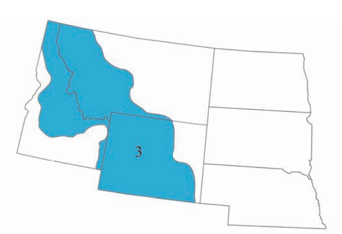
silica *• a chemical compound also known as silicon dioxide (SiO_2).*

Cordilleran Ice Sheet *• one of two continental glaciers that covered Canada and parts of the Western US during the last major Pleistocene ice age.*

Figure 2.33: The travertine terraces of Mammoth Hot Springs in Yellowstone National Park precipitated over thousands of years as hot water from the spring cooled and deposited calcium carbonate. Over two tons of carbonate minerals in solution flow through the hot springs every day.

The thermal features of Yellowstone are driven by heat from the cooling magma body beneath the caldera. Groundwater circulates through the hot rock, rises in hot springs, or erupts as geysers if there is a pressure buildup within the water. Fumaroles are openings that emit gaseous steam. Mudpots occur where hot water mixes with clay that has weathered from volcanic rock; the thick mud bubbles and spatters as it boils or releases gas. The **hydrothermal solutions** that circulate within Yellowstone's geysers and hot springs dissolve minerals from the bedrock, precipitating them out at the surface to form intricate structures made of **silica** or travertine (*Figure 2.33*).

During the Quaternary, the **Cordilleran Ice Sheet** covered part of the Rocky Mountains, and a small ice sheet covered Yellowstone. This glaciation event left behind glacial till, creating moraines and outwash deposits from sediments deposited by meltwater. Geyser and hot spring activity continued beneath the ice cover. The combination of ice, meltwater ponds and lakes, and underground heat sources caused hydrothermal explosions—these are not volcanic eruptions, but rather occur when water contained in near-surface rock at superheated temperatures flashes to steam and violently disrupts the confining rock. In the case of the Pocket Basin, located in the western part of the park, an ice-dammed lake existed over a heat source, and a hydrothermal explosion was triggered by an abrupt decrease in confining pressure when the dam failed and the lake drained. This event created a crater-like basin, in which steam works its way through silica-bearing volcanic silt to create mudpots (*Figure 2.34*)



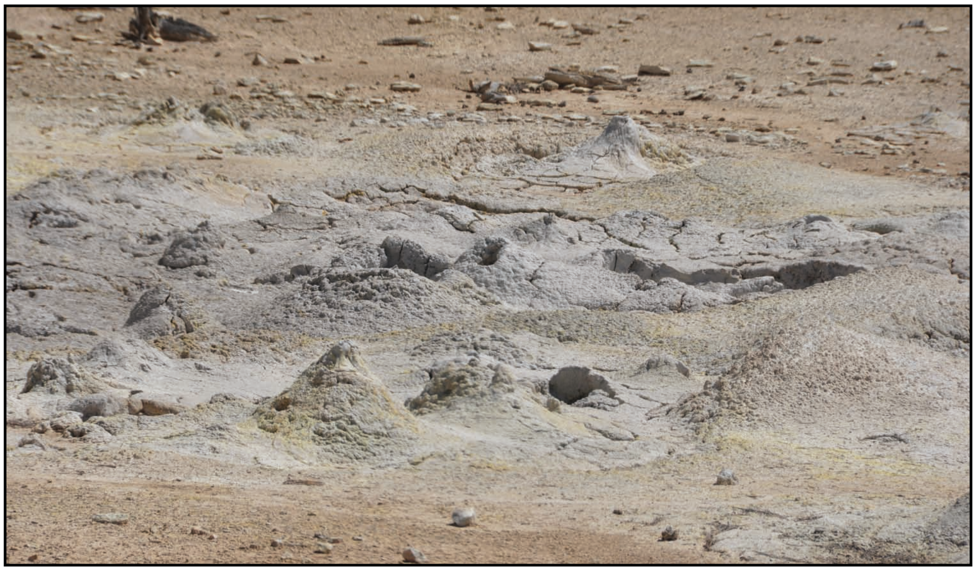


Figure 2.34: Mudpots in the Pocket Basin, Yellowstone National Park. The mud is composed of hot water mixed with volcanic clay.

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

Rocks of the Columbia Plateau
Region 4

The Columbia Plateau, also known as the Columbia Basin, is the site of one of the largest outpourings of lava that the world has ever seen. The Columbia Plateau flood basalts are a notable example of a "Large Igneous Province," where vast volumes of basalt are erupted over a relatively short period of time. Such a high volume of basaltic lava is erupted that the lava flows flood the land's surface. Between 15 and 6 million years ago, basaltic lava flooded approximately 163,000 square kilometers (63,000 square miles), covering large parts of Washington, Oregon, and Idaho (*Figure 2.35*). The thickness of the lava flows reached 1800 meters (6000 feet), burying almost all of the older rock in the area. Geological evidence suggests that many of these flows advanced over preexisting topography at a rate of five kilometers per hour (three miles per hour). This was made possible by the fact that basaltic lava erupts at a temperature of greater than 1100°C (2000°F), yielding a very hot and fluid form of lava that would have quickly inundated existing landforms. The Columbia Plateau in western Idaho is uniformly covered with basalt, although over geological time, a large degree of faulting and warping has altered once nearly uniform elevations to a range of 60 to 1500 meters (200 to 5000 feet). The basalt flows found in this region commonly exhibit spectacular examples of columnar jointing.

See Chapter 1: Geologic History to learn more about the progression of the Yellowstone hot spot.

Large areas of flood basalt are generally associated with **mantle** hot spots. In this case, they are associated with the

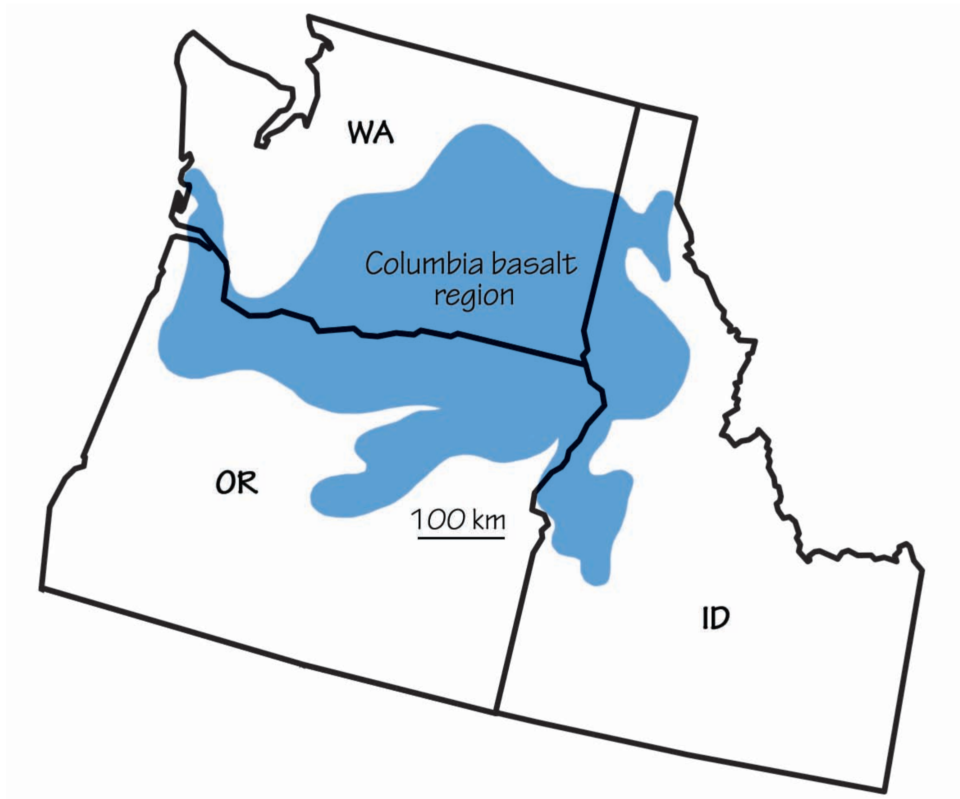


Figure 2.35: Extent of the Columbia Basin Flood Basalt.

Yellowstone hot spot, whose trail from Oregon to Wyoming has produced the Snake River Plain. As the North American plate passed over the hot mantle plume, melting the base of the crust and producing large volumes of magma, the hot spot's eruptive center moved northeastward across Idaho.

The rocks of the Snake River Plain cut across both the older Rocky Mountain and Basin and Range regions of Idaho. The plain is deeply filled with 30 to over 300 meters (100 to over 1000 feet) of rhyolite and basalt. Thick layers of rhyolite are generally capped by basalt on the surface—smaller basaltic eruptions tended to continue long after a major rhyolitic caldera eruption. Deeper rocks are seen in drillhole cores, but there are many places where the surface basalts or lava fields can be seen. Craters of the Moon National Monument is a lava field where basalts have been erupted over the last 15,000 years; the youngest flow there is only 2000 years old (*Figure 2.36*). Visitors can see flows, lava tunnels, spatter cones, and other volcanic features. Hell's Half Acre, Shoshone, Cerro Grande, and Wapi are also well known lava fields in the plain.

In addition to lava flows, eruptions from the Yellowstone hot spot often generated enormous clouds of ash created when rhyolite magma was erupted as tiny molten particles. The ash was buoyed through the air by hot gases and blanketed hundreds of kilometers (miles) of land. As it condensed, it solidified into thick layers of tuff (*Figure 2.37*).

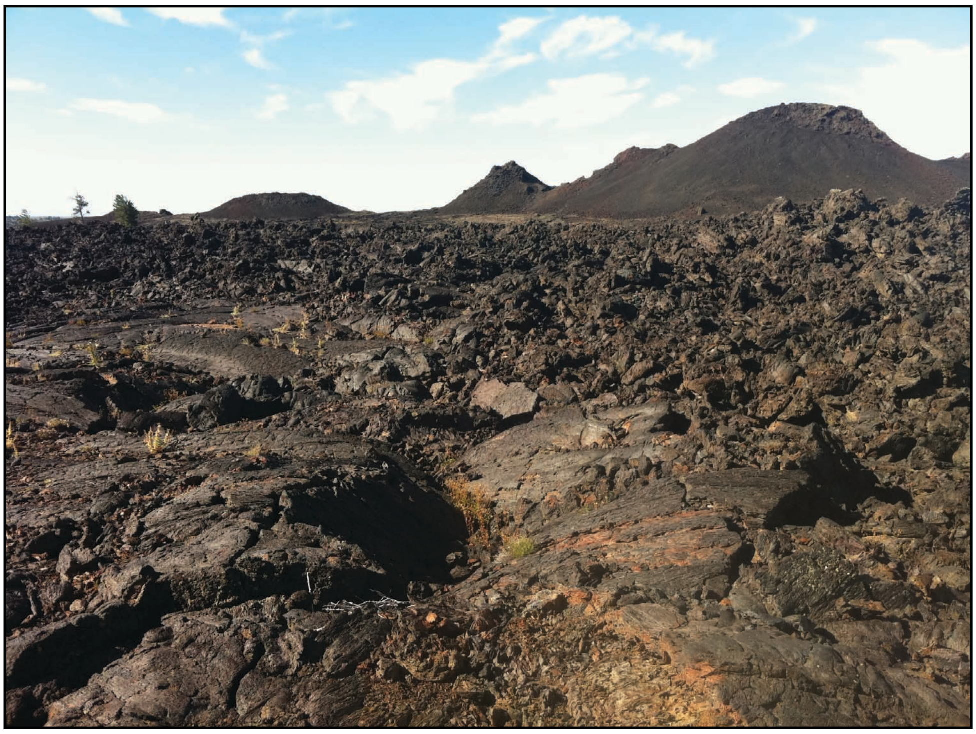
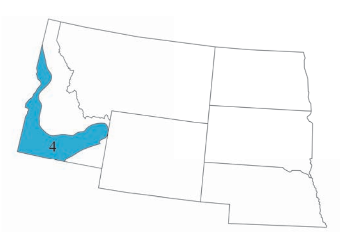


Figure 2.36: A lava field at Craters of the Moon National Monument, Idaho.

Figure 2.37: The Owyhee Canyonlands of southwestern Idaho cut through the Snake River Plain’s volcanic units, revealing layers of basalt, rhyolite, and welded tuff.



pahoehoe • *a type of lava resulting from the rapid motion of highly fluid basalt. It cools into smooth glassy flows, or can form twisted, ropey shapes.*

'a'a • *a dense and blocky lava flow, made up of a massive front of hardened fragments.*

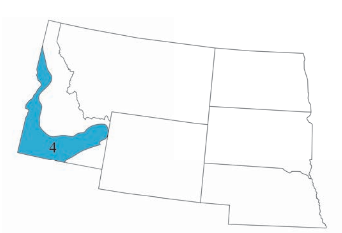
Types of Volcanic Flows

Pahoehoe **flows are fluid, fast flowing basaltic rivers of lava resulting in smooth, ropey surfaces. In contrast, *'a'a* flows are blocky, rubbly, slow-moving basaltic flows of cooling lava. They advance as cooled fragments tumble down the steep front and are buried by the advancing flow, producing a rough, spiny surface. Pillow lavas are formed when lava enters water, such as a lake, river, or ocean. The surface of the lava mass entering the water is cooled instantaneously, insulating the inner mass, which cools more slowly to form an irregular ovoid with a glassy external surface and a fine crystalline core.**

A pahoehoe lava flow at Craters of the Moon National Monument.

Not all features of Idaho's Columbia Plateau are related to igneous activity. As the Cordilleran Ice Sheet retreated back into Canada at the end of the ice age, meltwater ponded in lakes of all sizes. One of the largest glacial lakes was Glacial Lake Missoula in Montana, which was dammed by the ice sheet. When the ice dam failed, the lake was released in a catastrophic flood. The

See Chapter 6: Glaciers for more information about Glacial Lake Missoula.



resultant landforms from this violent flood event carved deep channels into the terrain and left giant ripple marks, **potholes**, and boulders in the Channeled Scablands of northern Idaho and western Washington.

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

Rocks of the Basin and Range
Region 5

A tiny corner of the Basin and Range region— a huge physiographic region that extends from southeastern Oregon to west central Mexico—extends into the Rocky Mountains of southeastern Idaho. While the formation of the Basin and Range is a recent event that began only 30 million years ago, the bedrock that makes up the region's up-thrust ranges and down-dropped basins is very old. In this tiny area of Idaho, rocks can be found from nearly all periods of the **Phanerozoic**. This is largely because the region's most recent geologic activity involved crustal extension that has exposed many deeper, older layers. During the Paleogene, magma upwelling from the mantle weakened the lithosphere, lowering its **density**. This stimulated uplift, stretching the bedrock in an east-west direction. The crust along the Basin and Range stretched, thinned, and faulted into some 400 separate mountain blocks. Movement along the faults led to a series of elongated peaks and down-dropped valleys, also called horst and graben landscapes. In a manner similar to books toppling when a bookend is removed from a shelf, the blocks slid against each other as they filled the increased space (*Figure 2.38*).

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

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

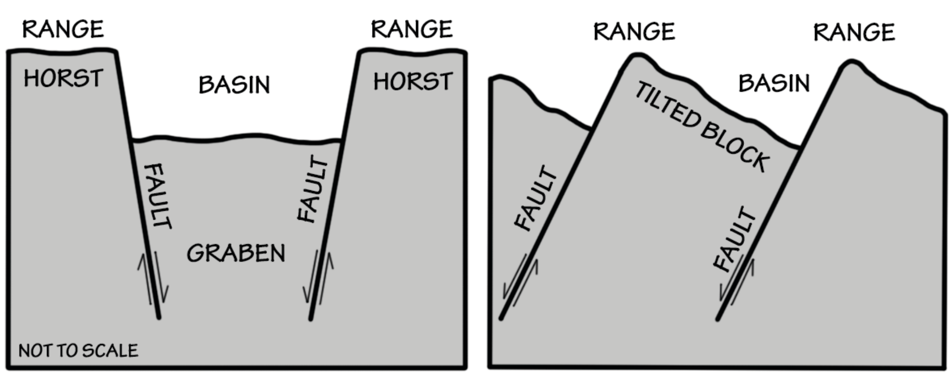
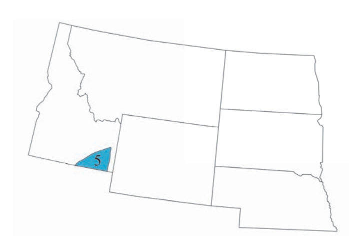


Figure 2.38: Alternating basins and ranges were formed during the past 17 million years by gradual movement along faults. Arrows indicate the relative movement of rocks on either side of a fault.

Since the region's formation, the bedrock of the basins has been covered by young deposits, including loose sediment washed down from the mountains and evaporite deposits left behind in dried-out lakes. The ranges, however, particularly the Sevier Orogenic Belt (also known as the "Overthrust Belt"), expose rocks whose ages span from Precambrian to Cenozoic. The Basin and Range's Paleozoic rocks, a succession of sandstones, limestones, and shales, were deposited on the western shore of North America during the Cambrian to



the Mississippian. This was followed during the Pennsylvanian to the Permian by a transition to shallow and evaporating seas, which deposited sandstones, mudstones, limestones, and phosphate-rich rocks. Mesozoic rocks include red beds, sandstones, mudstones, and limestones of the Dinwoody, Nugget, Twin Creek, Morrison, and Stump Formations. Good outcrops of these rocks can be seen in uplifted ranges such as the Bear and Aspen Range. These Paleozoic and Mesozoic sediments were thrusted during the Sevier Orogeny, then involved in the Basin and Range style of extension during the Paleogene. Valleys formed by this extensional faulting were filled with later Cenozoic sediments.

Younger rocks from the Cretaceous and the Cenozoic cover the valley floor, filling the region's basins (*Figure 2.39*). These rocks are mainly conglomerates, sandstones, and mudstones originating from erosion of the nearby uplifts. In the case of the Idaho Basin and Range, the basin fills also include Cenozoic volcanic rocks produced by nearby volcanic activity on the Snake River Plain. Pleistocene deposits include glacial till, outwash, and glacial lake deposits. These gravels, sands, silts, and tills are mostly associated with glaciers in the adjacent Teton and Snake River Ranges of Wyoming.

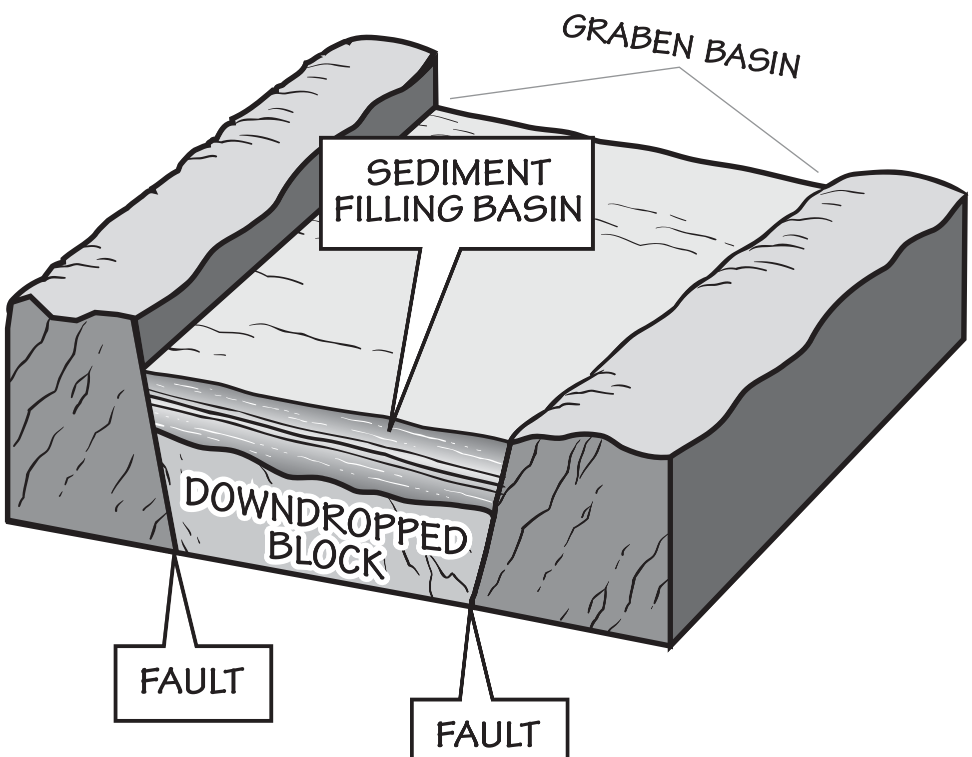
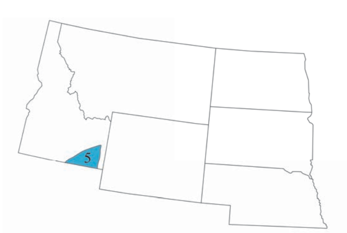


Figure 2.39: Basin fill in the Basin and Range.



State Rocks

gem • *a mineral that has been cut and polished for use as an ornament.*

agate • *a crystalline silicate rock with a colorful banded pattern. It is a variety of chalcedony.*

chalcedony • *a crystalline silicate mineral that occurs in a wide range of varieties.*

Oligocene • *a geologic time interval spanning from about 34 to 23 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).*

State Rocks, Minerals, and Gems

Idaho
Idaho has no state rock or mineral.

State **gem**: star garnet
These dark purple silicate crystals are found in great quantity in only two places in the world: India, and Idaho's panhandle. Star garnets have a unique property that causes them, when polished, to display a reflection that looks like a four- or six-pointed star.

Montana
Montana has no state rock or mineral.

State gems: Montana **agate** and sapphire.
Montana agates are usually light yellow or clear in color, and contain bands and inclusions of red and black iron and other mineral oxides. They are found in Pleistocene-aged gravel deposits around the Yellowstone River and its tributaries. Montana sapphires are found in four major areas: the Missouri River, the Sapphire Mountains, Yogo Gulch, and Deer Lodge. These gemstones appear in a greater variety of colors than sapphires found anywhere else in the world, leading to Montana's nickname as the "Treasure State."

Nebraska
State rock: prairie agate
Prairie agate is a semiprecious variety of **chalcedony** known for its lack of the coarse banding present in most types of agate. It is found in abundance in the Ogalalla National Grasslands.

State gem: blue agate
This dark blue variety of chalcedony often exhibits blue and white banding. Blue agates formed from wind-blown silt and claystone deposited during the **Oligocene** and are found in northwestern Nebraska.

North Dakota
North Dakota has no state rock, mineral, or gem.

South Dakota
South Dakota has no state rock.

State mineral: rose **quartz**
This silicate mineral is found in great quantities throughout the Black Hills. It was first discovered there in 1875, and the Scott Rose Quartz Mine was opened in 1902.

State gem: Fairburn agate

State Rocks

__jade__ • a word applied to two green minerals that look similar and have similar properties: jadeite (a kind of pyroxene) and nephrite (a kind of amphibole).

These colorful silicate minerals are named for a locality near Fairburn, South Dakota, where they were originally discovered. The Fairburn agate is notable for its variety of colorful, strikingly contrasted, thin red, pink, white, and yellow bands.

Wyoming

Wyoming has no state rock or mineral.

State gem: nephrite **jade**
This green stone was first described in the Granite Mountains of central Wyoming in 1936. Wyoming's jade is considered to be some of the world's finest nephrite, and it appears in many varieties and colors.

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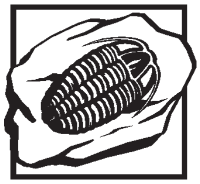

Chapter 3: Fossils of the Northwest Central US

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 weathering, is decomposed, or is 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 (but may, under special circumstances).

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

Lagerstätten

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. The Northwest Central States contain numerous examples of such exceptional preservation, also called lagerstätten, including the Miocene Clarkia fossil beds in northern Idaho, the Bear Gulch Beds of central Montana, the Florissant fossil beds of Colorado, the Agate bone beds of Nebraska, and the Eocene Green River Formation of Utah, Colorado, and Wyoming.

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

sedimentary rock • *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.*

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.*

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

CHAPTER AUTHORS

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3

Fossils

Overview

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

filter feeder • *an animal that feeds by passing water through a filtering structure that traps food.*

intertidal • *areas that are above water during low tide and below water during high tide.*

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

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 their environments were like. By studying the geological and biological information recorded in a rock that contains a fossil, scientists can determine some aspects of the paleoenvironment.

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.**

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, which show impressions of the exterior or interior of a shell. **Chemical fossils** are chemicals produced by an organism that leave behind an identifiable trace in the geologic record, and it is these fossils that provide some of the oldest evidence for life on Earth.

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

Fossils  3

Overview

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. This 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. This practice is called biostratigraphy. 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.**

__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.

Ancient Biodiversity

Since life began on Earth more than 3.7 billion years ago, it has continuously become more abundant and diverse. It wasn't until the beginning of the **Cambrian** period, around 541 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 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 pace. These intervals are known as **mass extinctions**. There were five particularly devastating mass extinctions in geologic history (*Figure 3.1*), 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, due mostly to human activity, and that we are currently experiencing a sixth mass extinction event.

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.

3 Fossils

Overview

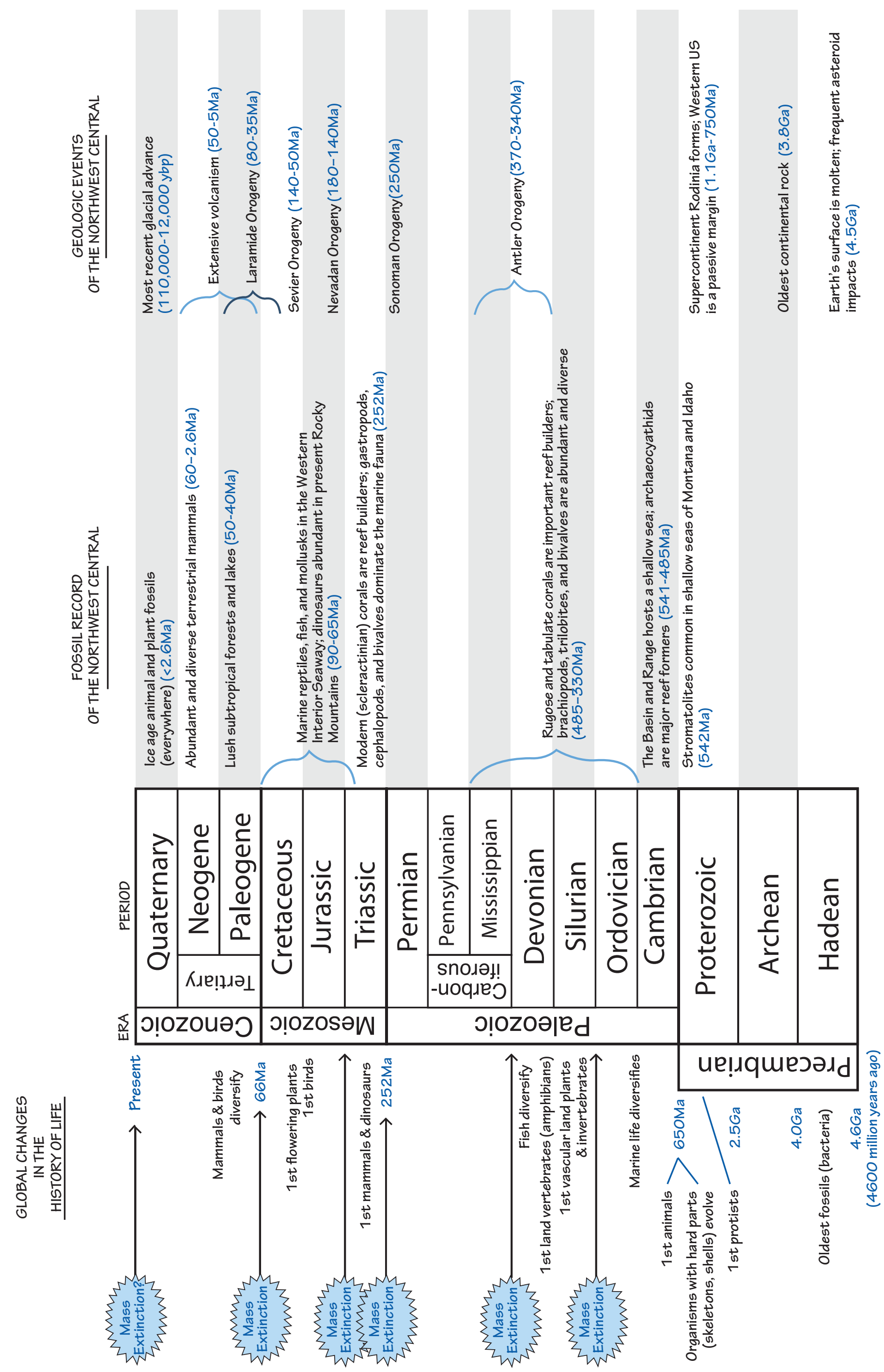


Figure 3.1: The history of life in relation to global and regional geological events and the fossil record of the Northwest Central US (Time scale is not to scale).

Fossils 3

Fossils of the Northwest Central US

The rocks of the Northwest Central United States contain abundant and spectacular fossils, and preserve an excellent fossil record of many aspects and intervals in the history of life (*see Figure 3.1*). Indeed, this area contains some of the most spectacular fossil deposits in the world, and in many places, fossils are almost everywhere. In the remainder of this chapter, we will highlight the major types of fossils present in most of the geologic periods represented by rocks in each state. The references at the end of the chapter should be consulted for details, especially for identifying particular fossils you might find.

Fossils of the Central Lowland

Region 1

The Central Lowland region composes the middle part of the North American continent, centered on the Mississippi River Valley. This region as a whole includes abundant and extensive fossils from the early **Paleozoic** (for example, in Ohio, Iowa, and Wisconsin), demonstrating that the area was covered by a warm, shallow sea during much of this time.

The portion of the Central Lowland region represented in the Northwest Central States—eastern Nebraska, eastern South Dakota, and eastern North Dakota—has very few Paleozoic rocks at the surface. The majority of fossils found in this region are from the **Cretaceous** period, which is the youngest bedrock in the area, although younger **Quaternary** sediments also yield fossils (*see, for example, Figure 3.50*). Cores drilled from the subsurface in eastern parts of the Dakotas, however, have yielded marine fossils of early and middle Paleozoic age similar to those found elsewhere in the region (*Figure 3.2*), revealing that these areas were also covered by the same warm, shallow sea. Fossils and other subsurface information indicate that coral **reefs** were well developed in what is now North Dakota during parts of the **Silurian** and **Devonian**.

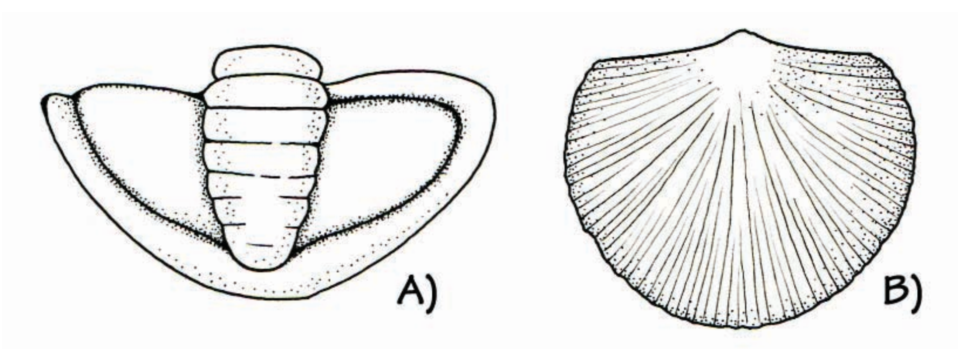


Figure 3.2: Cambrian trilobite and brachiopod found in cores from the Dakotas and Montana. A) Trilobite pygidium (tail), Lloydia valmyensis. *B) Brachiopod,* Nanorthis perilla. *Both fossils are about 5 millimeters (0.25 inches) wide.*

Region 1

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

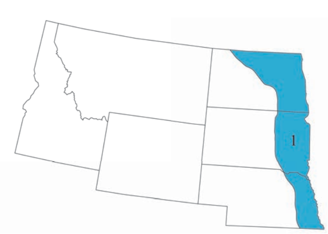
Cretaceous • *a geologic time period spanning from 144 to 66 million years ago.*

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

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.*

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.*



3 Fossils

Region 1

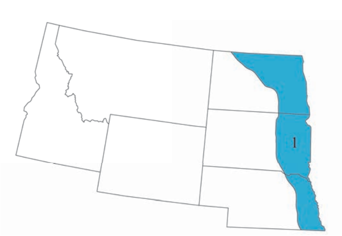
Pennsylvanian • a subperiod of the Carboniferous, spanning from 323 to 299 million years ago.

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

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).

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

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



Pennsylvanian rocks outcrop in easternmost Nebraska (in Cass, Otoe, and Sarpy counties), and contain a diversity of marine fossils, including **foraminifera**, **brachiopods**, **bryozoans**, **cephalopods**, **crinoids**, **gastropods**, **bivalves**, **trilobites**, corals, and the teeth of early **sharks** (*Figures 3.3–3.12*). The Beil Limestone, for example, is a rock layer containing abundant corals; it occurs in Cass County, Nebraska, and also extends into Mills and Montgomery counties in Iowa, Holt County in Missouri, and Doniphan, Atchison, Greenwood, and Douglas counties in Kansas (*Figure 3.13*).

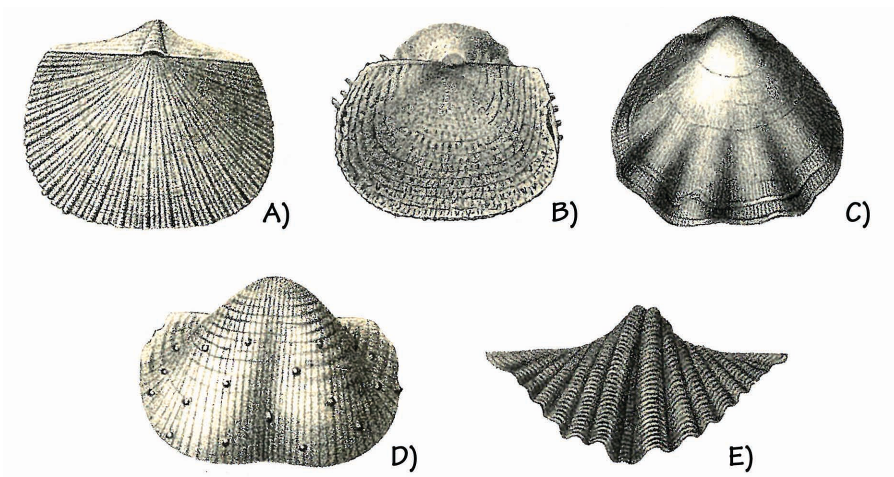


Figure 3.3: Pennsylvanian brachiopods from eastern Nebraska. A) Hemipronites crassus. *B)* Parajuresania nebrascensis. *C)* Syntrilasma hemiplicata. *D)* "Productus" costatus. *E)* Punctospirifer kentuckensis. *All specimens are 3–4 centimeters (1.25–1.5 inches) wide.*

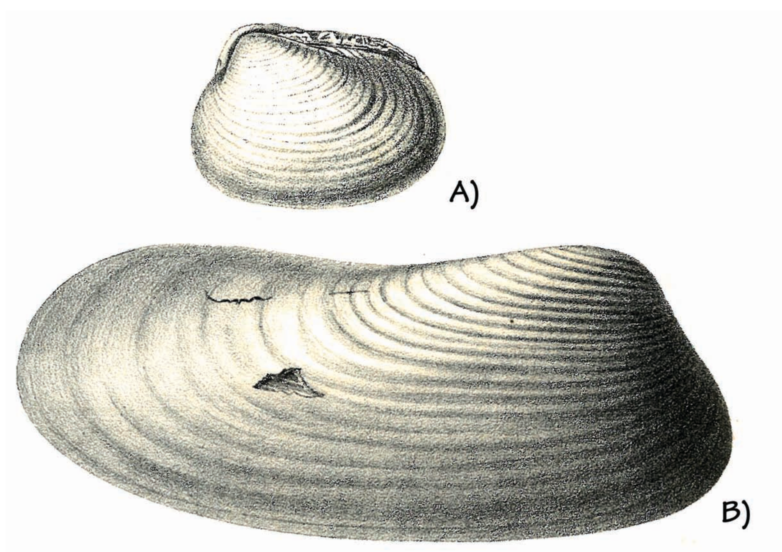
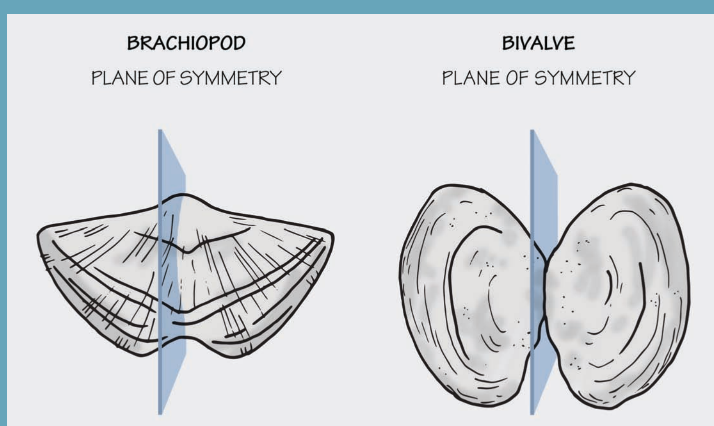


Figure 3.4: Pennsylvanian bivalves from eastern Nebraska. A) Allorisma subcuneata*, about 3 centimeters (1.25 inches) wide. B)* Edmondia aspinwallensis*, about 9 centimeters (3.5 inches) wide.*

Brachiopods

Brachiopods are filter-feeding animals that have two shells and are superficially similar to bivalves (such as clams). Instead of being mirror images between shells (symmetrical like your hands), brachiopod shells are mirror images across each shell (symmetrical like your face). Internally, brachiopods are substantially different from bivalves, with a lophophore (filter-feeding organ made of thousands of tiny tentacles), and a small and simple gut and other organs. Bivalves, in contrast, have a fleshier body and collect their food with large gills.



The difference between the shells of a typical brachiopod (left) and a typical bivalve mollusk (right). Most brachiopods have a plane of symmetry across the valves (shells), whereas most bivalves have a plane of symmetry between the valves.

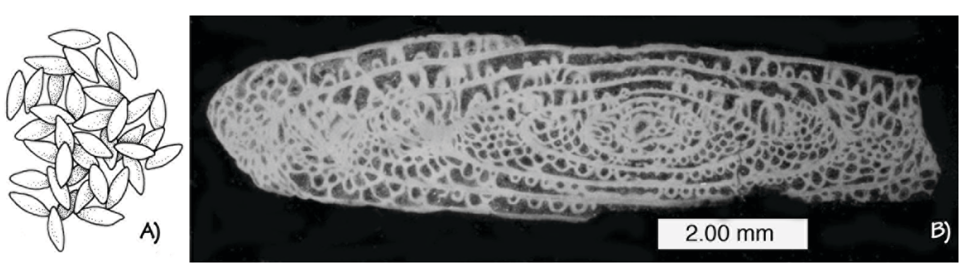


Figure 3.5: Single-celled fusulinid foraminifera from the Permian. A) A cluster of the shells, about the size and shape of large rice grains. B) Photograph of a cross-section through a single fusulinid, as seen through a microscope. Fusulinids can be a major component of carbonate rocks, composing up to 70% of some limestones in eastern Nebraska.

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.*

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

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

shark • *a large fish characterized by a cartilaginous skeleton and five to seven gill slits on the side of the head.*

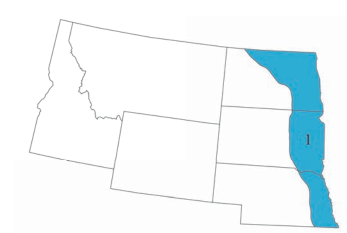


Figure 3.6: Pennsylvanian bryozoan from eastern Nebraska. Fenestella *sp., about 4 centimeters (1.5 inches) wide.*

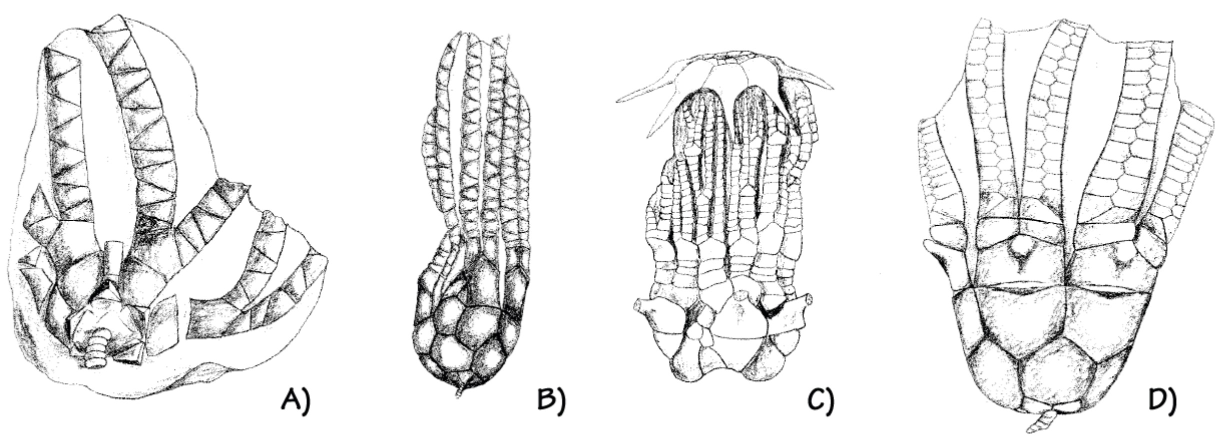


Figure 3.7: Pennsylvanian crinoid crowns from eastern Nebraska. A) Stellarocrinus. *B)* Apographiocrinus. *C)* Stenopeerinus. *D)* Exaetocrinus. *All specimens are about 4–5 centimeters (1.75–2 inches) tall.*

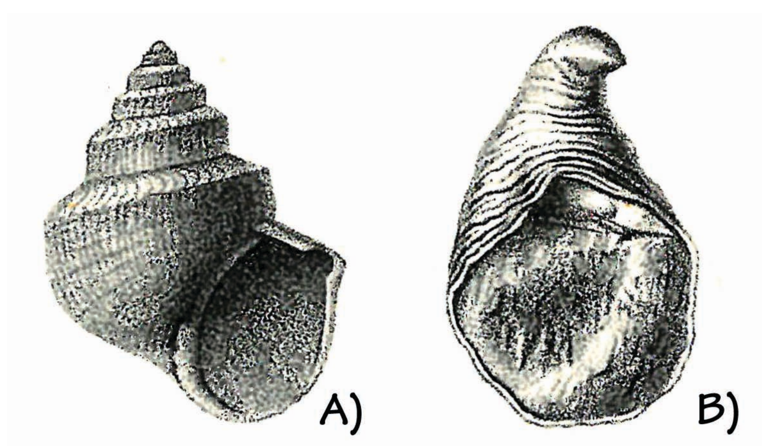
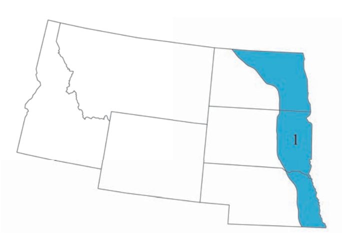


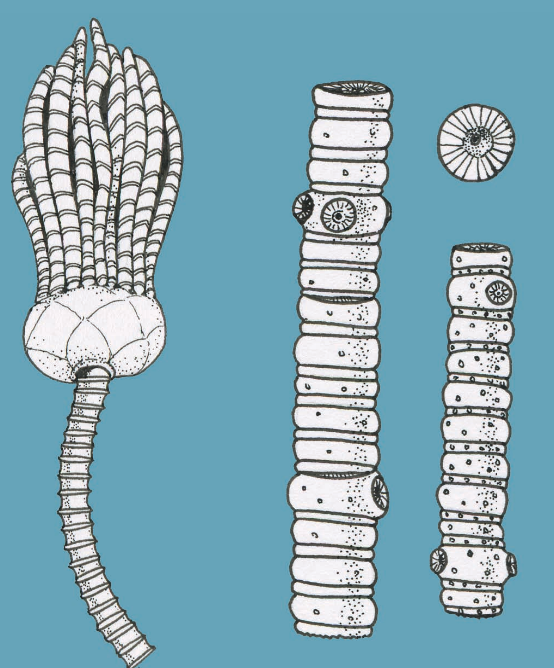
Figure 3.8: Pennsylvanian gastropods from eastern Nebraska. A) Hypselentoma perhumerosa, *about 2 centimeters (0.8 inches) tall. B)* Platyceras nebrascensis*, about 3 centimeters (1.25 inches) tall.*



Region 1

Crinoids

Crinoids are *echinoderms*, related to sea urchins and sea stars. These invertebrate animals feed by using their arms to filter food out of the water. Most are attached to the sediment by a stalk that ends in a root-like structure called the holdfast—however, some forms are free floating. Crinoid fossils are most commonly found as "columnals," pieces of the stalk that hold the head (*calyx*) above the surface. The calyx and the holdfast are only occasionally preserved as fossils.



Crown and stem, about 15 centimeters (6 inches) long.

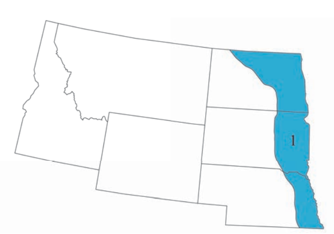
Stem fragments.

The northeastern corner of North Dakota (Pembina County) contains the Central Lowland's only **Jurassic** bedrock. By that time, a shallow sea had flooded the region again, and fossil marine gastropods, bivalves, and crinoids are found in the state's Jurassic deposits. Cretaceous rocks occurring in the Central Lowland, as well as the few **Cenozoic** deposits that extend into northeastern Nebraska, are identical to those found in the Great Plains region and will be discussed in detail in the next section.

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

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

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



Cephalopods

Cephalopods, such as squid, octopods, nautiloids, ammonoids, and belemnites, are mollusks with tentacles and beak-shaped mouths for catching prey. Some cephalopods such as belemnites and living cuttlefish have internal shells, while others have straight or coiled shells, such as those of ammonoids or nautiloids. Still other cephalopods, such as the octopus, have no shell. The mass extinction at the end of the Cretaceous (famous for eliminating the non-avian dinosaurs), also eliminated belemnites and ammonoids, which had been extremely diverse during the Mesozoic.

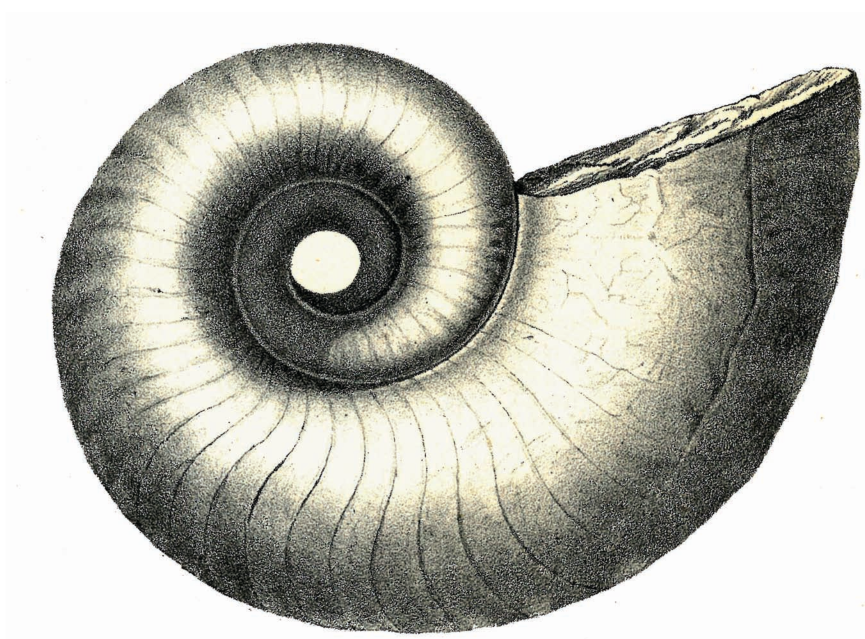
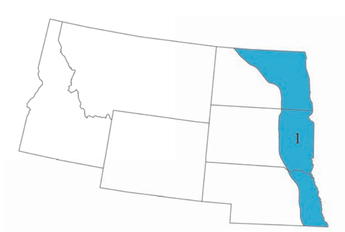


Figure 3.9: Pennsylvanian nautiloid cephalopod from eastern Nebraska, Titanoceras ponderosus, *about 15 centimeters (6 inches) in diameter.*



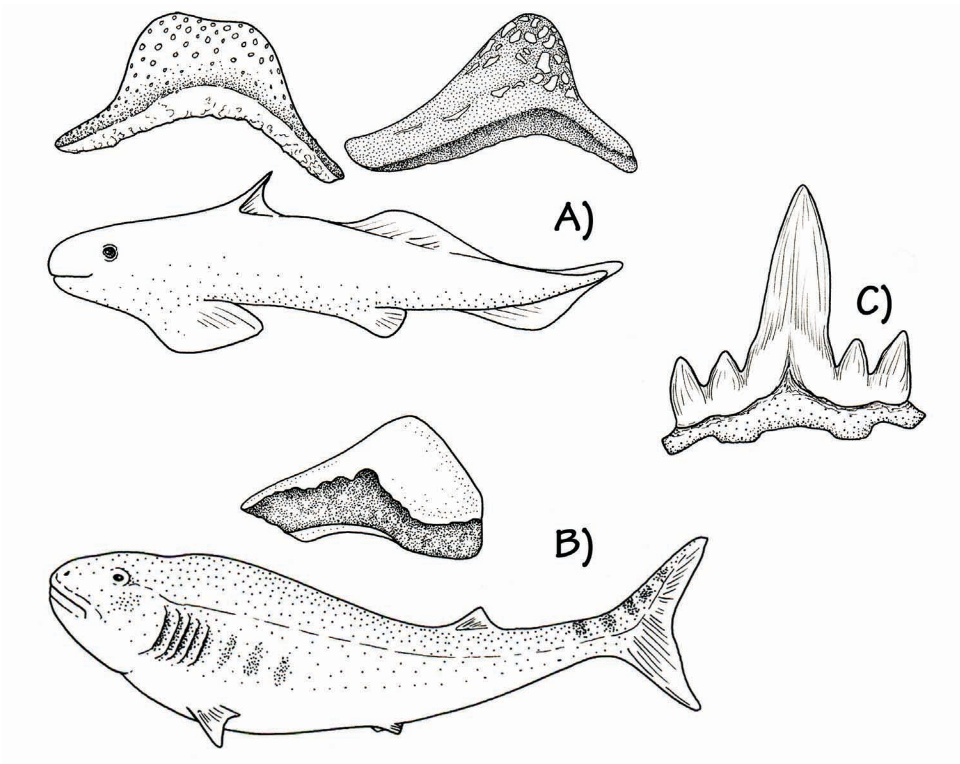


Figure 3.10: Early sharks from the Pennsylvanian of Nebraska. A) *Helodus simplex, teeth and restoration. Teeth about 2 centimeters (0.8 inches) wide; body about 30 centimeters (1 foot) long. B)* Orodus *sp., tooth and restoration. Tooth about 1 centimeter (0.4 inches) wide; body about 1 meter (3 feet) long. C)* Cladodus occidentalis*, tooth, about 1.5 centimeters (0.5 inches) tall.*

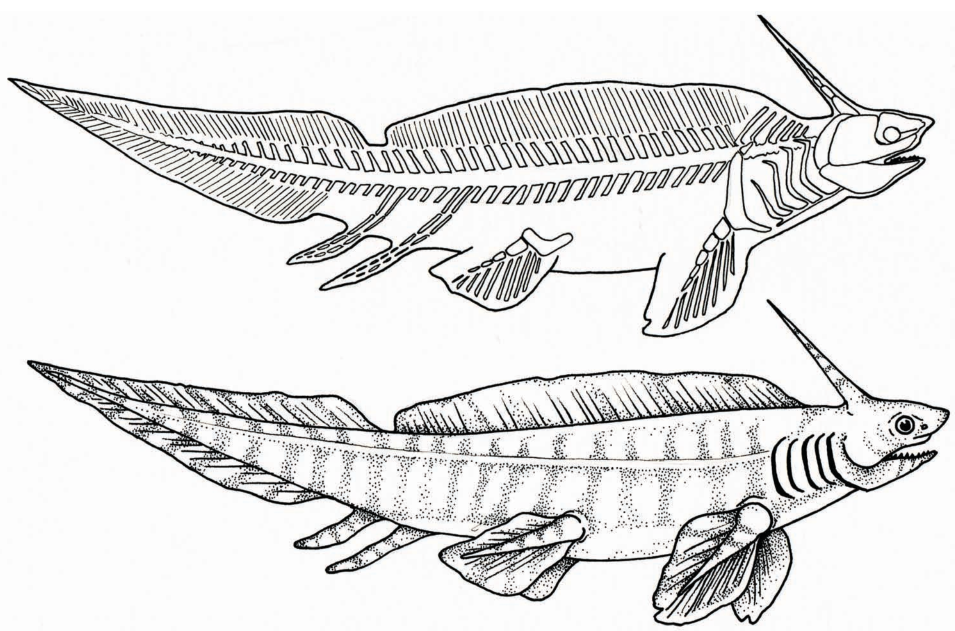
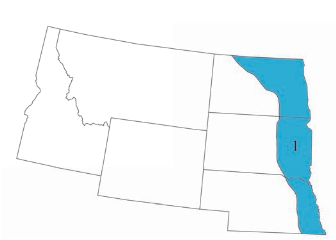


Figure 3.11: Skeleton and restoration of Xenacanthus. *Xenacanths were freshwater sharks that lived during the Pennsylvanian and Permian periods. Body about 30 centimeters (1 foot) long.*



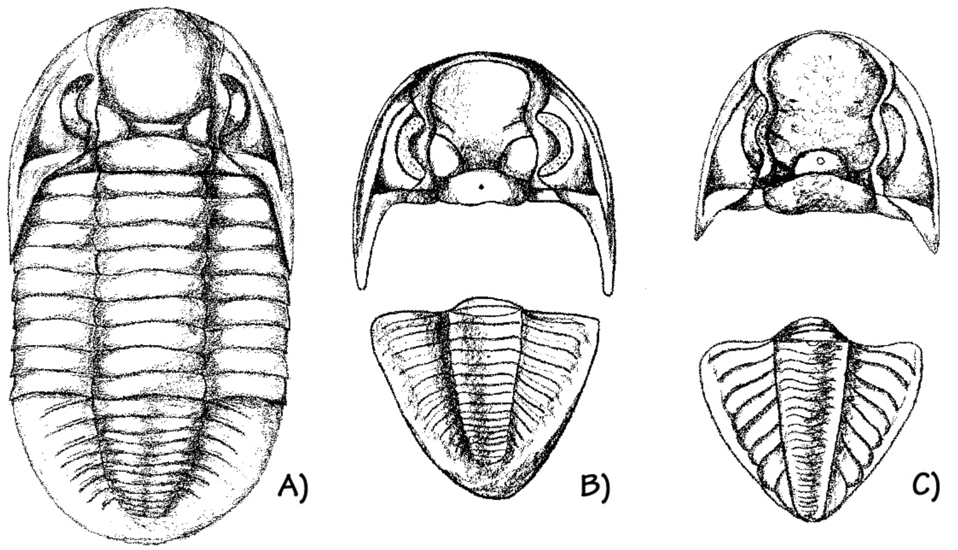


Figure 3.12: Pennsylvanian trilobites from eastern Nebraska. A) Ditomopyge*, about 2 centimeters (0.8 inches) long. B)* Ameura *cephalon (head) and pygidium (tail), each about 1 centimeter (0.4 inches) in maximum width. C)* Anisopyge *cephalon (head) and pygidium (tail), each about 1 centimeter (0.4 inches) in maximum width.*

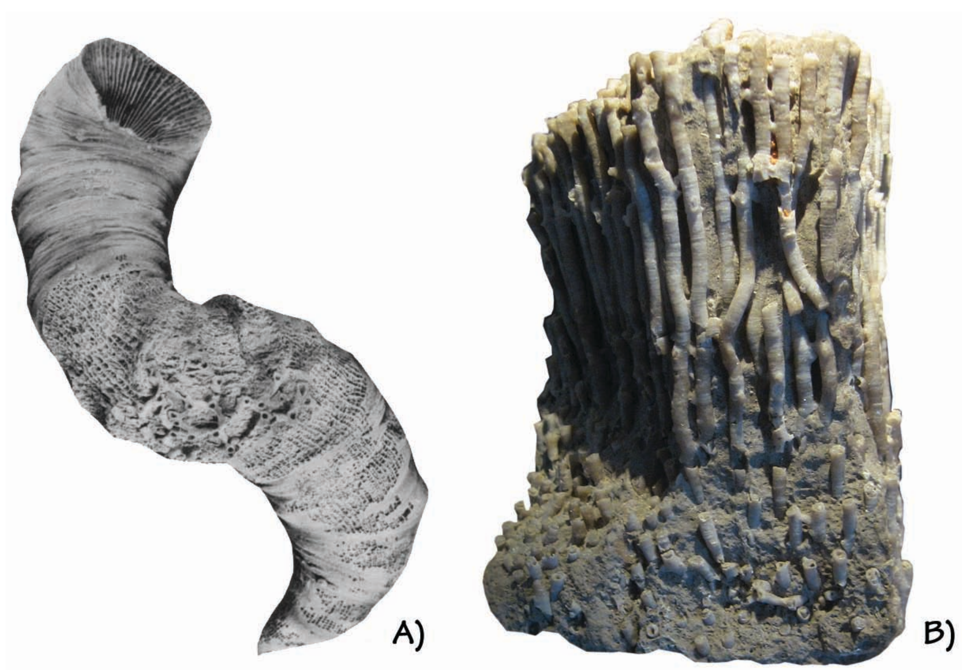
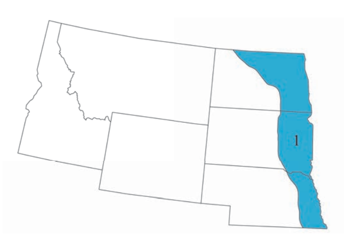


Figure 3.13: Common corals of the Beil Limestone. A) Solitary rugose ("horn") coral, Caninia torquata*, Upper Pennsylvanian. Specimen about 14 centimeters (4.5 inches) long. B) Colonial tabulate coral,* Syringopora *sp. Specimen is about 6 centimeters (2.3 inches) tall.*



sessile • *unable to move, as in an organism that is permanently attached to its substrate.*

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

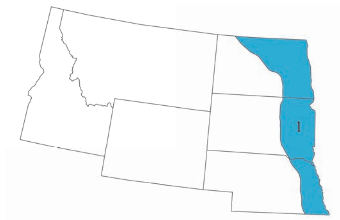
Trilobites

Trilobites are iconic Paleozoic fossils, but were more common in the Cambrian and Ordovician than in later periods. They were arthropods, and had well-defined head, tail, and thoracic (leg-bearing) segments. Most had large compound eyes, often with lenses that are visible to the naked eye. In life, they had antennae like many other arthropods, but since these were not mineralized, they only fossilize under exceptional circumstances. Many could roll up for protection, and several species also had large spines.

Corals

Corals are *sessile* relatives of jellyfish and sea anemones. They possess stinging tentacles, which they use to feed on small planktonic prey. Each group of coral possesses distinctly shaped "cups" that hold individual animals, or polyps. Colonial corals live in colonies of hundreds or even thousands of individuals that are attached to one another. Solitary coral lives independently, as a single isolated polyp.

Rugose corals were both colonial and solitary (solitary forms are often called "horn corals"). Tabulate corals were exclusively colonial and produced a variety of shapes, including sheetlike and chainlike forms. These corals receive their name from the table-like horizontal partitions within their chambers. Both rugose and tabulate corals went extinct at the end of the *Permian*. Modern corals—scleractinians—appeared in the Triassic, and include both solitary and colonial species. Many scleractinian corals have photosynthetic symbiotic algae in their tissues, called zooxanthellae. This algae provides nutrition to the coral polyps, helping them to grow more rapidly.



3 Fossils

Region 2

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

erosion • *the transport of weathered materials.*

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).*

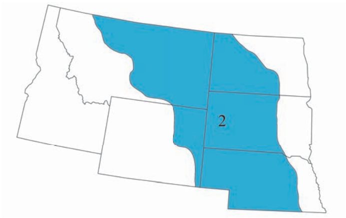
sandstone • *sedimentary rock formed by cementing together grains of sand.*

Fossils of the Great Plains
Region 2

Paleozoic rocks occur at the surface in the Great Plains only because of tectonic forces that have **uplifted** the younger rocks and caused them to **erode**, exposing the older rocks beneath. The Black Hills of western South Dakota are a particularly striking example of this phenomenon. The center of the Black Hills consists of **Precambrian** igneous rocks, surrounded by a rim of Paleozoic sedimentary rocks. The oldest sedimentary rock formation in the Black Hills is the Deadwood Formation, a layer of late Cambrian **sandstone** that outcrops around the town of Deadwood. The Deadwood Formation contains abundant marine fossils, including trilobites, brachiopods, trace fossils (burrows) (*Figure 3.14*), and bony plates from one of the oldest known armored fishes (*Anatolepsis*). Cambrian trilobites and brachiopods are also known from rocks in central Montana (*see Figure 3.2*).

See Chapter 4: Topography for more information about the formation of the Black Hills.

Figure 3.14: Skolithos *burrows from the Deadwood Formation, Deadwood, South Dakota. Rocks containing abundant* Skolithos *are sometimes called "pipe rock." The organism that made these burrows is unknown, but their shape suggests a worm-like creature that lived in vertical burrows.*



The **Ordovician** Whitewood and **Mississippian** Pahasapa **limestones** overlie the Deadwood, forming concentric rings farther from the core of the Black Hills. These younger layers also contain abundant and diverse marine fossils, including corals, snails, and cephalopods (*Figure 3.15*). Mississippian-aged rocks in this part of the Great Plains are correlated—determined to be the same age—mostly by using tiny fossils called **conodonts** as index fossils. Mississippian-aged rocks in North Dakota include the Bakken Shale, which is an important **oil**-producing layer. The oil comes from the altered remains of organisms that lived in a shallow sea.

See Chapter 6: Energy to learn more about oil shales and petroleum resources throughout the Northwest Central.

Figure 3.15: Fossils from the Ordovician Whitewood and Mississippian Pahasapa Formations of South Dakota. A) Tabulate coral, Favosites, *Pahasapa Formation. Specimen is about 27 centimeters (10.5 inches) long. B) Cephalopod,* Cyclendoceras annulatus, *Whitewood Formation. Specimen is about 79 centimeters (31 inches) long.*

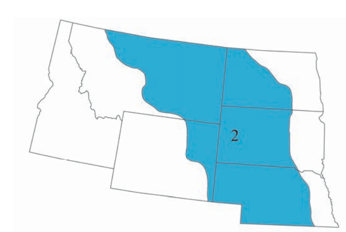
Ordovician • *a geologic time period spanning from 485 to 443 million years ago.*

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

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

conodont • *an extinct, eel-shaped animal classified in the class Conodonta and thought to be related to primitive chordates.*

oil • *See petroleum: a naturally occurring, flammable liquid found in geologic formations beneath the Earth's surface and consisting primarily of hydrocarbons*



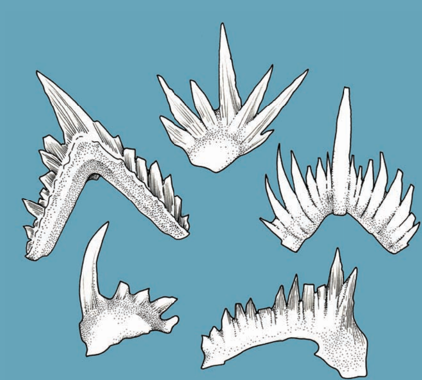
Fossils

arthropod • *an invertebrate animal, belonging to the Phylum Arthropoda, and posessing an external skeleton (exoskeleton), body segments, and jointed appendages.*

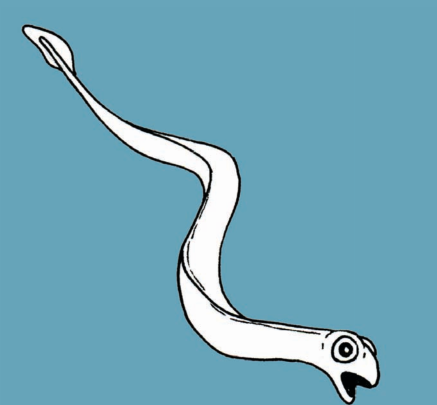
sponge • *a marine invertebrate belonging to the Phylum Porifera, and characterized by a soft shape with many pores and channels for water flow.*

Conodonts

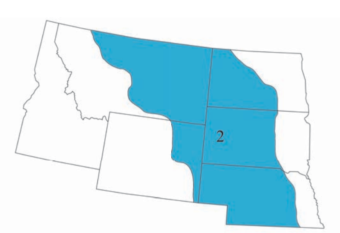
Conodonts are tiny, tooth-shaped microfossils (0.2–5 millimeters long), found in Cambrian- through Triassic-aged marine rocks. They have long been among the most important index fossils in these rocks, allowing the latter to be dated through biostratigraphy. For many years, paleontologists did not know what kind of animal they belonged to, but in 1983 the discovery of a whole conodont animal in Scotland revealed that they belonged to small, fish-like animals that were distant relatives of bony fish.



Isolated conodont elements (Silurian).



Restoration of a live conodont animal. Length 2–4 centimeters (1–2 inches).



The Mississippian Bear Gulch Beds of central Montana reveal a rare preservational "window" into the marine life of this time. The Bear Gulch Beds consist of layers of fine-grained limestone (similar to the Jurassic Solnhofen limestone in Germany that preserves many spectacular fossils, including *Archaeopteryx*, the oldest known bird). These rocks are exposed at the surface only because of the Potter Creek Dome, an uplifted outcrop located about 30 kilometers (18.6 miles) northeast of the Big Snowy Mountains in Fergus County, Montana. Bear Gulch preserves one of the most diverse fossil fish assemblages in the world (*Figure 3.16*), as well as fossils of many beautifully-preserved soft-bodied organisms, including **arthropods**, snails (gastropods), sea stars, nautiloid cephalopods, brachiopods, **sponges**, worms, and algae (*Figure 3.17*).

Figure 3.16: The small shark Falcatus falcatus. *A) Well-preserved specimen from the Mississippian Bear Gulch Beds. B) Life restoration.* Falcatus *reached 25–30 centimeters (10–12 inches) as an adult, and is the most abundant shark preserved in the Bear Gulch Beds. A peculiar feature is the dorsal spine on the top of some individuals, interpreted to be mature males; it may have been used during mating.*

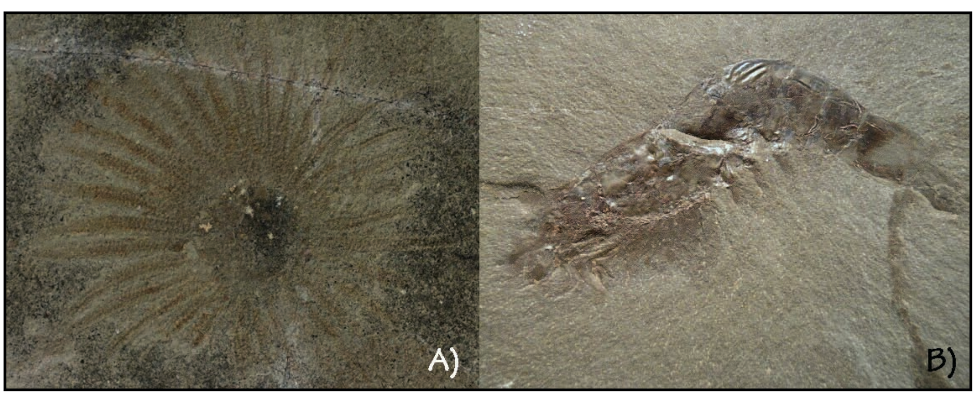
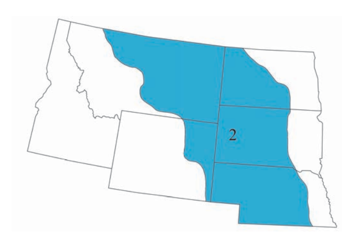


Figure 3.17: Invertebrates from the Bear Gulch Formation, Montana. A) Lepidasterella, *a starfish, 10.5 centimeters (4 inches) in diameter. B)* Aenigmacaris, *a shrimp, 10.2 centimeters (4 inches) long.*



3 Fossils

Region 2

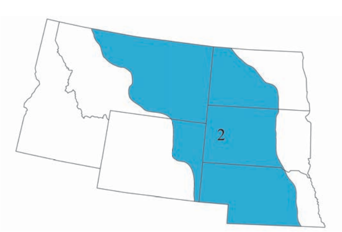
shale • *a dark, fine-grained, laminated sedimentary rock formed by the compression of successive layers of silt- and clay-rich sediment.*

delta • *a typically wedge-shaped deposit formed as sediment is eroded from mountains and transported by streams across lower elevations.*

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

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

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



In yet another concentric band even farther from the core of the Black Hills, fossiliferous early Jurassic-aged rocks outcrop in in eastern Wyoming, eastern Montana, and western South Dakota. These Jurassic sediments eroded from the highlands to the north and west, and record several cycles of sea level rise and fall across the region. These limestones, sandstones, and **shales** are rich in fossil cephalopods, oysters, and other marine invertebrates (*Figure 3.18*).

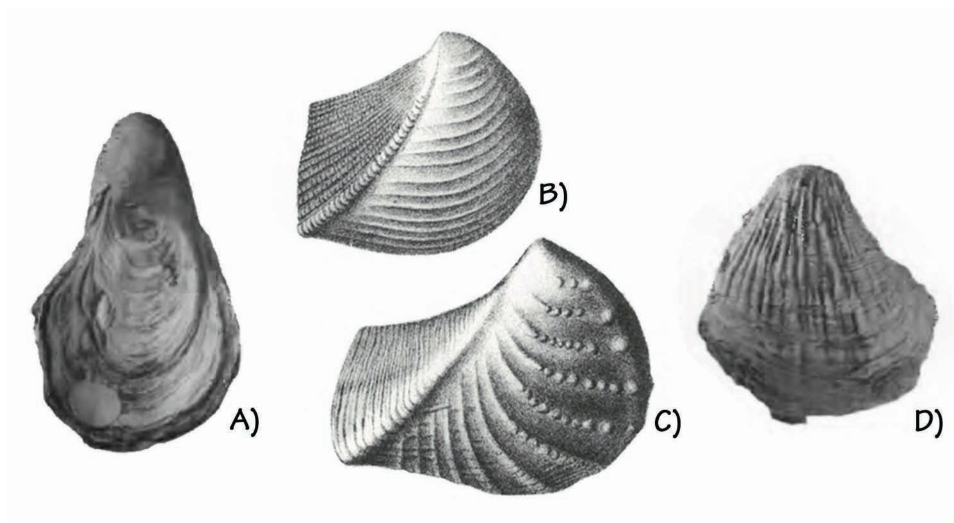


Figure 3.18: Jurassic bivalves of the Western Interior Seaway. A) Gryphaea nebrascensis. *B) and C)* Trigonia *sp. D)* Gryphaea impressimarginata. *All specimens about 5–8 centimeters (2–3 inches) in maximum width.*

Bivalves

Clams and their relatives, such as mussels, scallops, and oysters, are mollusks possessing a pair of typically symmetrical shells. Most are filter feeders, collecting food with their gills. Bivalves are among the most important marine fossils of the Pacific margin. Paleozoic bivalves typically lived on the surface of the sediment ("epifaunally"), but in the Mesozoic they evolved the ability to burrow more deeply into the sediment and live "infaunally." This innovation led to the rapid evolution of a large number of groups present in today's ocean.

By the late Jurassic, the shallow sea had begun to retreat to the east, and marine deposits of the middle Jurassic were replaced by **deltas** and freshwater deposits. The Morrison Formation is a layer of late Jurassic-aged rock exposed across a wide swath of the Rocky Mountains and Great Plains (*Figure 3.19*) The **silty** sediments of the Morrison were deposited by eastward-flowing rivers sweeping across broad, swampy **floodplains**, and contain extraordinary accumulations of **dinosaur** bones, as well as fossils of land plants including **conifers**, **cycads**, and **ginkgoes**, and also fish, frogs, lizards, crocodiles, turtles, and small mammals. The Morrison Formation's abundant dinosaurs include some of the most famous, such as *Apatosaurus*, *Stegosaurus, Allosaurus, Diplodocus, Camarasaurus* and many more (*Figure 3.20*).

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

cycad • *a palm-like, terrestrial seed plant (tree) characterized by a woody trunk, a crown of stiff evergreen leaves, seeds without protective coatings, and no flowers.*

ginkgo • *a terrestrial tree belonging to the plant division Ginkgophyta, and characterized by broad fan-shaped leaves, large seeds without protective coatings, and no flowers.*

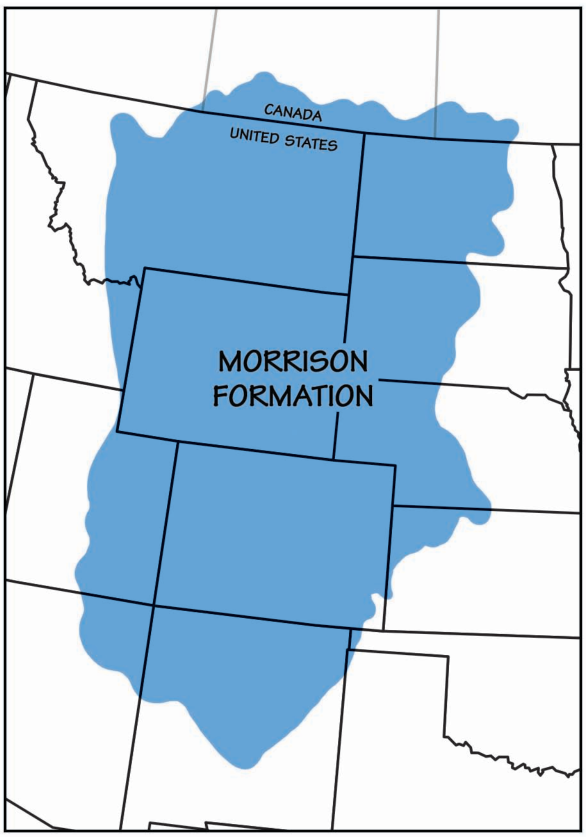
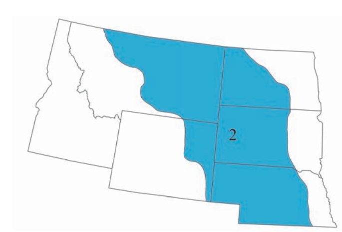


Figure 3.19: Geographic extent of the Jurassic-aged Morrison Formation.

In the Cretaceous, global sea levels rose, spreading shallow epicontinental seas over much of the continent. The Western Interior Seaway stretched across the center of North America from the Gulf of Mexico to the Arctic Ocean, and from the foot of the still-forming Rocky Mountains to as far east as Iowa. It covered most of the Dakotas and Nebraska, as well as eastern Montana, east-central Wyoming, and eastern Colorado. An abundance of aquatic life thrived there for tens of millions of years, and most of the bedrock in those states is of Cretaceous age. Over the course of the Cretaceous, the shores of this seaway



chalk • *a soft, fine-grained, easily pulverized, white-to-grayish variety of limestone, composed of the shells of minute planktonic single-celled algae.*

carbonate rocks • *rocks formed by accumulation of calcium carbonate, often made of the skeletons of aquatic organisms.*

coccolithophore • *a marine phytoplankton with a skeleton made up of microscopic calcareous disks or rings, and forming much of the content of chalk rocks.*

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

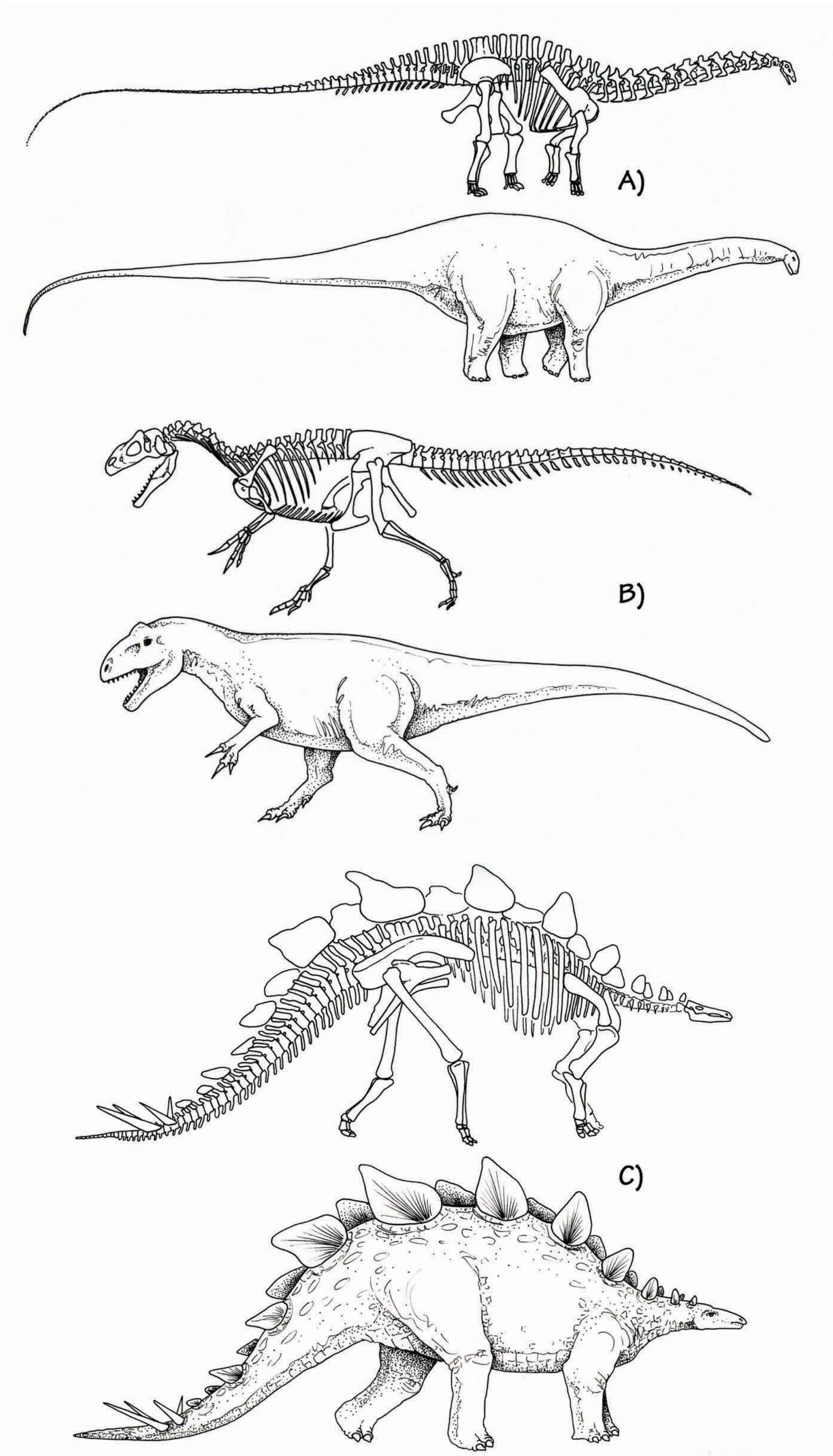
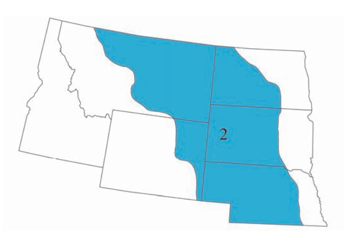


Figure 3.20: Some common and familiar dinosaurs from the Morrison Formation. A) Apatosaurus *(about 23 meters [75 feet] long), skeleton and restoration; B)* Allosaurus, *(about 8.5 meters [28 feet] long), skeleton and restoration; C)* Stegosaurus *(about 9 meters [30 feet] long), skeleton and restoration.*



swept back and forth, resulting in the deposition of alternating layers of marine and terrestrial rocks. Deeper waters toward the center of the Seaway led to the deposition of **chalk**—a **carbonate rock** made up primarily of the shells of microscopic marine algae, called **coccolithophores** (*Figure 3.21*). Today, such sediments accumulate mainly in the deep sea; during the Cretaceous, when sea levels were much higher than today, chalk accumulated throughout the extensive shallow **inland seas**. The Cretaceous period is in fact named for the abundance of chalk that accumulated during this time. (The Latin word for chalk is *creta*.) The Western Interior Seaway was also home to huge marine reptiles, including **plesiosaurs**, **mosasaurs**, and turtles (*Figures 3.22–3.24*), which are frequently found as fossils in Cretaceous rocks in Nebraska and the Dakotas, as well as bony fish, sharks, and sea birds (*Figure 3.25*).

See Chapter 1: Geologic History to learn more about the Western Interior Seaway and other North American inland seas throughout geologic time.

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

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

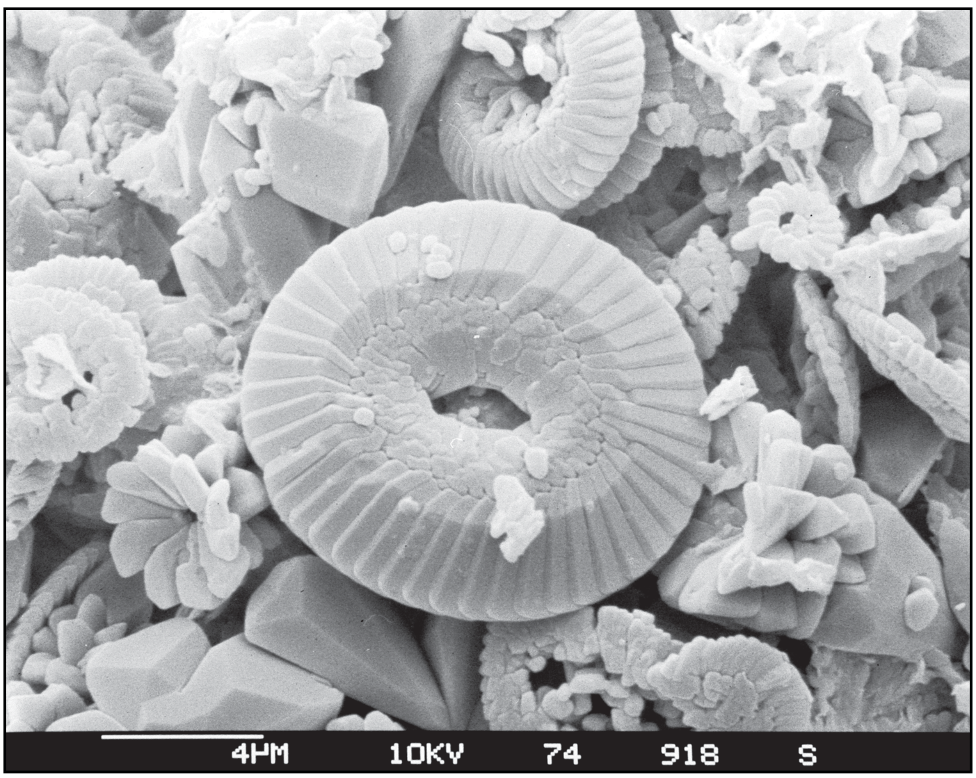
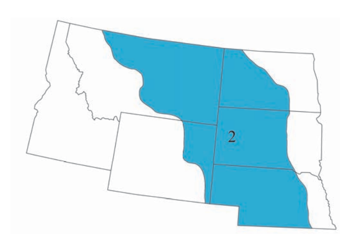


Figure 3.21: A microscopic view of chalk, showing that it is composed almost completely of the shells of protists called coccolithophores. Scale bar = 4 nanometers (4 x 10^{-9} meters; about 0.0000001575 inches).



3

Fossils

Region 2

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

rugose coral • *an extinct group of corals that were prevalent from the Ordovician through the Permian.*

tabulate coral • *an extinct form of colonial coral that often formed honeycomb-shaped colonies of hexagonal cells.*

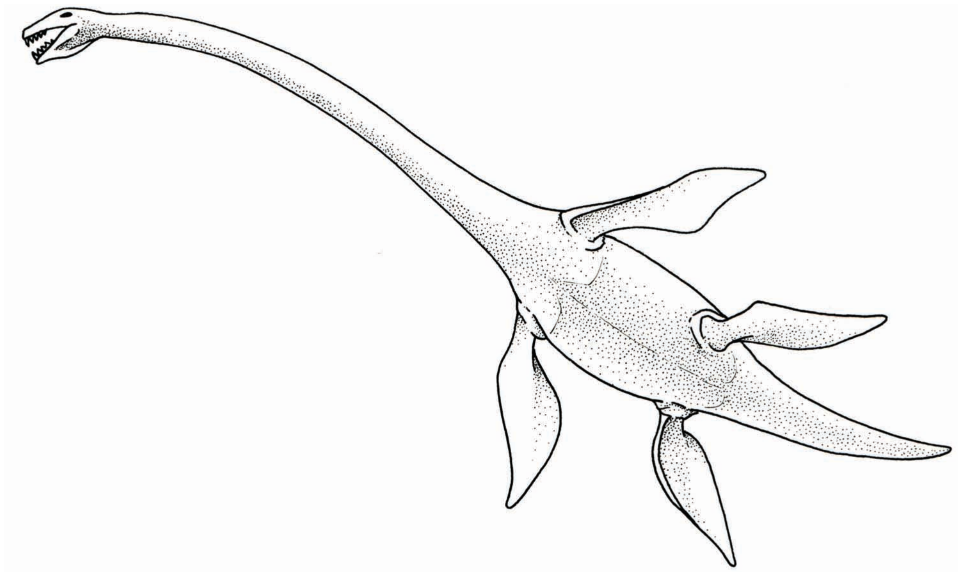


Figure 3.22: Restoration of Elasmosaurus, *a large plesiosaur from Nebraska. About 14 meters (46 feet) long.*

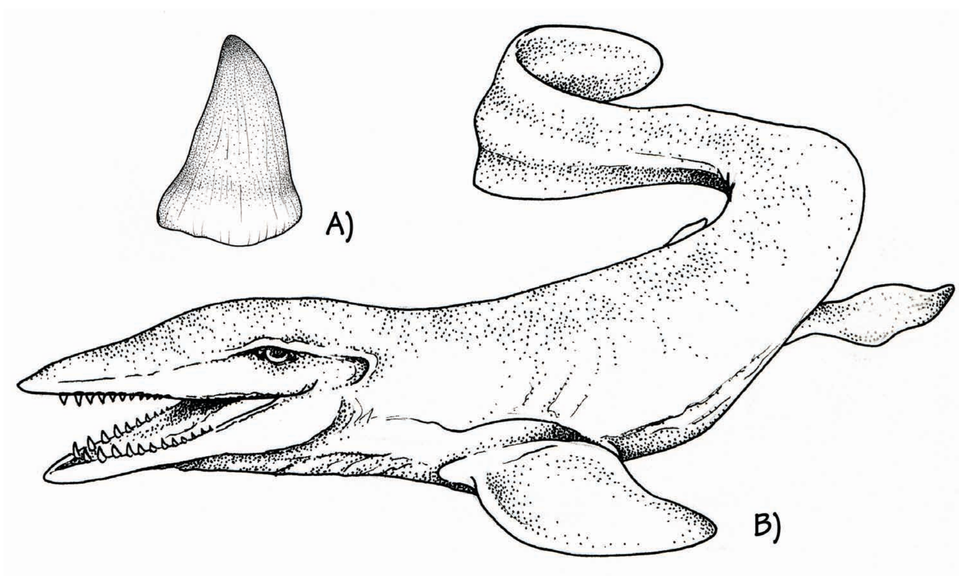
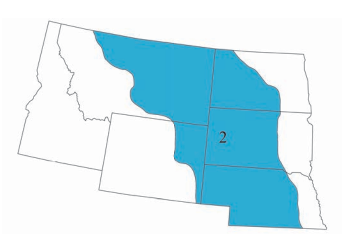


Figure 3.23: A) Mosasaur tooth, about 5 centimeters (2 inches) long. B) Restoration of the Cretaceous mosasaur Tylosaurus. *About 15 meters (50 feet) long.*



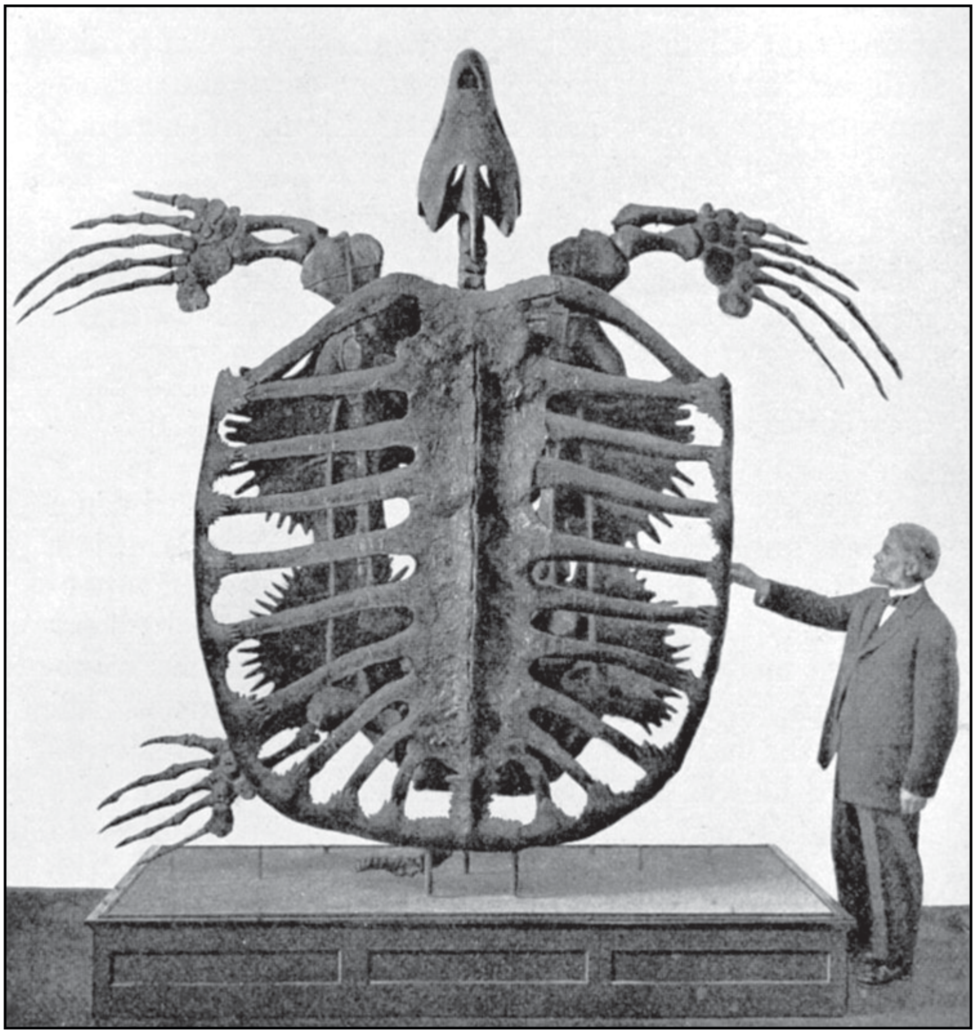


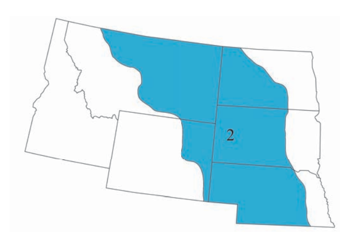
Figure 3.24: The giant marine turtle Archelon ischyros*, approximately 4 meters (13 feet) long. The skeleton in this photograph is the type specimen for the species, housed in the Yale Peabody Museum.*

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).*

rudists *• an extinct group of box- or tube-shaped bivalves that arose during the Jurassic.*

ammonoid *• a member of a group of extinct cephalopods belonging to the Phylum Mollusca, and posessing a spiraling, tightly coiled shell characterized by ridges, or septa.*

Marine invertebrates in these **Mesozoic** seas were very different from those that had filled the seas of the Paleozoic. **Rugose** and **tabulate corals** were replaced by **scleractinians—**modern corals (*Figure 3.26*). Brachiopods declined dramatically in abundance and diversity at the end of the Paleozoic, their ecological niches being filled in many cases by bivalves. In the Cretaceous, two bizarre groups of clams were particularly abundant: **rudists** formed reefs, while inoceramids lived on flat parts of the sea floor (*Figures 3.27–3.28*). *Inoceramus* was a large, usually flat, thick-shelled bivalve with tightly interlocking shells. The largest species could reach diameters of up to 1.5 meters (5 feet)! Inoceramids were relatives of living oysters—among today's most common and well-known bivalves that cement themselves to the bottom—and were diverse and abundant during the Cretaceous. **Ammonoids** also became



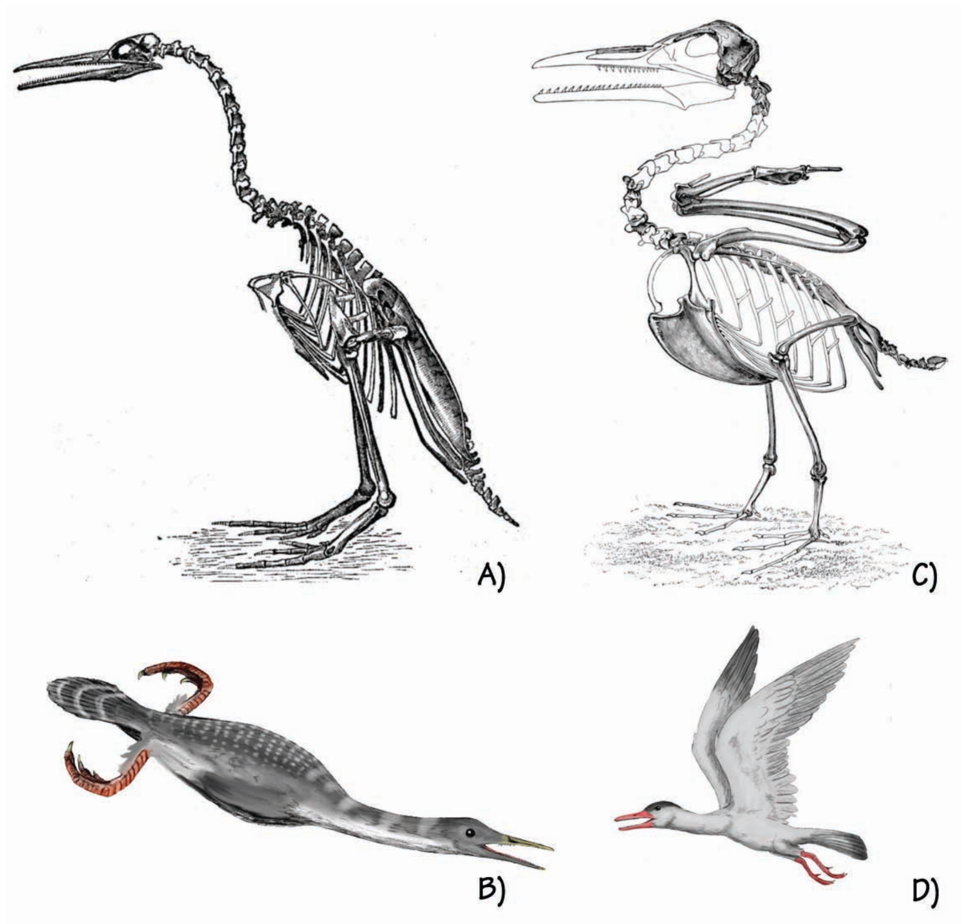
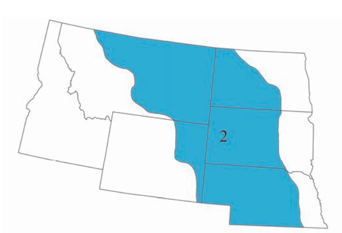


Figure 3.25: Toothed birds found in Cretaceous deposits of the Western Interior Seaway. A) and B) The large, flightless Hesperornis. *About 6 feet (1.8 meters) long. Reconstructed skeleton and life restoration. C) and D) The smaller flying* Icthyornis*, with a wingspan around 50 centimeters (20 inches). Reconstructed skeleton and life restoration.*

diverse and abundant, and are especially common fossils in Cretaceous rocks of the Dakotas, Wyoming, and Montana (*Figure 3.29*). The late Cretaceous Pierre Shale, which is exposed widely across this area, is especially famous for its beautifully preserved ammonoids. Most ammonoids are coiled flat, in a single plane. One fascinating aspect of ammonoid evolution, however, was the appearance of shells with bizarre shapes, called heteromorphs ("different shape"). These unique ammonoids were especially prevalent in the Cretaceous period. The shells of heteromorphs were uncoiled or three-dimensionally (helically) coiled (*see Figure 3.29B–D*). Since there are no similar life forms today to which to compare them, it has been difficult to figure out how they lived—most current paleontological thinking suggests heteromorphs floated or swam.



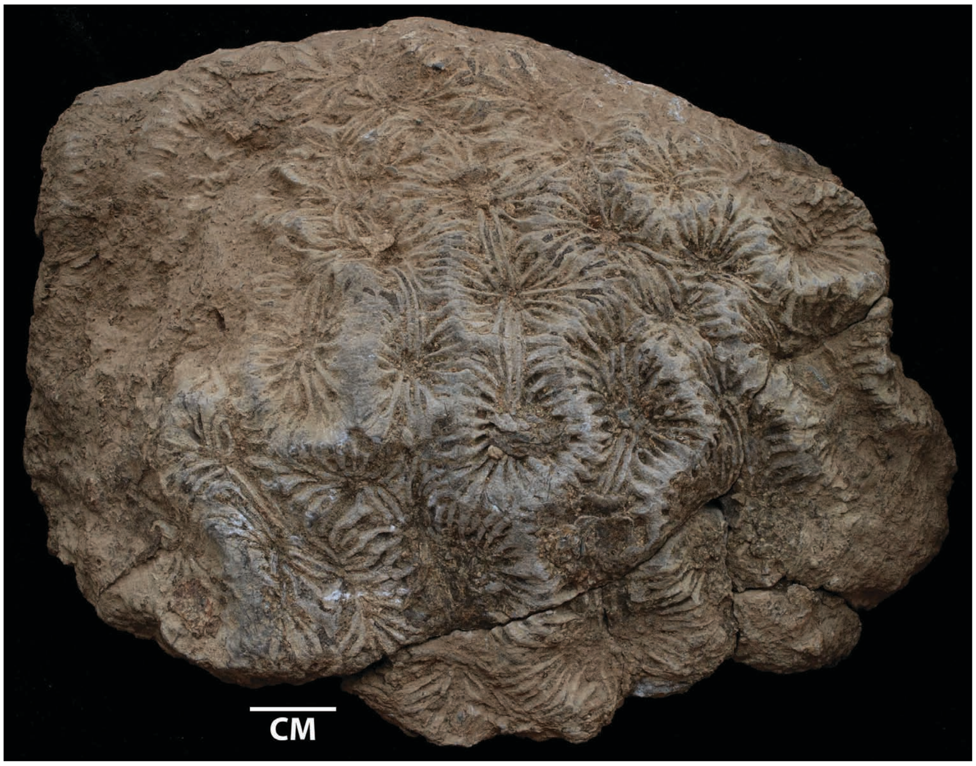


Figure 3.26: Jurassic coral, Thecomeandra vallieri, *from western Idaho. Specimen about 10 centimeters (4.25 inches) across.*

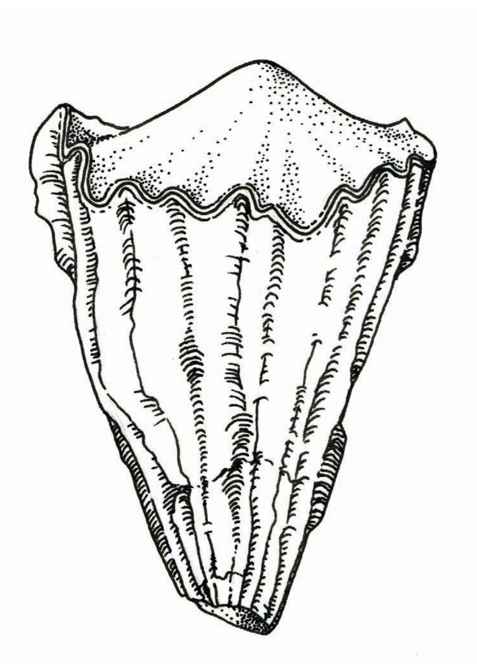
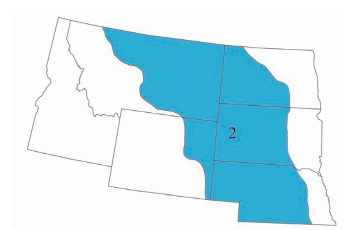


Figure 3.27: Rudists were unusual cone- or cylinder-shaped bivalves that clustered together in reef-like structures and went extinct at the end of the Mesozoic era. They ranged in size from a few centimeters to more than 50 centimeters (1.5 feet) tall.



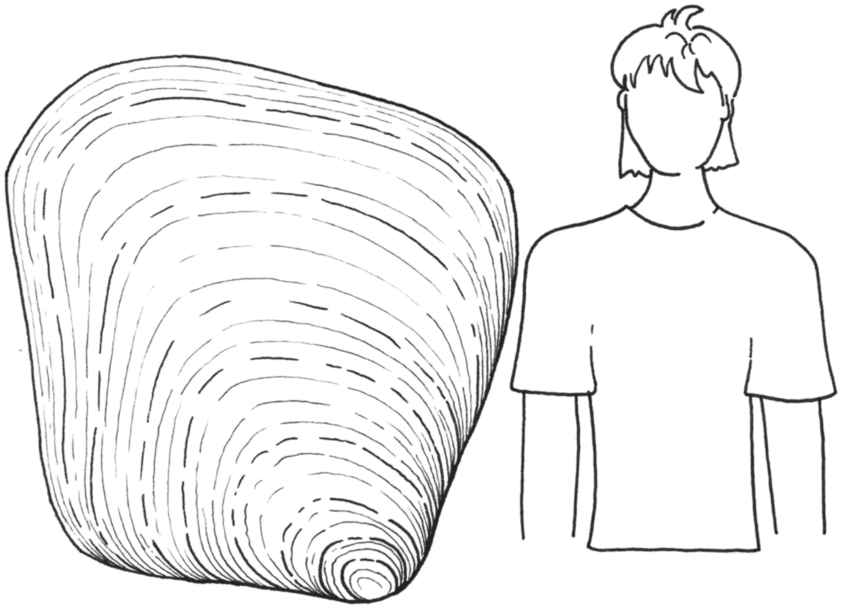


Figure 3.28: *Giant inoceramid bivalve,* Platyceramus platinus, *from the Cretaceous Niobrara Chalk of Kansas. About 1.2 meters (4 feet) in diameter.*

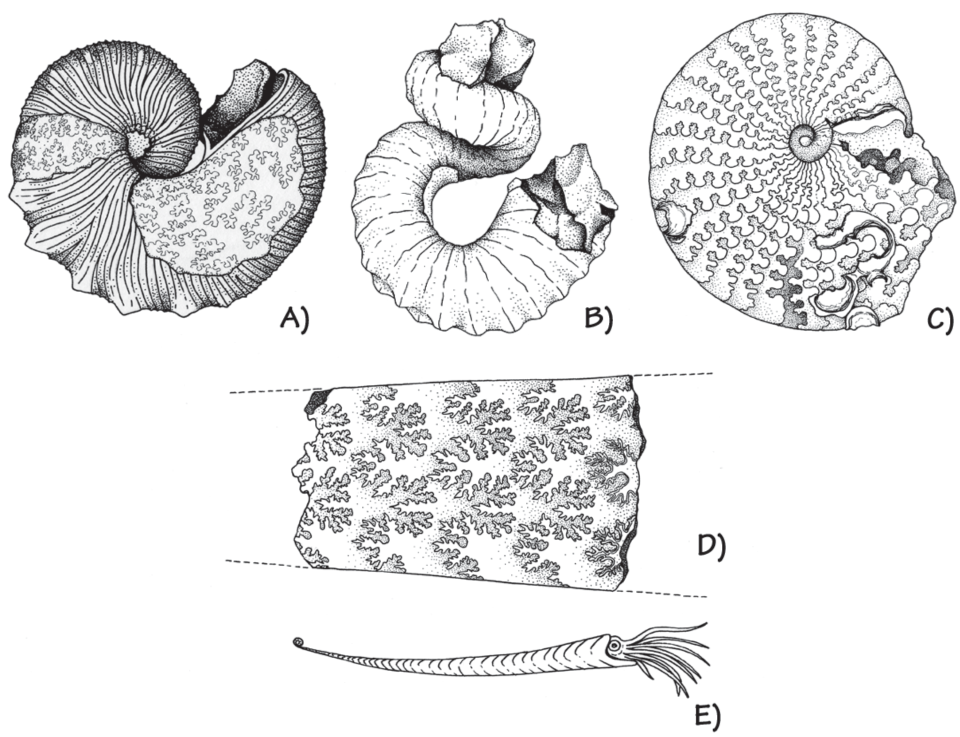
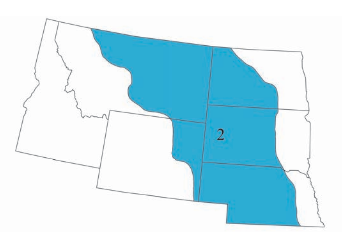
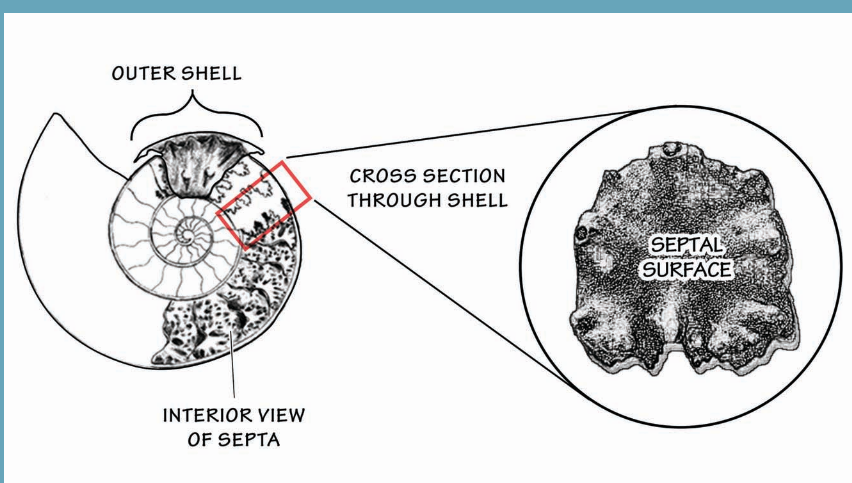


Figure 3.29: Ammonoids from the late Cretaceous of the Western Interior Seaway. A) Ammonite, Jeletzkytes, *about 10 centimeters (4 inches) in diameter. B) Heteromorph ammonite,* Didymoceras, *about 15 centimeters (6 inches) in diameter. C) Ammonite,* Engonoceras, *about 15 centimeters (6 inches) in diameter. D) Straight heteromorph ammonite,* Baculites, *fossil, usually 3-4 centimeters (2 inches) in diameter and 60 centimeters (2 feet) long. E)* Baculites *life restoration.*

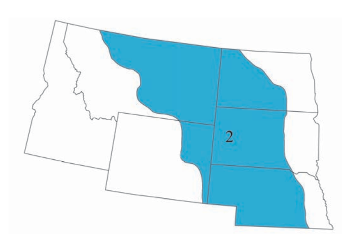


Ammonoids

Ammonoids are a major group of cephalopods that lived from the Devonian to the end of the Cretaceous. Both nautiloids (the group that today contains the chambered nautilus) and ammonoids have chambered shells subdivided by walls, or septa (plural of septum). These shells are frequently, but not always, coiled. The term "ammonoid" refers to the larger group of these extinct cephalopods, distinguished by complex folded septa. Within ammonoids, "ammonites" is a smaller sub-group, distinguished by the extremely complex form of their septa. Ammonites were restricted to the Jurassic and Cretaceous periods. The form of the septa in nautiloids and ammonoids is not visible in a complete shell; it is most often seen in the trace of the intersection between the septum and the external shell. This trace is called a suture. Sutures are usually visible in fossils when sediment has filled the chambers of a shell, and the external shell has been broken or eroded away.



Ammonite shell break-away cross-section; surface plane of a septum and sediment-filled chamber.



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

calcium carbonate • *a chemical compound with the formula $CaCO_3$, commonly found in rocks in the mineral forms calcite and aragonite, as well as the shells and skeletons of marine organisms.*

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

meteorite • *a stony or metallic mass of matter that has fallen to the Earth's surface from outer space.*

Abundant tiny fossils called foraminifera (*Figure 3.30*) are found throughout Cretaceous sediments of the Western Interior Seaway. Foraminifera, or "forams," as they are frequently called, are single-celled organisms (**protists**) with shells made of **calcium carbonate**. They live in the ocean in huge numbers, both at the bottom and floating in the water column, and are extremely important as index fossils and paleoenvironmental indicators.

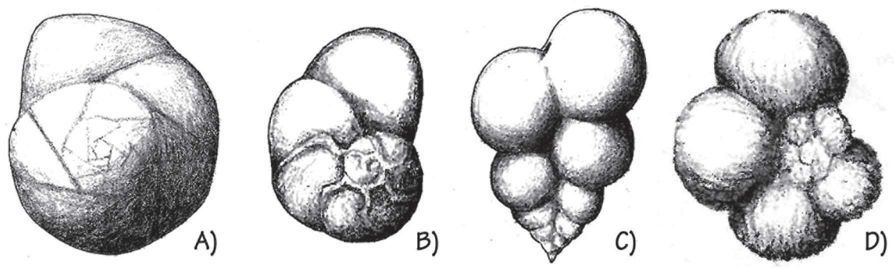
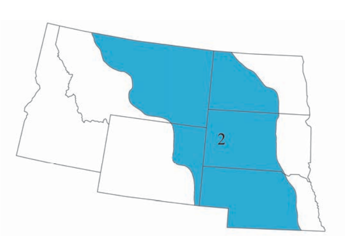


Figure 3.30: Cretaceous foraminifera. A) Pulvinulina*, 0.3 millimeters (0.01 inches). B)* Rotalia*, 0.4 millimeters (0.02 inches). C)* Pseudotextularina*, 0.3 millimeters (0.01 inches). D)* Globigerina*, 0.4 millimeters (0.02 inches).*

During the late Cretaceous period (67–65 million years ago), the area that is now southeastern Montana, northeastern Wyoming, and northwestern South Dakota was a broad floodplain to the east of the developing Rocky Mountains, leading into the shallow marine Western Interior Seaway. The sediments deposited in these transitional environments (*Figure 3.31*) contain the remains of organisms that lived both on land and in the sea. The terrestrial layers, deposited by meandering rivers, contain abundant plant fossils—including numerous flowering plants (*Figure 3.32*), which had just begun to colonize the landscape. Terrestrial deposits also contain abundant fossils of land-dwelling animals that lived near the seaway, including insects, freshwater snails and clams, turtles, **pterosaurs**, small mammals (*Figure 3.33*), birds, amphibians, and, most famously, dinosaurs (*Figure 3.34*).

In the early twentieth century, the first skeletons of *Tyrannosaurus rex* were discovered in one of these floodplain deposits, the Hell Creek Formation. The boundary between the Cretaceous and Paleogene periods was also identified at the top of this sandstone layer. Detailed work in the late twentieth century refined the placement of the boundary; it is now marked by a concentration of the element iridium, usually at the top of the Hell Creek but sometimes in the lower part of the overlying Fort Union Formation (*Figure 3.35*). The iridium is thought by most geologists to have come from the impact of a large comet or **meteorite**, which was likely a primary cause of the mass extinction that marks the end of the Cretaceous period.

Until recently, *Tyrannosaurus* was known from only a few specimens. In recent decades, however, remains of more than 40 individuals have been discovered in the Hell Creek Formation in Montana and South Dakota, and *T. rex* is today one of the best-known dinosaurs.



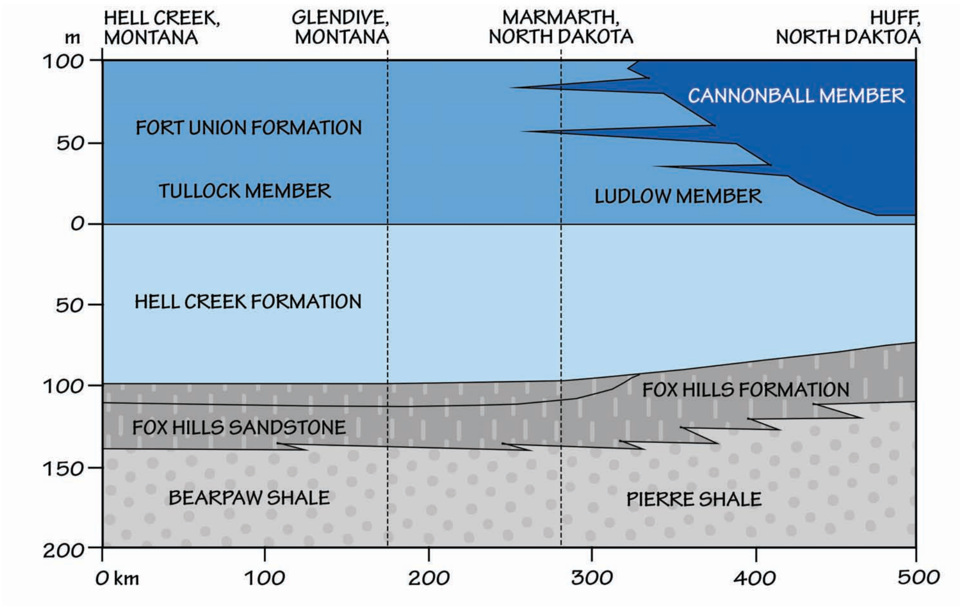


Figure 3.31: Simplified stratigraphy of the western margin of the Western Interior Seaway across Montana and North Dakota during the late Cretaceous period.

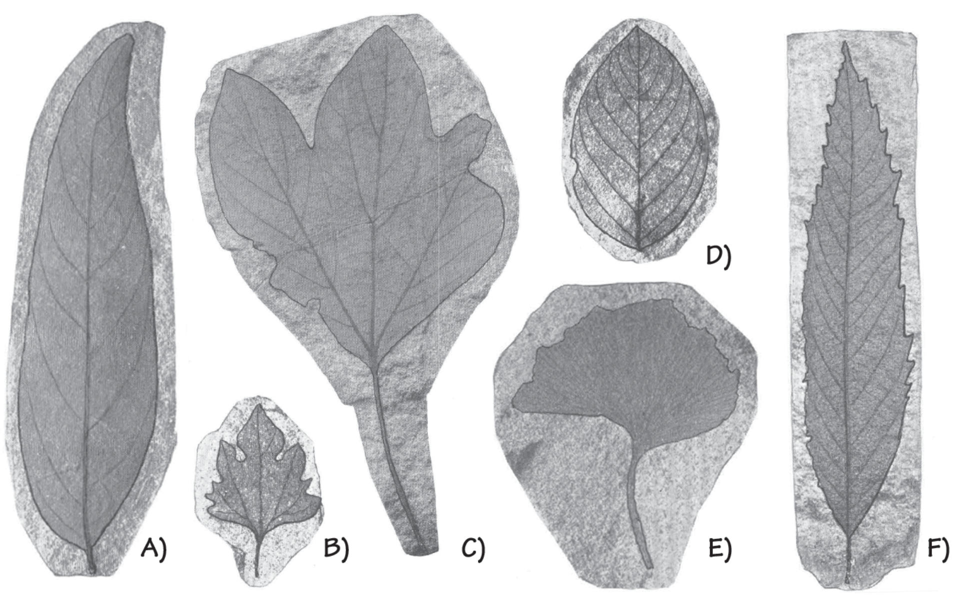
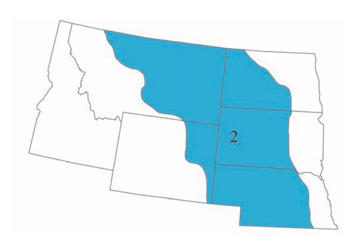


Figure 3.32: Late Cretaceous terrestrial plant fossils from the Fox Hills and Hell Creek formations. *A)* Sapindus cretaceus. *B)* Cissites colgatensis. *C)* Sassafras montana. *D)* Cornus praeimpressa. *E)* Gingko laramiensis. *F)* Dryophyllum subfalcatum. *Leaves range from 5 to 15 centimeters (2 to 6 inches) in length. All to scale.*

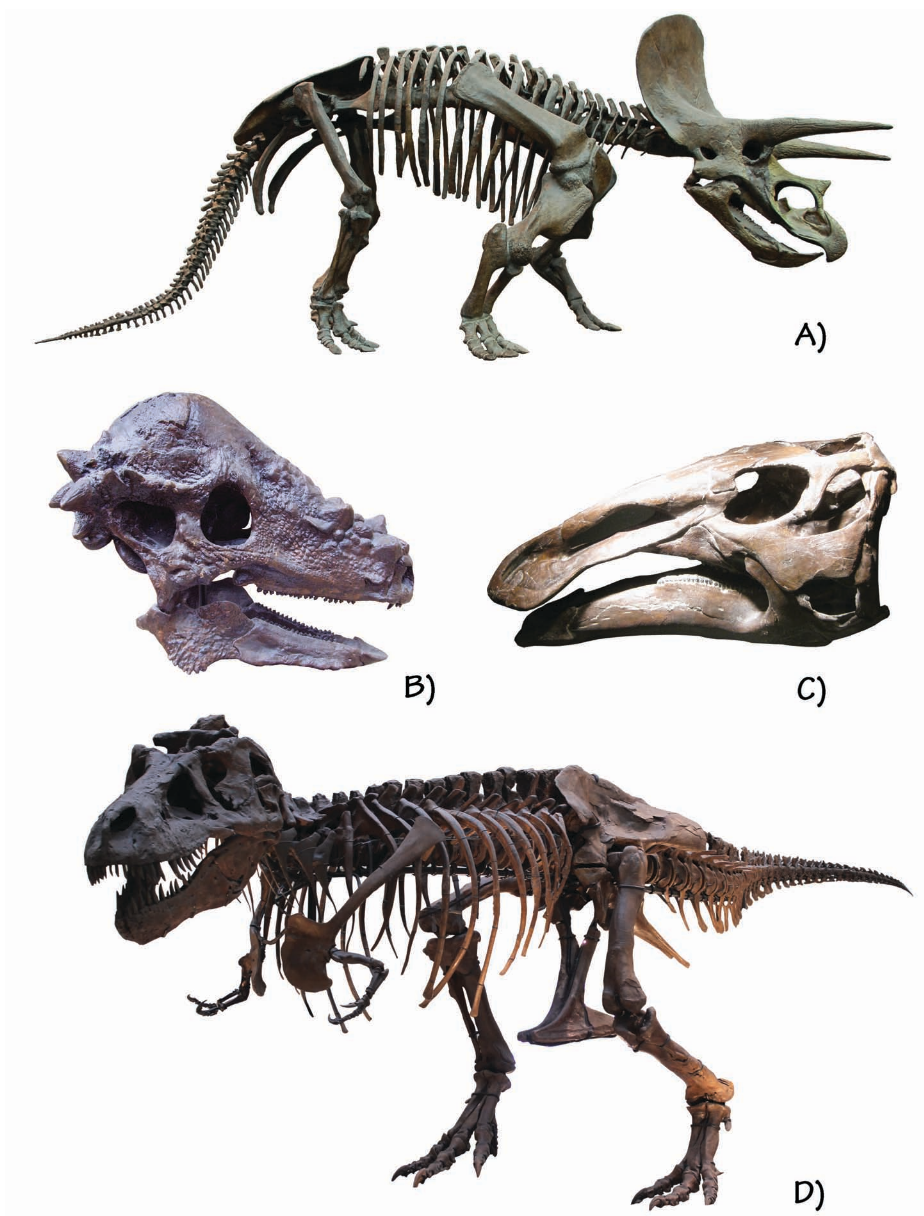


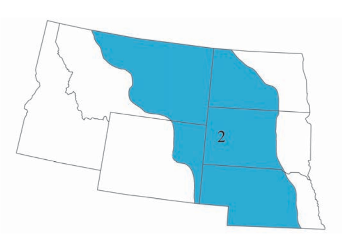
3 # Fossils

Region 2

Figure 3.33: Didelphodon vorax*, a marsupial from the late Cretaceous period. About 1 meter (3 feet) long.*

Figure 3.34 (at right): Late Cretaceous dinosaurs found in South Dakota and Wyoming. A) Triceratops horridus*, about 8 meters (28 feet) long. B) Skull of* Pachycephalosaurus*, body length about 4.5 meters (15 feet). The bony dome on the skull can be up to up to 25 centimeters (10 inches) thick. C) Skull of* Edmontosaurus*, body length up to 13 meters (43 feet). D)* Tyrannosaurus rex*, about 12.5 meters (40 feet) long.*

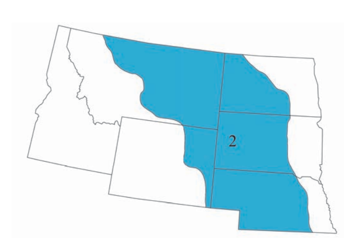




The Hell Creek Formation is most famous for its multiple bone beds containing abundant dinosaurs, including (in addition to *T. rex*) the giant horned *Triceratops*, the "ostrich dinosaurs" *Struthiomimus* and *Ornithomimus*, the armored *Ankylosaurus* and dome-headed *Pachycephalosaurus*, and the large hadrosaurs *Edmontosaurus* and *Anatotitan* (*see Figure 3.34*). Several dinosaur "mummies" have also been found in the Hell Creek beds (*Figure 3.36*). These exceptionally preserved fossils were formed when a dinosaur was buried suddenly, preserving impressions of skin and other traces of soft anatomy.

Figure 3.35: The Cretaceous–Paleogene (K–Pg) boundary (red arrow) along Interstate 25, Raton Pass, Colorado. (See TFG website for full-color version.)

Figure 3.36 (at left): A fully articulated and partially mummified skeleton of a subadult hadrosaur, Brachylophosaurus canadensis, *nicknamed "Leonardo." The specimen was found in northern Montana and is exhibited at the Phillips County Museum in Malta, Montana. Brachylophosaurus reached 9 meters (30 feet) in length. Inset: Skin impression from a hadrosaur,* Edmontosaurus, *nicknamed "Dakota." This specimen was found in North Dakota and is now on display at the North Dakota Heritage Center in Bismarck. Photograph about 15 centimeters (6 inches) in width.*

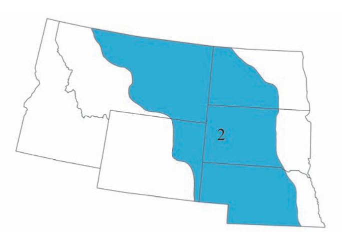


Fossils

Maiasaura

In the late 1970s and 1980s, nests of dinosaur eggs—some containing embryos—were discovered in rocks of Montana's Two Medicine Formation, as well as adult skeletons of the same dinosaur. It was named *Maiasaura*, meaning "good mother lizard." *Maiasaura* was a medium-sized hadrosaur, about 8 meters (26 feet) long. It was bipedal and plant-eating. *Maiasaura* was the first dinosaur ever found associated with nests of babies, and its embryos were the first ever found of a dinosaur. One of the sites where these fossils were found was named Egg Mountain, west of Choteau in Teton County, Montana. The fossils showed that *Maiasaura* made a shallow nest in the ground about 2 meters (6.5 feet) in diameter, in which it laid clutches of 30 to 40 eggs. Because different nests had different-sized babies, paleontologists suggested that the babies were living in the nests when they died, and were being cared for by their parents. *Maiasaura* has only been found in Montana, and is the Montana state fossil.

Model of a Maiasaura *nest with hatchlings.* Maiasaura *eggs were about 15 centimeters (6 inches) long.*



Region 2

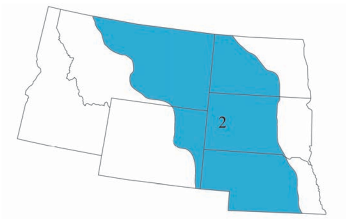
The early and mid-Cenozoic was a time of significant tectonic activity in the Northwest Central States. The Western Interior Seaway disappeared by the end of the **Paleocene**, and most of the region became dry land, yet extensive sedimentary deposits represent lakes, rivers, and floodplains. The uplift of mountain ranges to the west was a source of sediment that was transported and deposited by rivers in **basins** throughout the Great Plains and Rocky Mountain regions. Thick ash beds were also deposited in this area by periodic **volcanic** eruptions throughout the Cenozoic. The shrinking Western Interior Seaway is represented in the Dakotas by the Paleocene Cannonball Formation, which contains abundant and diverse mollusks, shark teeth, and occasional land plants (*Figure 3.37*).

See Chapter 2: Rocks to learn about igneous deposits left by Cenozoic volcanism.

Paleocene *• a geologic time interval spanning from about 66 to 56 million years ago.*

Figure 3.37: Teredo Petrified Wood, the state fossil of North Dakota, from the Paleocene Cannonball Formation. Specimen approximately 15 centimeters (about 6 inches) in diameter. Before burial and fossilization, this permineralized "petrified" wood was bored by a group of clams known as teredinids (one genus of which is Teredo*). These clams are also known as "shipworms" for their tendency to "foul" wooden ships, docks, and other human structures.*

Cenozoic rocks preserve a fossilized view of ecosystems dramatically different from those of the Cretaceous. The dinosaurs disappeared, and mammals replaced them as the dominant large vertebrates on land. During this time, the environment was initially warm and humid, with widespread tropical



Region 2

Eocene • *a geologic time period extending from 56 to 33 million years ago.*

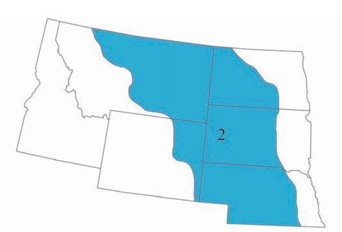
Oligocene • *a geologic time interval spanning from about 34 to 23 million years ago.*

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).*

Miocene • *a geological time unit extending from 23 to 5 million years ago.*

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

badlands • *a type of eroded topography that forms in semi-arid areas experiencing occasional periods of heavy rainfall.*



and subtropical forests, but as global temperatures fell in the late **Eocene** and **Oligocene**, the **climate** of the Northwest Central became more arid, and grasslands replaced forests in many areas. Fossil land mammals are particularly common in Cenozoic sediments of the Great Plains, beginning with the Paleocene and Eocene, and continuing through the **Miocene**. These fossils can be found in thick sequences of layered sedimentary rock, which accumulated in lakes and rivers that fed into the numerous basins across the region (*Figure 3.38*). The abundant fossil mammals preserved in these rocks form one of the most complete records of mammal evolution known anywhere in the world. Mammals are so numerous and diverse here that they are commonly used as index fossils. (It is unusual to use vertebrates for biostratigraphy, because they are frequently much rarer than invertebrate fossils.) There is even a special series of terms—known as the North American Land Mammal Ages—used to describe the relative ages determined by fossil mammals.

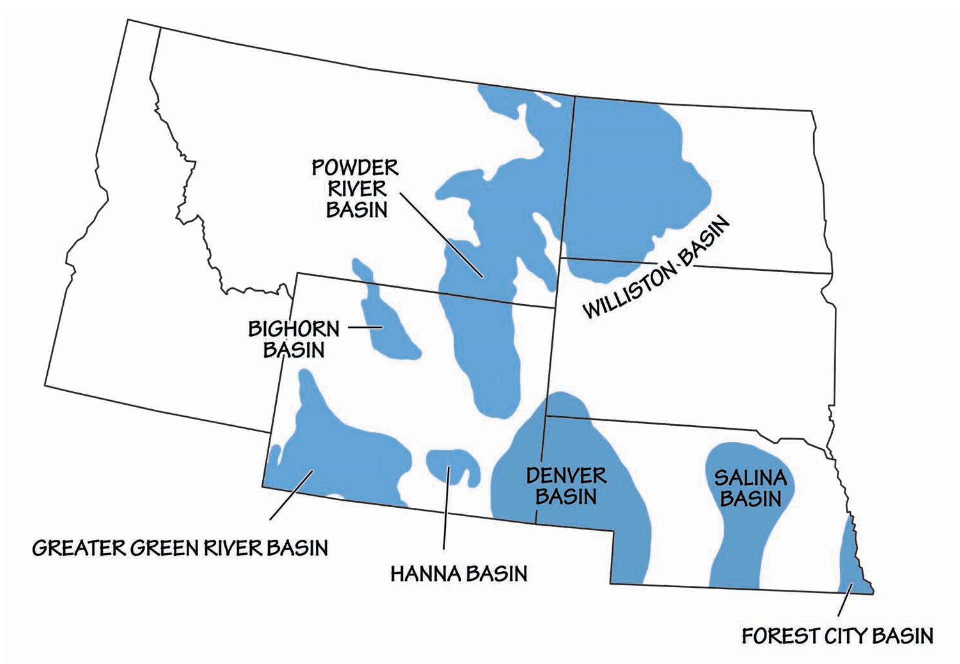


Figure 3.38: Sedimentary basins of the Northwest Central.

Paleogene and early **Neogene** mammals from this region include a great diversity of hoofed mammals, as well as carnivores, and—surprisingly—primates (*Figures 3.39–3.40*). Paleocene and Eocene mammals, as well as fossil plants, are particularly common and diverse in the Williston Basin of the Dakotas and the Bridger and Uinta Basins of Wyoming and Utah (*Figure 3.41*). Oligocene mammals are best known from the White River **Badlands**—an area of western South Dakota with a deeply eroded landscape, through which the White River flows. The rocks here are late Eocene to Oligocene in age (about 40–30 million years old), and were deposited by rivers moving through an environment much warmer and wetter than it is today. These rocks contain some of the most abundant, diverse, and well-preserved Paleogene fossil mammals found anywhere in the world (*Figure 3.42*), including extinct relatives of modern groups, such as camels and horses; groups that left no living descendants, such as the pig-like **entelodonts**; and the sheep-like **oreodonts**, which were the most abundant mammals in this savannah-like environment.

See Chapter 4: Topography to learn more about badland topography in the Northwest Central.

entelodont • *an extinct family of omnivorous artiodactyl mammals that look somewhat like pigs but are actually thought to be more closely related to hippos.*

oreodont • *an extinct ungulate (hoofed animal) related to modern camels.*

volcanic ash • *fine, unconsolidated pyroclastic grains under 2 millimeters (0.08 inches) in diameter.*

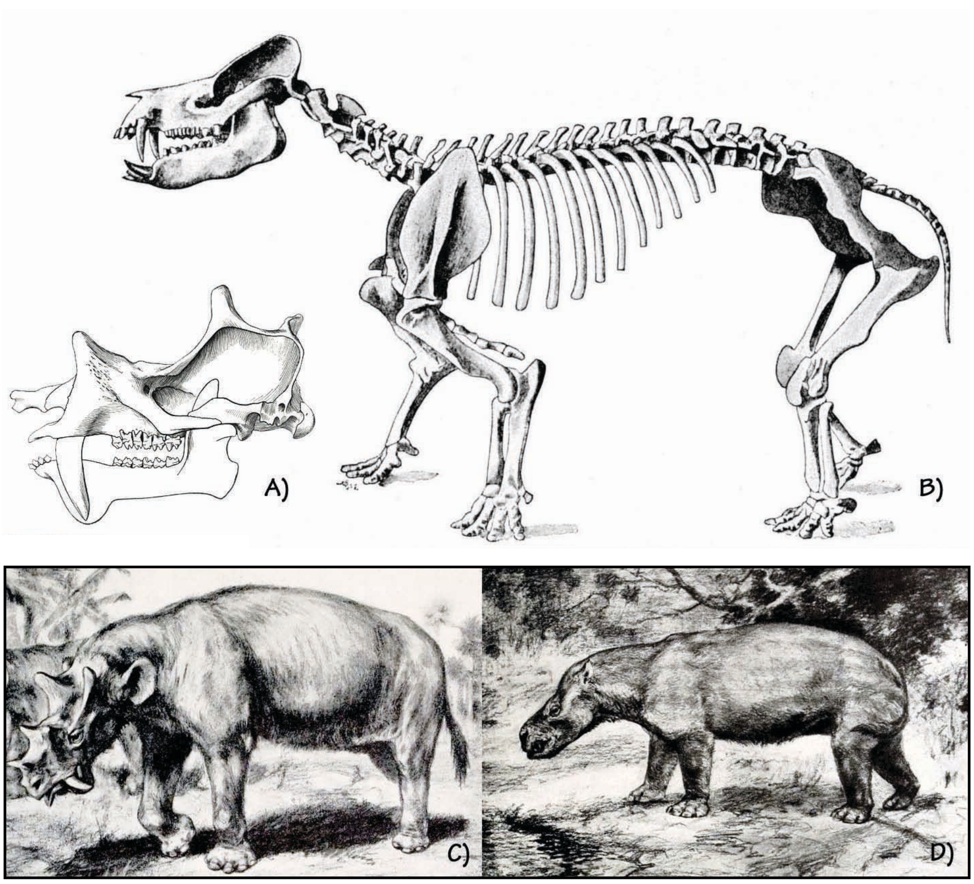
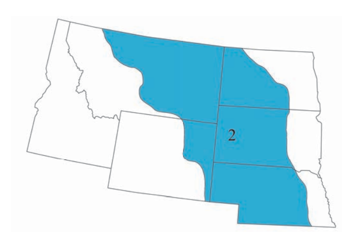


Figure 3.39: Paleocene-Eocene browsing mammals of the Great Plains. A) and C) Uintatherium *skull and life restoration. Body about 4 meters (13 feet) long. B) and D)* Coryphodon *skeleton and life restoration. Body about 2.25 meters (2.4 feet) long.*

Miocene mammals are abundantly preserved in a number of deposits, including the spectacular Agate Fossil Beds of western Nebraska, and the Ashfall Fossil Beds of northeastern Nebraska. Many of these fossil beds formed as a result of rapid burial in **volcanic ash**. The spectacular fossils exposed at Agate Fossil Beds National Monument and Ashfall Fossil Beds State Historical Park reveal that during the early Miocene (about 21–19 million years ago), this area was a grassy savanna, similar to those in today's East Africa. Miocene Nebraska was filled with diverse and abundant large mammals (*Figure 3.43*), including the



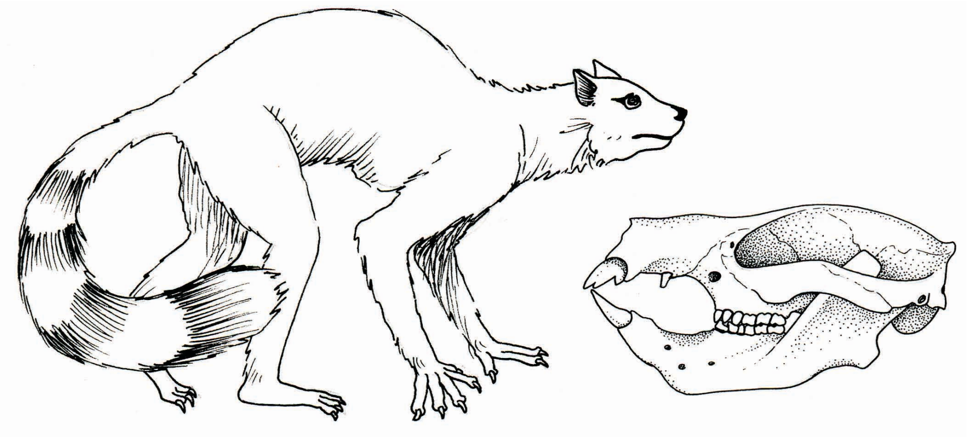


Figure 3.40: Skull and restoration of Plesiadapis*, a Paleocene arboreal primate-like mammal. Body about 60 centimeters (2 feet) long.*

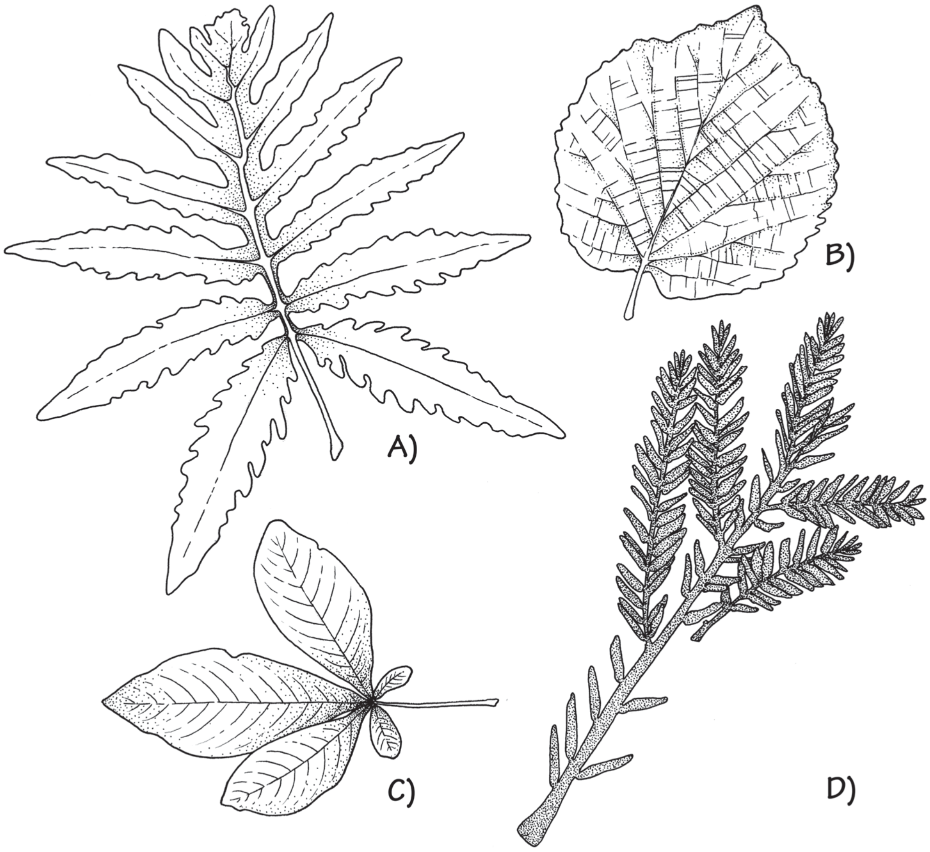
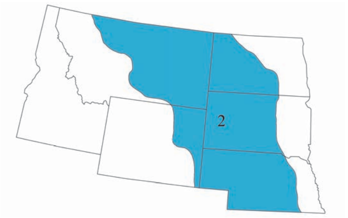


Figure 3.41: Leaves of the Fort Union Formation, a geological unit extending into the Williston Basin. A) Onoclea sensibilis. *B)* Davidia antiqua. *C)* Aesculus hickeyi. *D)* Metasequoia occidentalis. *Leaves range from 10 to 20 centimeters (4 to 8 inches) long. All to scale.*



Region 2

agate • *a crystalline silicate rock with a colorful banded pattern. It is a variety of chalcedony.*

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

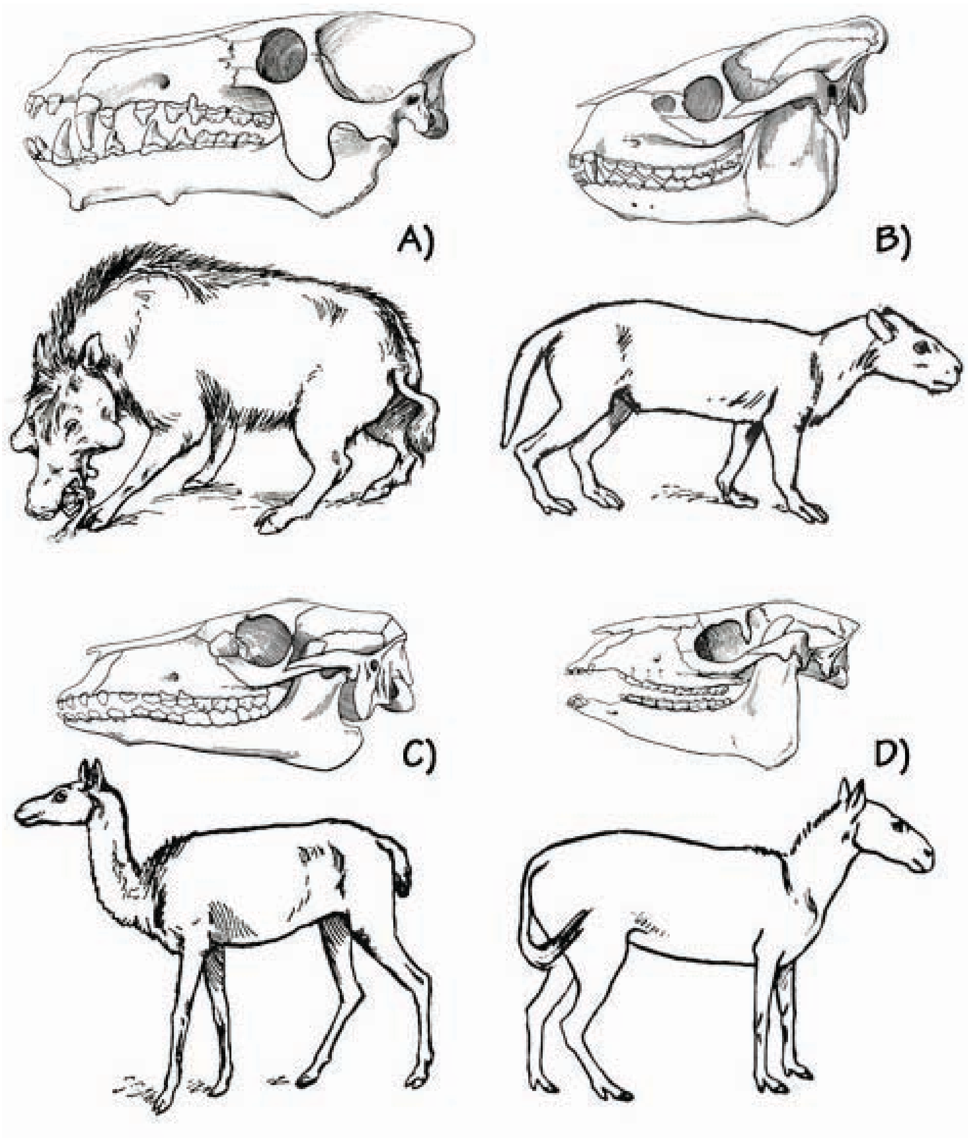
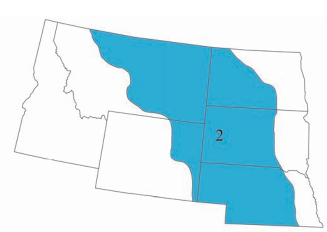


Figure 3.42: White River mammals. A) Archaeotherium, *an entelodont; skull and restoration. Skull about 6.5 centimeters (2 feet) long; body 1.4 meters (4.5 feet) tall at the shoulder. B)* Merycoidodon, *an oreodont; skull and restoration. Body about 1.4 meters (4.5 feet) long. C)* Poebrotherium, *a proto-camel; skull and restoration. Skull about 13 centimeters (5 inches) long; body about 90 centimeters (3 feet) tall. D)* Mesohippus, *an early horse; skull and restoration. Body about 60 centimeters (2 feet) tall.*

chalcedony • *a crystalline silicate mineral that occurs in a wide range of varieties.*

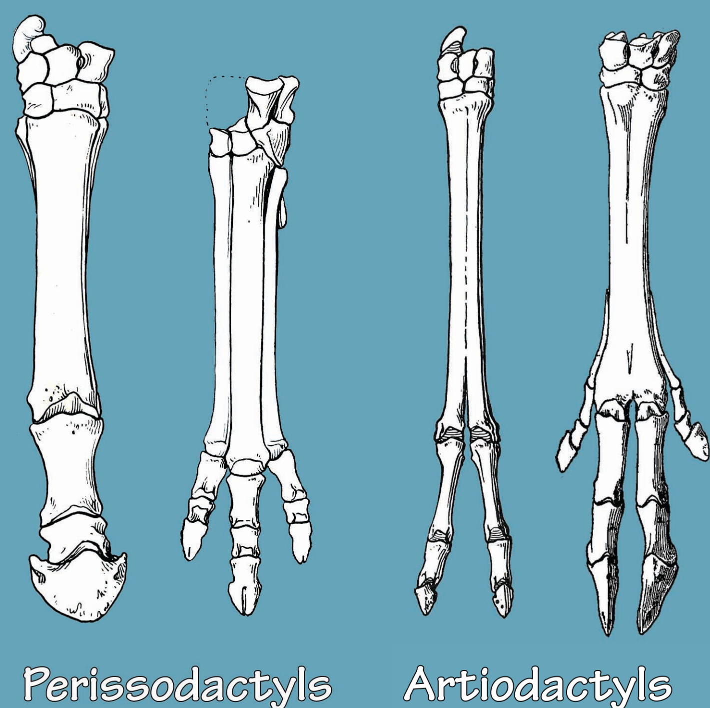
small "gazelle-camel" *Stenomylus*, the short-legged rhino *Menoceras* (the first rhino with horns), the carnivorous "beardog" *Daphoenodon*, the fierce-looking giant entelodont *Daeodon* (formerly *Dinohyus*), the bizarre clawed herbivore *Moropus*, and the "land beaver" *Paleocastor*, which dug spectacular long spiral burrows known today as the trace fossil *Daemonelix* (*Figure 3.44*).

The *agate* that gives this deposit its name is a variety of *quartz* called *chalcedony*. It is found in a thin band along ash deposits just above the Miocene bone beds, and ranges in color from amber to light gray.



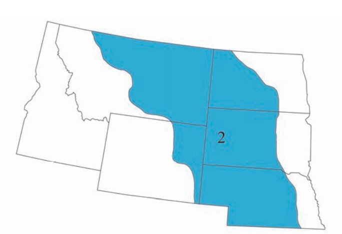
Hoofed Mammals

Herbivorous (plant-eating) ungulates (hoofed mammals) are classified into two major groups depending on the number of hooves (toes) per foot. Artiodactyls have an even number of hooves on each foot. This group of animals includes pigs (two hooves), deer, and cows (both with four hooves per foot). Perissodactyls have an odd number of hooves on each foot, and include horses (one hoof) as well as tapirs and rhinoceroses (three hooves).



Equus, *a horse (left) and* Hyracodon, *a rhinoceros (right).*

Procamelus, *a camel (left) and* Hippocamelus, *a deer (right).*



Most of the fossils in the Agate Springs quarries were excavated from a bone bed that is as much as 60 centimeters (2 feet) thick in some areas. Particularly famous are clusters of skeletons from the rhino *Menoceras* (*Figure 3.45*). These animals may have preferred to spend most of their time lying in shallow ponds or stream courses. When a multi-year drought occurred and the food supply disappeared, the *Menoceras* remained at the waterhole where they died. When water flowed again, the seasonal stream buried their bodies beneath layers of mixed **sandy** sediments and volcanic ash.

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

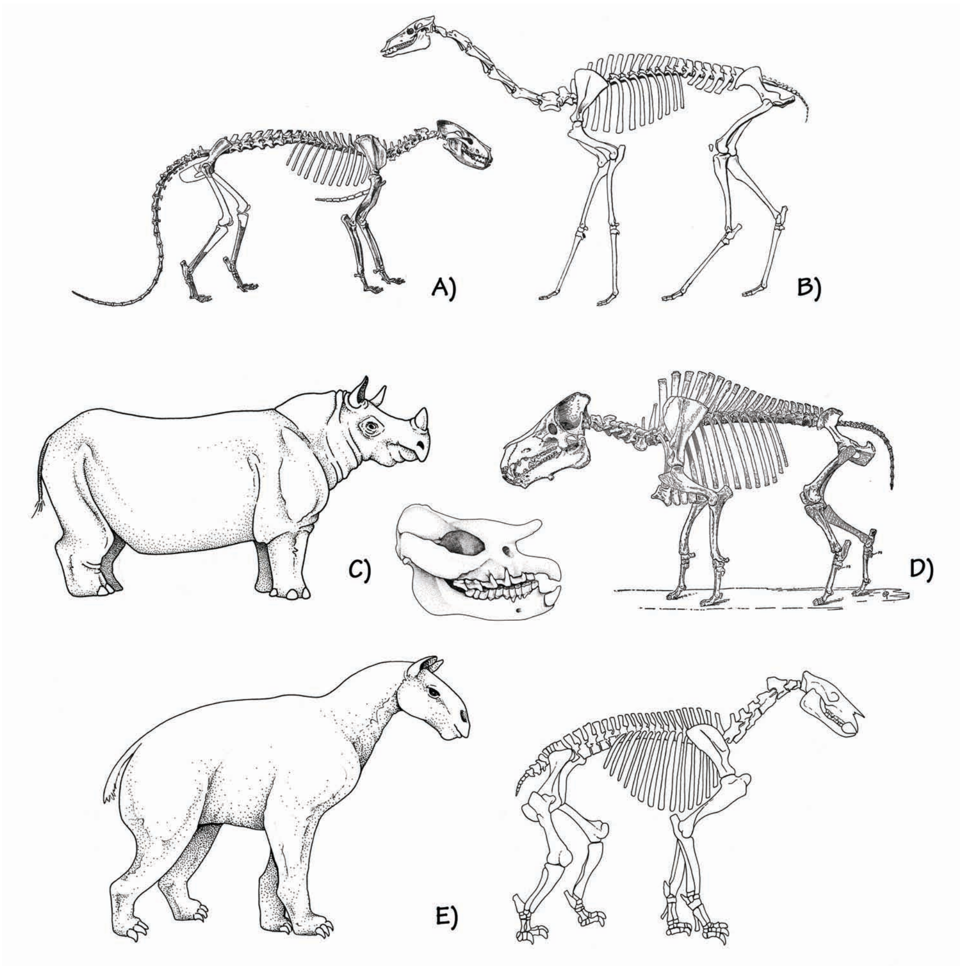
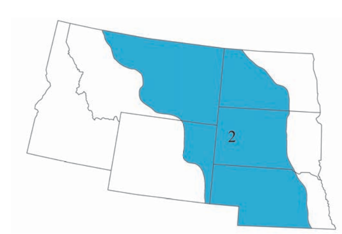


Figure 3.43: Fossil mammals from the Miocene of Nebraska. A) Beardog, Daphoenodon*; skeleton about 1.6 meters (5.5 feet) long. B) Camel,* Oxydactylus*; skeleton about 2.5 meters long (8.2 feet) long, 1.2 meters (3.9 feet) tall at the shoulder. C) Rhinoceros,* Teleoceras*; restoration and skull. Body about 4 meters (13 feet) long. D) Entelodont,* Daeodon*; skeleton. Skull about 90 centimeters (3 feet) long; body about 1.8 meters (6 feet) tall at the shoulder E. Chalicothere,* Moropus*; restoration and skeleton. Body about 2.4 meters (8 feet) tall at the shoulder.*

Some of the most common vertebrate fossils in Eocene and Oligocene sediments in Nebraska and the Dakotas are not mammals, however, but tortoises. Tortoises are a group of turtles that live on land, and have short, strong legs used for support and digging burrows. In contrast, most turtles live in the water and have webbed feet to help them swim efficiently, but will venture onto land occasionally to lay eggs. Two of the most common types of fossil tortoise are *Stylemys* from the Oligocene of Nebraska and *Hesperotestudo* from the Miocene of Nebraska and Kansas (*Figure 3.46*).



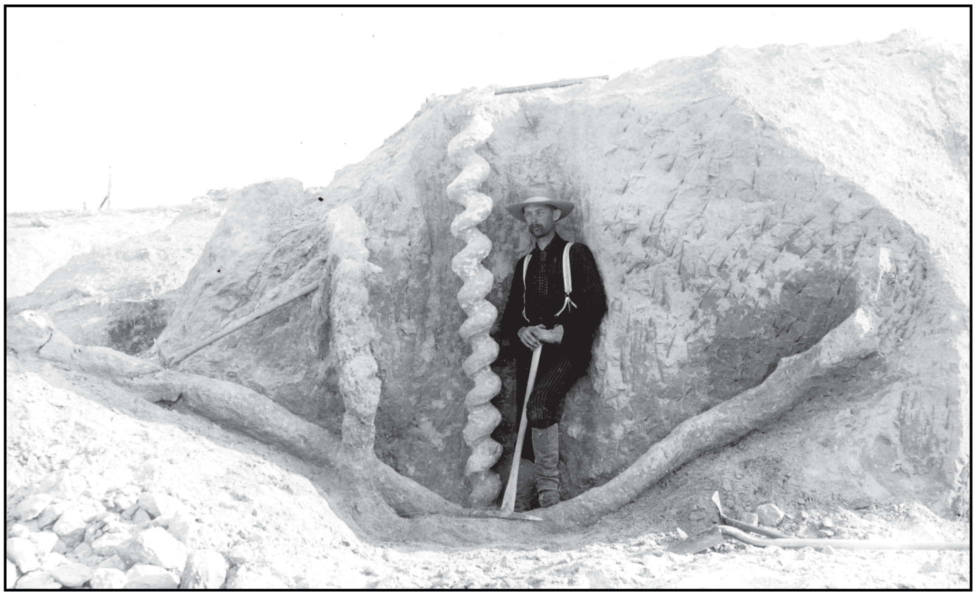
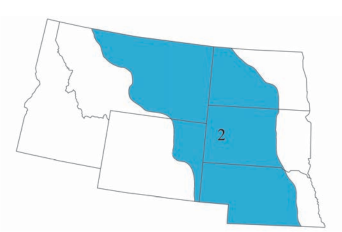


Figure 3.44: Fossil burrows, known as Daemonelix *("devil's corkscrew"), of the extinct beaver* Palaeocastor*. This large burrow was discovered in the late 19th century at Agate Fossil Beds National Monument.*

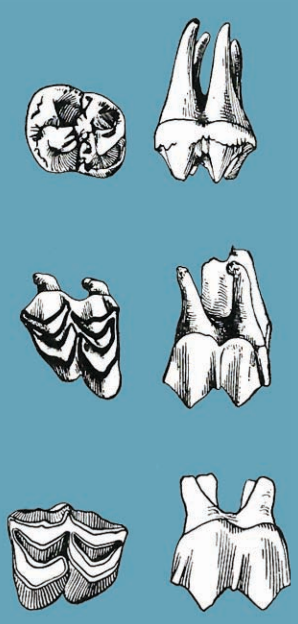
Figure 3.45: Bone bed of the Miocene rhinoceros Menoceras *at Agate Springs, Sioux County, western Nebraska. Slab is about 2 meters (6 feet) across.*



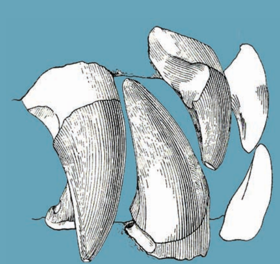
Fossil Mammals: It's (almost) all about the teeth

Mammals have evolved into an amazing variety of shapes and sizes, and much of this diversity and success is due to their teeth! Mammals are "warm-blooded," meaning they can regulate their own body temperature. This requires a high metabolism, energy that is derived from food. Mammals meet their heavy food requirements with the help of a distinctive chewing system, starting with their teeth. Unlike reptiles, most mammals – including humans – have several different kinds of teeth in their mouths. Also unlike reptiles, some of these teeth are highly complex, with many bumps and grooves on the chewing surfaces. This range of tooth forms allows mammals to efficiently eat many different kinds of food. It also allows different kinds of mammals to eat different foods. This means that different mammals usually have very different teeth, and that you can often identify a mammal species using only its teeth. This is extremely important for studying fossils, because mammal teeth are frequently found as fossils. Mammal paleontology is therefore largely the study of fossil teeth.

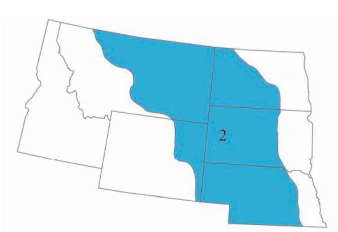
Upper right side dentition of Hyaenodon*, a dog-like carnivore.*



Upper molar of peccary (Tagassu), *deer* (Odocoileus), *and camel* (Poebrotherium).



Incisors and canines of the entelodont Archaeotherium.



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

mammoth • *an extinct terrestrial mammal belonging to the Order Proboscidea, from the same line that gave rise to African and Asian elephants.*

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.*

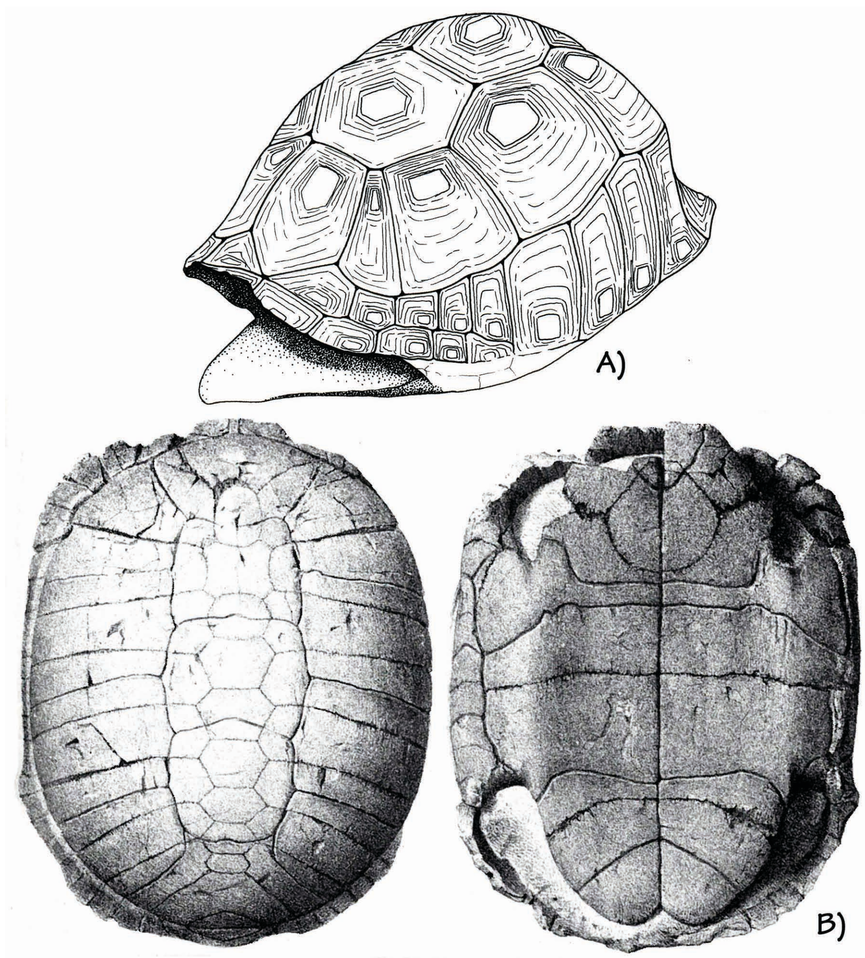
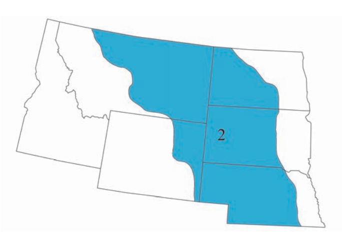


Figure 3.46: Tortoise fossils of the Great Plains. A) Geochelone orthopygia*, about 1 meter (3 feet) long. B)* Stylemys nebrascensis*, top (left) and bottom (right). Shell about 10 centimeters (4 inches) long.*

The cooling temperatures that affected all of North America at the beginning of the **Pleistocene** epoch, around 2.5 million years ago, brought an influx of new mammals to the Great Plains. These included **mammoths**, rodents, bison, and musk oxen.

Bison first appear in North America in the late Pleistocene, around 200,000 years ago, having migrated from Asia across the Bering Land Bridge. The oldest and largest of the several species that evolved here was the “giant bison,” *Bison latifrons*, which had horns measuring up to seven feet tip-to-tip, a shoulder height of 2.5 meters (8.2 feet), and may have weighed over 2000 kilograms (4400 pounds)—up to twice the size of the modern American bison (*Figure 3.47*). The giant bison became extinct around 20,000–30,000 years ago, at the beginning of the **last glacial maximum**. Bones of this species, as well as those of other extinct species such as *Bison antiquus*, are common throughout the Great Plains, especially in Nebraska.



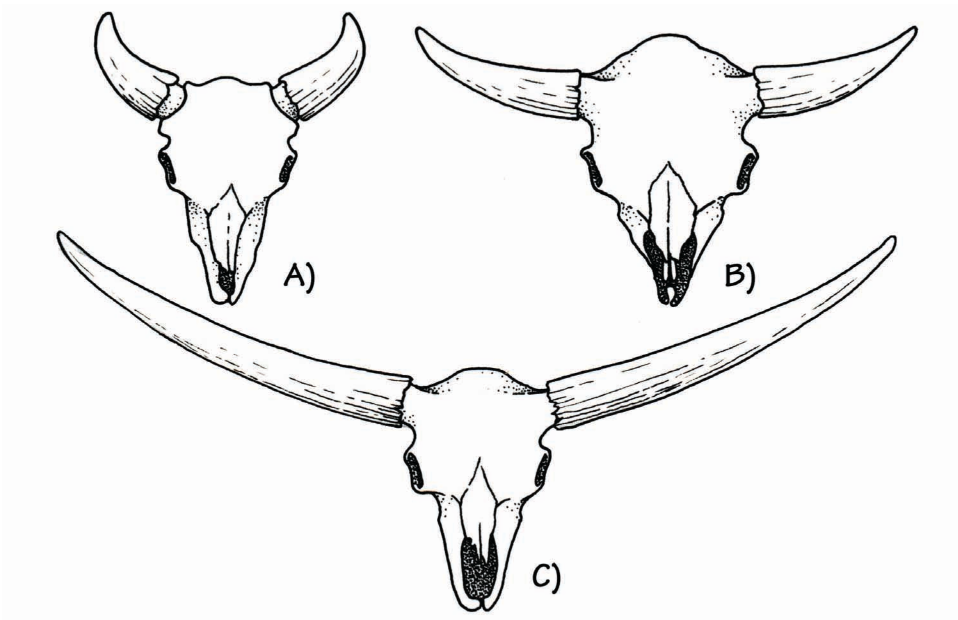
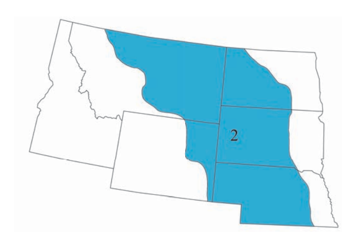


Figure 3.47: Skulls of two of the most common Pleistocene bison species, compared to the modern American bison (to scale). A) Bison bison *(Recent), horn span 66 centimeters (2 feet). B)* Bison antiquus *(extinct), horn span 1 meter (3 feet). C)* Bison latifrons *(extinct), horn span 2 meters (7 feet).*

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

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.*

Mammoths were close cousins of modern elephants that lived across North America and Eurasia for several million years. A number of different kinds of mammoths lived throughout North America (including the Rocky Mountains and Great Plains regions), until they became extinct around 10,000 years ago. The most familiar kind of mammoth is the woolly mammoth, *Mammuthus primigenius*, which lived in colder climates close to the **glacial** front (*Figure 3.48*). Farther south, other large mammoths were abundant. The Columbian mammoth, *Mammuthus columbi (Figure 3.49),* and the imperial mammoth, *Mammuthus imperator,* were previously thought to have been separate species, but paleontologists have recently concluded that they actually belonged to the same species. At Mammoth Site in Hot Springs, South Dakota, the skeletons of at least 60 mammoths (mostly Columbian) are preserved together with the bones of many other **ice age** mammals, including camel, llama, giant short-faced bear, wolf, coyote, and prairie dog. This extraordinary fossil assemblage formed around 26,000 years ago, when a cavern in the Minnelusa Limestone collapsed, creating a sinkhole into which the animals fell.



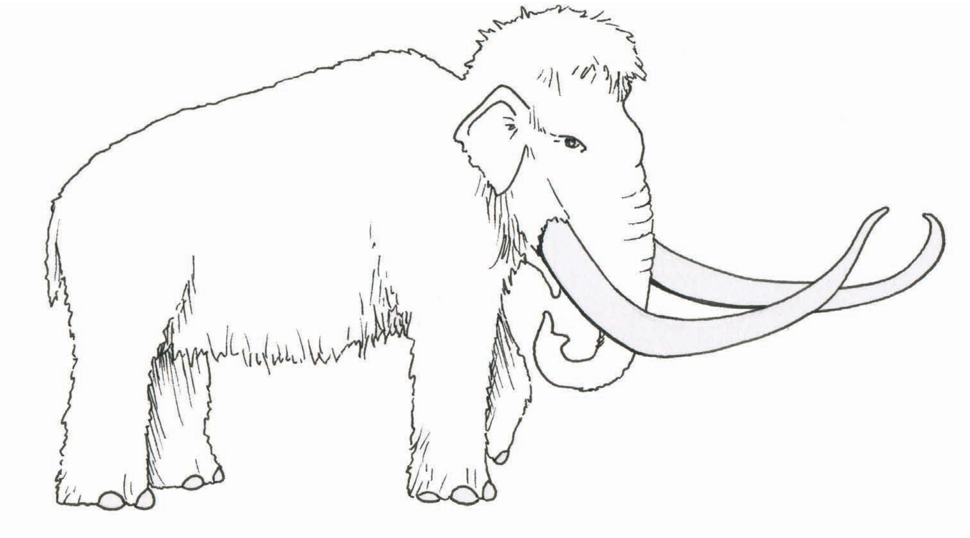


Figure 3.48: Woolly mammoth, Mammuthus primigenius*; about 3.5 meters (10 feet) high at the shoulder.*

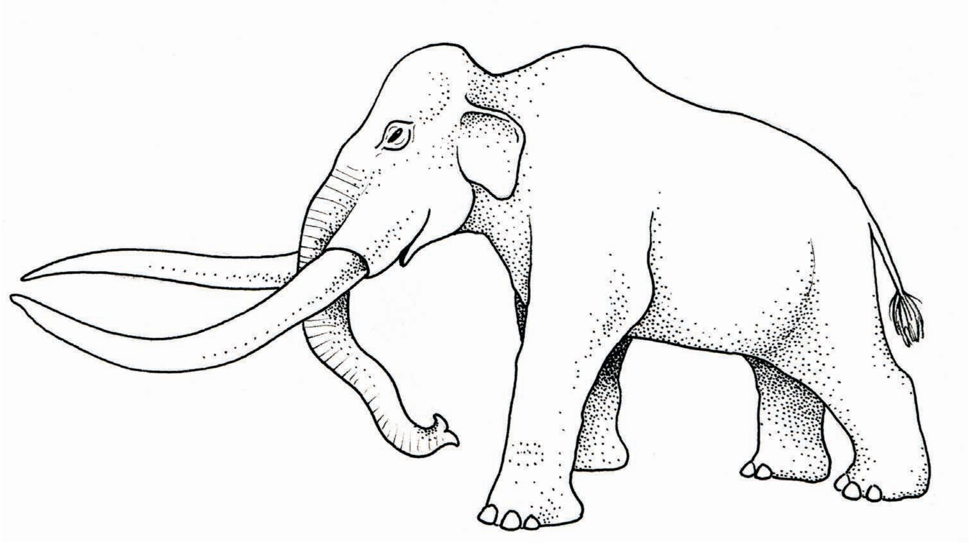
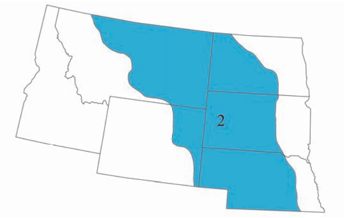


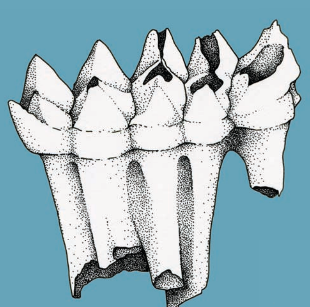
Figure 3.49: Columbian mammoth, Mammuthus columbi; *about 4 meters (13 feet) high at the shoulder.*



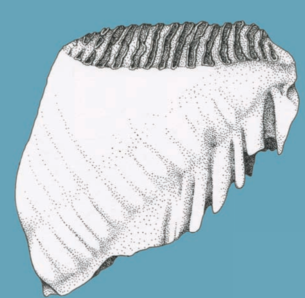
Region 2

Mastodons and Mammoths

These two kinds of ancient elephants (or, more technically, proboscideans) are frequently confused. Both were common during the Pleistocene, but they had different ecological preferences and are usually found separately. Mammoths are close cousins of modern African and Asian elephants; *mastodons* are more distant relatives, 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.

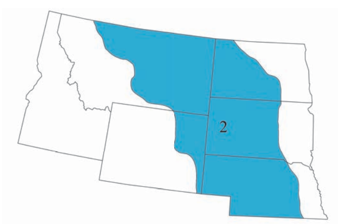


A mastodon tooth, suitable for chewing twigs and tree leaves. About 20 centimeters (8–9 inches) long.



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

mastodon • *an extinct terrestrial mammal belonging to the Order Proboscidea, characterized by an elephant-like shape and size, and massive molar teeth with conical projections.*



Large mammals are not the only life forms preserved from the ice age. Freshwater and land mollusks are common to abundant in many soft sediment deposits across the Great Plains (*Figure 3.50*).

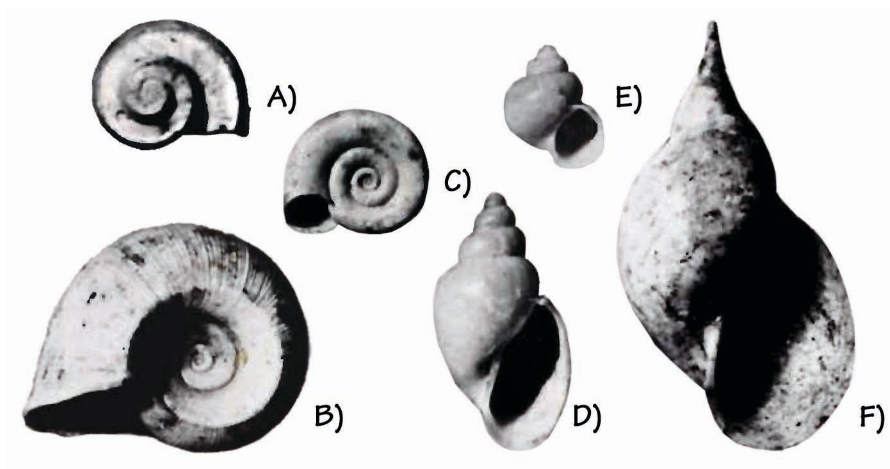
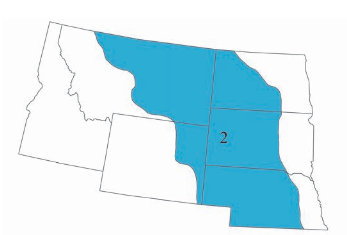


Figure 3.50: Pleistocene land snails of North Dakota. A) Valvata tricarinata*, about 4 millimeters (0.25 inches) in diameter. B)* Helisoma anceps*, about 6 millimeters (0.3 inches) in diameter. C)* Gyraulus parvus*, about 2 millimeters (0.1 inches) in diameter. D)* Lynnaea humilis*, about 6 millimeters (0.3 inches) tall. E)* Amnicola limosa*, about 4 millimeters (0.25 inches) tall. F)* Lynnaea stagnalis*, about 4 centimeters (1.6 inches) tall.*

Gastropods

Commonly known as snails, gastropod mollusks encompass terrestrial, freshwater, and marine species, and include varieties with and without shells (e.g., slugs). Gastropods are among the most diverse groups of organisms—only insects have more named species. The soft parts of gastropods are similar to those of bivalves, but the former typically have coiled shells and are usually much more active. Gastropods are present in Paleozoic and Mesozoic rocks, but are more commonly found in Cenozoic rocks.



Fossils of the Rocky Mountains
Region 3

Late Precambrian rocks are exposed in northwestern Montana (especially in Glacier National Park) and northern Idaho. They include limestones formed from carbonate sediments deposited on a warm, shallow sea floor. These rocks contain fossils called **stromatolites**, layered domes formed by mats of bacteria known as blue-green algae or cyanobacteria (*Figure 3.51*).

See Chapter 2: Rocks to learn more about stromatolites.

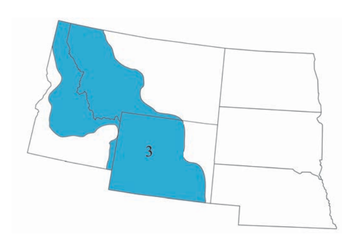
stromatolite • *regularly banded accumulations of sediment created by the trapping and cementation of sediment grains in bacterial mats.*

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

unconformity • *the relation between adjacent rock strata for which the time of deposition was separated by a period of nondeposition or erosion.*

Figure 3.51: Stromatolites lie exposed on the surface of the Grinnell Glacier cirque in Glacier National Park, Montana. These fossils were previously covered by ice and have only recently been exposed. Large specimens are greater than 0.6 meters (2 feet) in diameter.

Shallow marine waters continued to cover most of this area through the early part of the Paleozoic (Cambrian-Silurian), supporting a great diversity of life including trilobites, **graptolites**, brachiopods, and cephalopods. The sea retreated briefly during the middle Devonian, exposing the earlier rocks to erosion and resulting in **unconformities** in the geological record. Sea level rose again in the late Devonian, covering nearly all of Montana, Wyoming, and part of Idaho. These late Paleozoic seas were filled with diverse and abundant fusulinid foraminifera (*see Figure 3.3*) as well as crinoids, conodonts, mollusks, sponges, brachiopods, graptolites, and fish, including sharks.

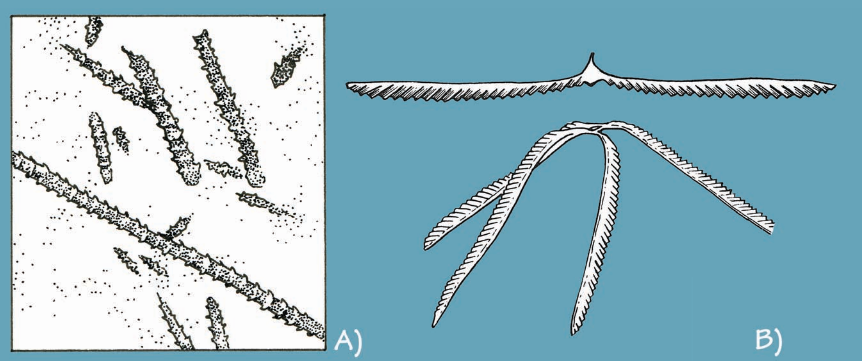


Triassic • *a geologic time period that spans from 252 to 201 million years ago.*

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

Graptolites

Graptolites (meaning "rock writing") are an extinct group of colonial, free-floating organisms. They lived from the Cambrian to the Carboniferous, and were relatives of modern hemichordates such as acorn worms. Graptolites are frequently preserved as thin, black, sawblade-like streaks across black shale; tiny cups along these structures held individual animals. Graptolites are often useful as index fossils.

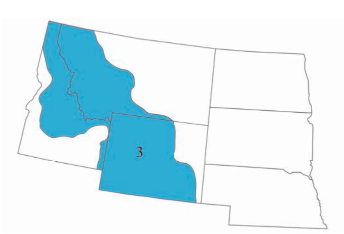


A) Specimen with many fragments of colonies of* Climacograptus. *Slab is 7.5 centimeters (3 inches) on each side.
B) Restoration of what graptolite colonies may have looked like when they were alive and floating in the water.

Mesozoic rocks in eastern Idaho contain abundant marine invertebrates, especially clams, snails, and ammonoids, of **Triassic** and Jurassic age (*Figure 3.52*). Fossils from the early Cretaceous include those of fish, turtles, crocodilians, gastropods, bivalves, and plants (*Figure 3.53*). In addition, a variety of dinosaur fossils (bone, teeth, and eggshell fragments) have been found from ceratopsians, *Ankylosaurus*, and theropods. Similarly, late Cretaceous deposits of Idaho contain **coal**, leaves, and freshwater clams.

Cretaceous rocks are well exposed in many parts of Wyoming, particularly around the edges of the Bighorn Basin. Notable fossils here include flat clams, such as *Inoceramus*, some of which reached enormous sizes (*see Figure 3.28*), and heteromorph ammonoids including *Didymoceras* (*see Figure 3.29B*).

During the Paleogene, the Western Interior Seaway advanced across the continent for the final time before tectonic uplift caused it to drain away. The warm, humid climate allowed the growth of lush forests. Plants that grew in these



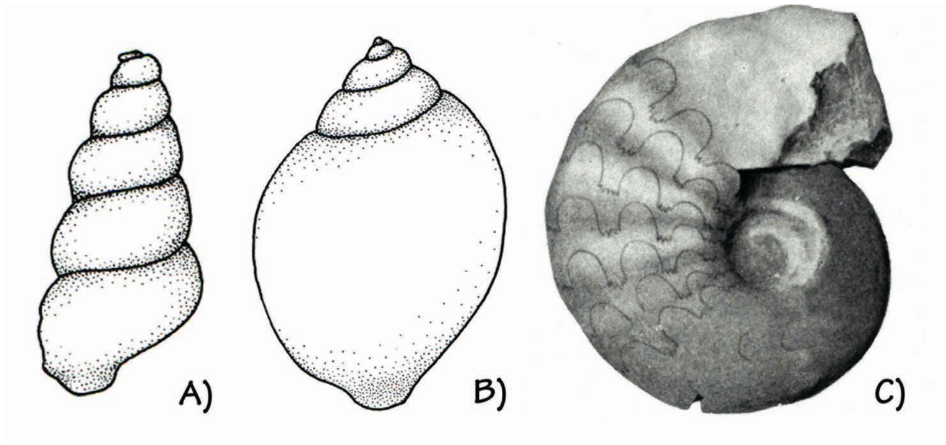


Figure 3.52: Triassic fossils of Idaho. A) and B) Gastropods, Polygyrina *(A) and* Naticopsis *(B), each about 5 centimeters (1.5 inches) tall. C) Ammonoid cephalopod,* Meekoceras, about 6 centimeters (2.5 inches) in diameter.

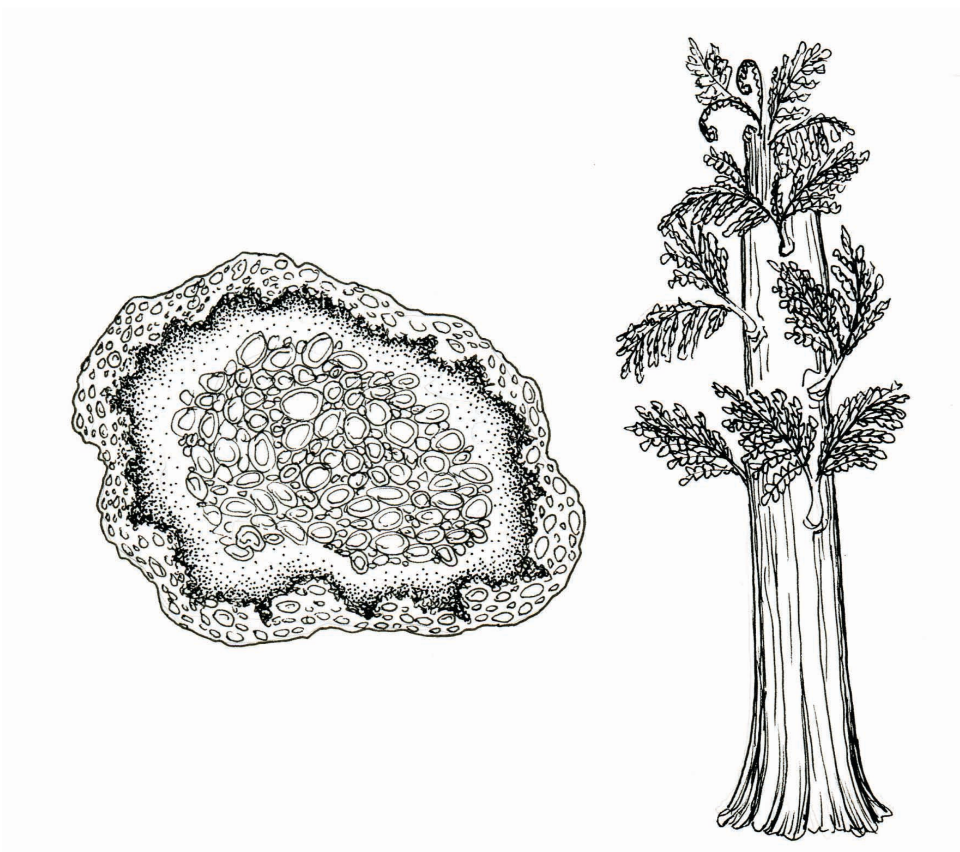
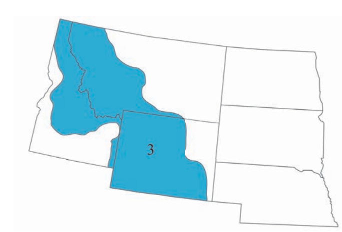


Figure 3.53: Tree fern, Tempskya*, Cretaceous; cross-section and reconstruction. Cross-section about 30 centimeters (1 foot) in width.*



Region 3

color (mineral) *• a physical property determined by the presence and intensity of certain elements within the mineral.*

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

lacustrine *• of or associated with lakes.*

forests, including magnolia, ginkgo, sequoia and cypress, were preserved as the coal that is mined today in places such as Wyoming. Lakes were widespread, and were sites of deposition for thick, organic-rich sediments. The most extensive and well-known of these is the Green River Formation, a layer of cream-**colored** shale 600–2000 meters (1970–6560 feet) thick, with occasional layers of **chert** and limestone.

See Chapter 7: Energy to learn about fossil fuel deposits in the Northwest Central.

The Green River Formation outcrops across a large area of southwest Wyoming, northwest Colorado, and northwest Utah, and composes the largest known accumulation of **lacustrine** sedimentary rock in the world. Its sediments accumulated in a system of lakes that covered this area during the Eocene, between 58 and 40 million years ago (*Figure 3.54*). The Green River is famous for the great number of well-preserved fossils found in its lake and river sediments, especially aquatic organisms such as fish, gastropods, and algae, but also many terrestrial plants and animals, including the oldest known bat (*Figures 3.55–3.57*). Well-preserved specimens of the fish *Knightia* are commonly found in the Green River Formation, and it is one of the most abundant vertebrate fossils in the world. A member of the herring family, the average *Knightia* is 7–12 centimeters (3–5 inches) long. *Knightia* are thought to have fed on algae, tiny crustaceans, and insects, and they were a major source of food for many of the larger fish in these Eocene lakes. They are commonly found in mass mortality or "death bed" layers because they swam in schools. The abundant plant and animal life preserved in the Green River Formation is also the reason for its status as a major oil shale deposit.

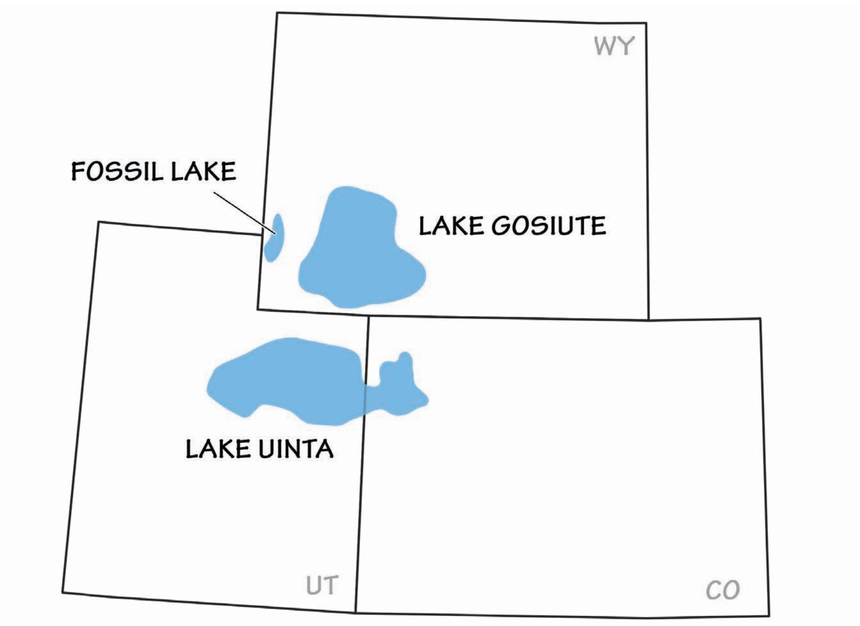


Figure 3.54: The Eocene Green River Formation. This map shows the size and location of the various lakes in which Green River sediments were deposited at different times during the Eocene epoch.

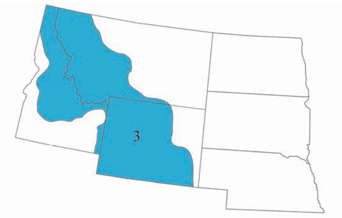


*Figure 3.55: The fossil-rich silicate rock known as "*Turritella *agate" is a popular gemstone from the Green River, but it is actually a misnomer.* Turritella *is a marine gastropod, whereas these snails—properly assigned to the genus* Elimia*—lived in freshwater. Slab is 6 centimeters (2.3 inches) wide.*

Figure 3.56: The perch-like fish Knightia*, the most common fossil vertebrate in the Green River rocks. Specimen is about 10 centimeters (4 inches) long.*

The Eocene was a time of extensive volcanism in the Rocky Mountain region. This is reflected in the occurrence of **silica**-rich layers in the Green River Formation, which formed from **weathered** volcanic ash, as well as the famous Yellowstone Petrified Forest (*Figure 3.58*). This extraordinary assemblage of multiple layers of volcanic ash contains numerous upright-standing, petrified **tree** trunks and abundant transported logs and stumps. It formed when ash was repeatedly eroded off of volcanoes and re-deposited in **braided streams** and rivers.

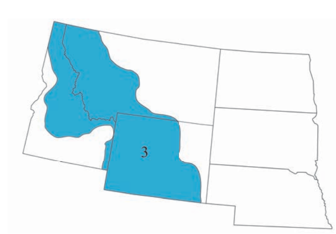
Region 3

silica • *a chemical compound also known as silicon dioxide (SiO_2).*

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

tree • *any woody perennial plant with a central trunk.*

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



Fossils

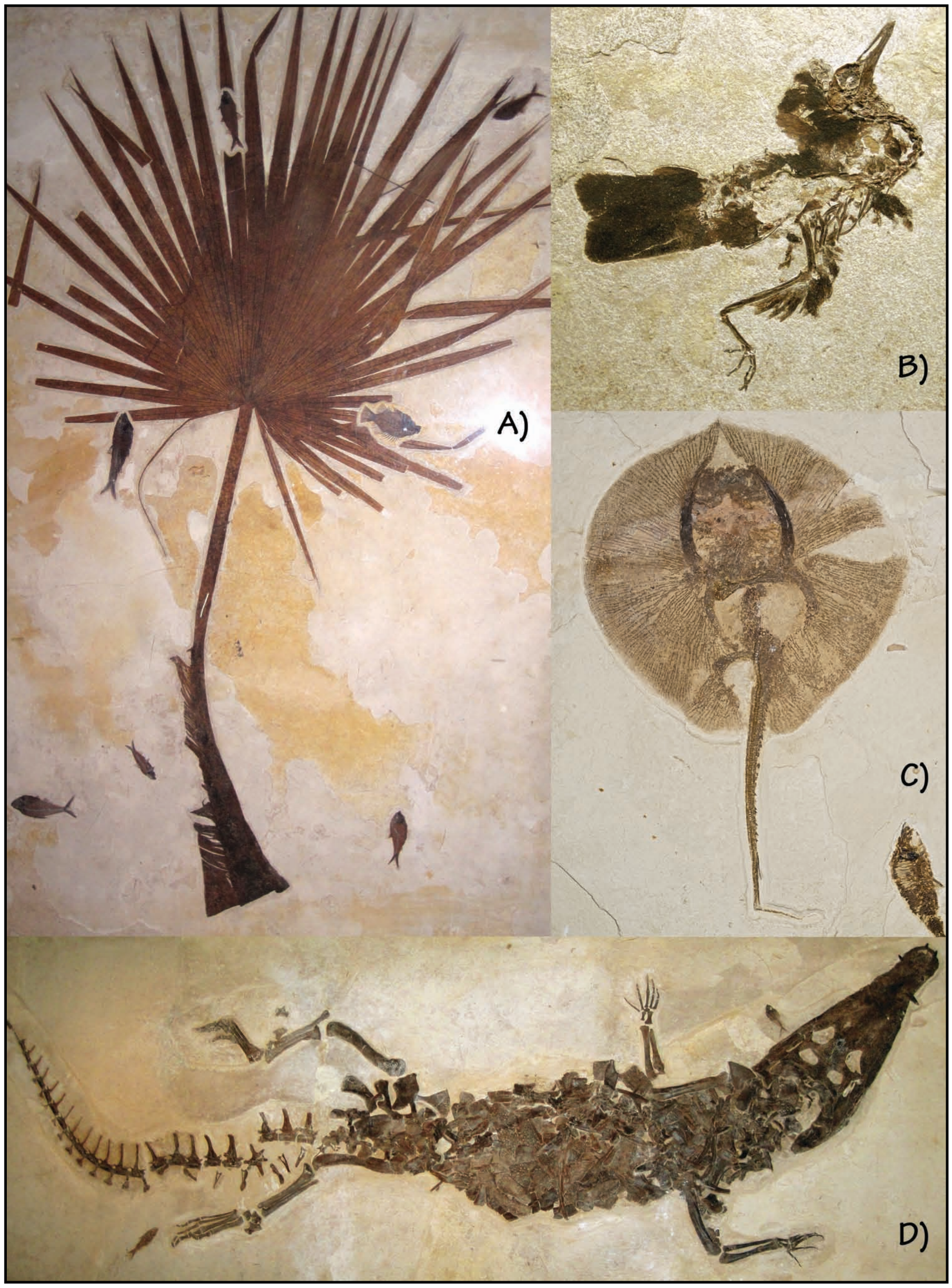
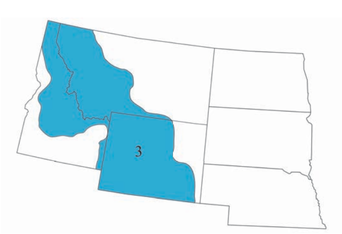


Figure 3.57: Well-preserved fossils from the Green River Formation, southwestern Wyoming. A) Palm frond, Sabalites powelli, *about 1.2 meters (4 feet) long, with fossil fish* Knightia. *B) An undetermined bird species with preserved feathers, about 25 centimeters (10 inches) long. C)* Heliobatis radians, *a stingray, about 40 centimeters (16 inches) long, with fossil fish. D)* Borealosuchus wilsoni, *a crocodilian, reached lengths of 4.5 meters (15 feet).*



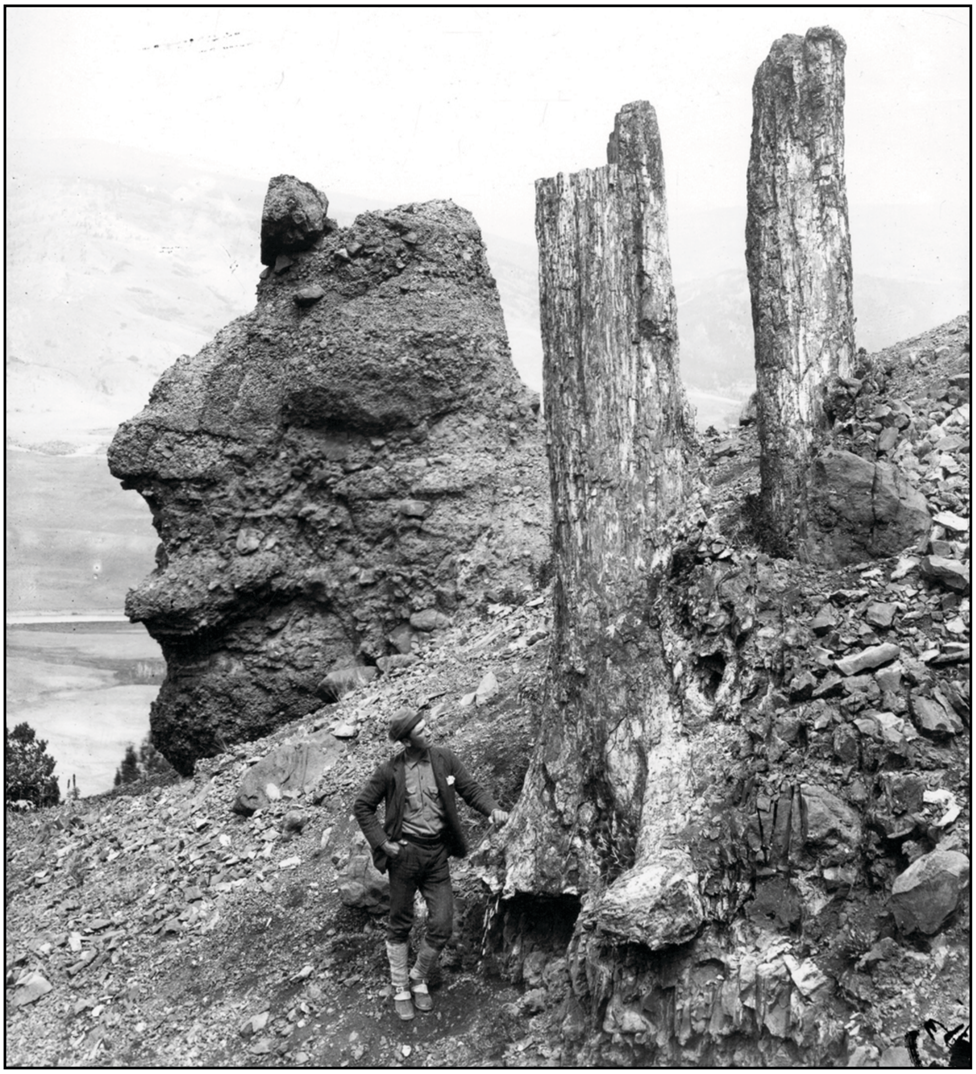
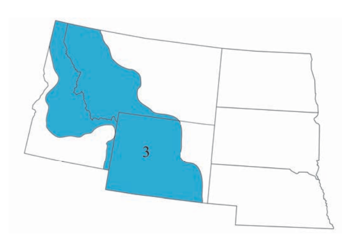


Figure 3.58: Specimen Ridge, overlooking the Lamar River, Yellowstone National Park, Wyoming. These fossil tree trunks are preserved in the position they occupied when they were alive, around 48 million years ago during the Eocene epoch, before they were buried suddenly in a volcanic eruption. This photo was taken around the year 1887. Note man standing at bottom for scale.

oxidation *• a chemical reaction involving the loss of at least one electron when two substances interact.*

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

During the Paleocene and Eocene epochs (65 to 34 million years ago) a number of archaic groups of mammals arose and went extinct (*see Figure 3.39*), and many of today's modern mammal groups evolved. Fossil bones of these mammals occur in several areas of northern Idaho, including the Tolo Lake Fossil Site in Idaho County. Abundant leaf and plant remains from this time period can also be found in northern Idaho (Shoshone and surrounding counties), where an ancient lake (approximately 15 million years old) provided ideal conditions for the fossilization of soft plant parts. Fossils in the Miocene Clarkia Fossil Beds (*Figure 3.59*) are so well preserved that some leaves even retain their original color; most are yellow, orange, and brown since they were shed during fall months (although they rapidly **oxidize** and turn black when exposed to air). The lake formed when a basin was dammed by **basalt** flows on the Columbia River



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

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

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

Plateau. Although best known for its plants, the Clarkia Beds also contain well-preserved fossil fish, snails, and insects. Like most **lagerstätten** deposits, the Clarkia Beds probably formed in a low-oxygen sedimentary environment, which slowed decay of the organic remains.

See Chapter 4: Topography for more information about the Columbia River Flood Basalts.

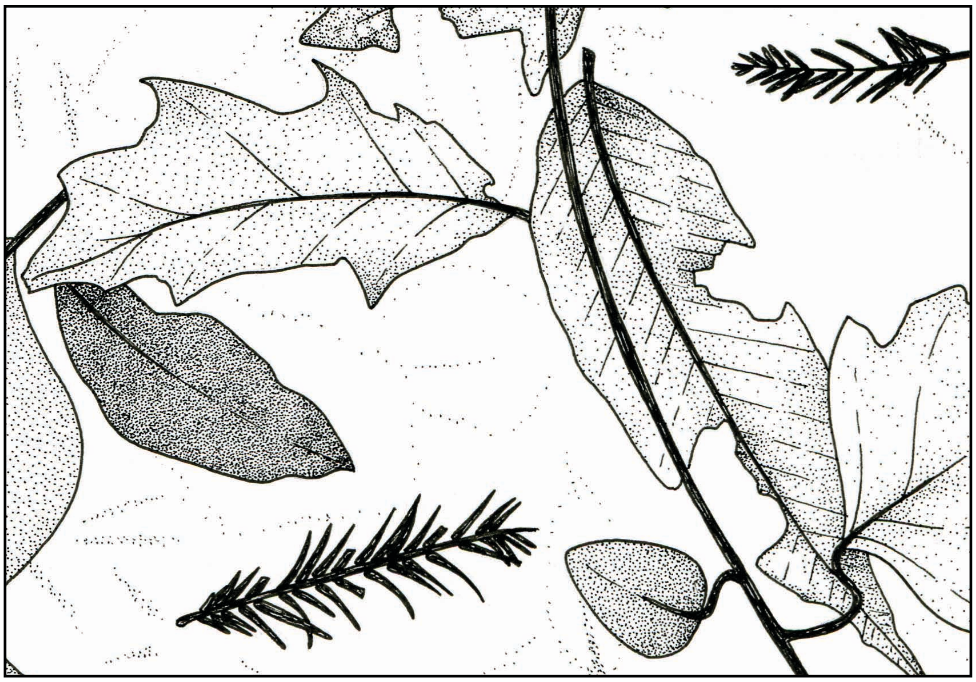


Figure 3.59: A slab of leaves from the Clarkia flora, about 13 centimeters (5 inches) across.

Fossils of the Columbia Plateau
Region 4

Rock formations from the late **Proterozoic** are the oldest fossil-bearing formations in the Columbia Plateau region. The earliest fossils found here are stromatolites, similar to those seen in Montana's Glacier National Park (*see Figure 3.51*), which have been reported in the Gospel Peak area of northwestern Idaho.

See Chapter 2: Rocks to learn more about rhyolite and basalt in the Columbia Plateau.

Paleozoic rocks are not present in the Columbia Plateau, as the land has been covered with igneous rock related to eruptions of the Yellowstone **hot spot** as it moved along the track of the Snake River Plain.

Triassic rocks occur in two areas of Idaho. Along the state's border with Oregon and southern Washington lie deposits of metamorphosed volcanic and sedimentary rocks that contain a variety of marine fossils, primarily from adjacent areas of Oregon. These include corals, sponges, ammonoids, clams, gastropods, echinoids, and bryozoans. In southeastern Idaho, Triassic deposits are largely composed of marine sedimentary rocks with sparse fossils, except for the Thaynes Formation, which contains fossils of fish, crinoids, bivalves, gastropods, ammonoids (*see Figure 3.52*), crustaceans, and shark teeth. The Columbia Plateau has Triassic red beds and thin deposits of coal, both of which indicate some terrestrial deposition.

Outcrops of Jurassic-aged rocks occur in western Idaho, along the border with Oregon and southern Washington. These rocks, formed mostly in deep water marine environments, have been slightly metamorphosed. Fossils from these rocks include ammonoids and oysters. Jurassic rocks in the southeastern part of the state are mostly shallow marine yielding mostly poorly preserved fossils, including crinoids, oysters, sea urchin spines, ammonoids, and corals (*see Figure 3.26*).

The Neogene river and lake sediments of westernmost central and southern Idaho contain abundant and beautifully preserved fossils of fish, rhinos, rodents, rabbits, horses, camels, and many other species. The Hagerman Fossil Beds National Monument on the Snake River just northwest of Twin Falls, in south-central Idaho is the most famous of these deposits, and includes Horse Quarry. This particular outcrop has yielded hundreds of fossils of zebra-like horses, *Equus simplicidens*, that are about 3.5 million years old (*Figure 3.60*). Tolo Lake in western Idaho near the Washington-Oregon border is known for its Quaternary-aged mammoth fossils.

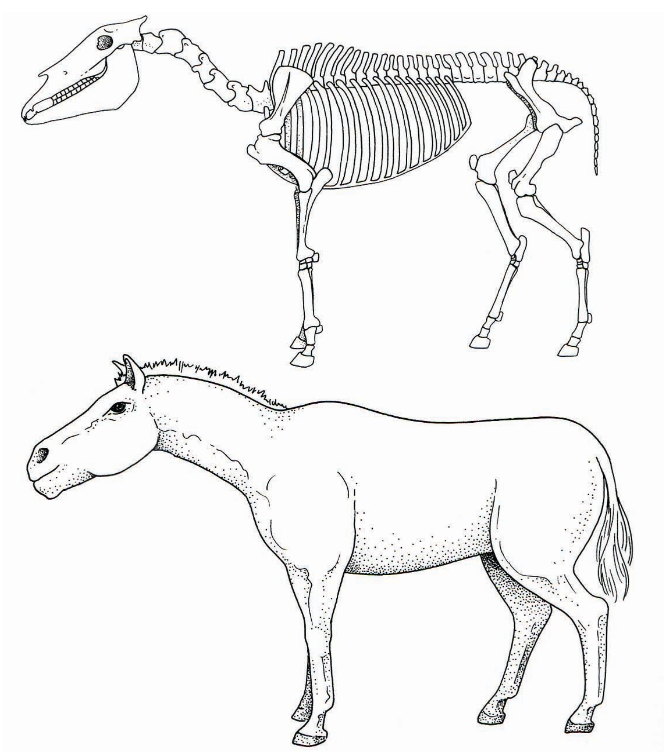


Figure 3.60: Neogene horse, Equus simplicidens*; skeleton and reconstruction 110–145 centimeters (43–57 inches) tall at the shoulder.*

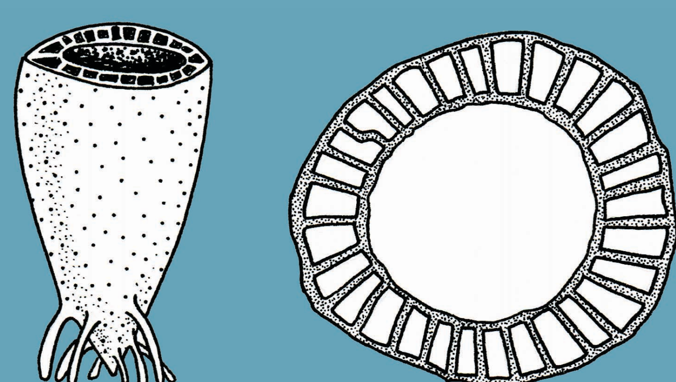
archaeocyathid • *a vase-shaped organism with a carbonate skeleton, generally believed to be a sponge.*

Fossils of the Basin and Range
Region 5

The mountain ranges of southeastern Idaho contain thick sections of early Paleozoic marine sedimentary rocks, mostly sandstones and limestones, deposited during the Cambrian and Ordovician periods. Early Cambrian rocks (variously assigned to the Brigham, Camelback Mountain, and Gibson Jack formations) contain *Skolithos* and other Cambrian trace fossils (*see Figure 3.14*), as well as occasional trilobites. Sponge-like **archaeocyathids** are present in shale and limestone formations. The Ordovician Swan Peak Quartzite contains abundant large trace fossils, as well as trilobites and brachiopods.

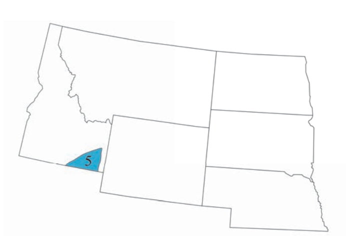
Archaeocyathids

Archaeocyathids were the first important animal reef builders, originating in the early Cambrian. These vase-shaped organisms had carbonate skeletons and are generally believed to be sponges. They went extinct in the late Cambrian, but were very diverse. Archeocyathids are often easiest to recognize in limestones by their distinctive cross-sections.



Side Cross-section

Archaeocyathids are found in lower Cambrian rocks in northern California and southern Oregon. Their vase-shaped calcite skeletons commonly reached lengths of 5 to 20 centimeters (2 to 8 inches).



The most abundant Paleozoic rocks in this region are early **Carboniferous** (Mississippian) marine sediments consisting mostly of carbonates, but also some sandstones and shales. Mississippian limestones (known variously as the Madison, Mission Canyon, or Lodgepole formations) contain abundant horn corals, tabulate corals, and spiriferid brachiopods (*Figure 3.61*), and represent a warm, clear-water carbonate environment. The late Carboniferous (Pennsylvanian) is represented by the same marine sediments, but both the variety and quantity of fossils are inferior to those found in Mississippian strata. Nonetheless, fossil algae, foraminifera, bryozoa, brachiopods, crinoids, and corals have been reported from sediments of this age.

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

gravel • *unconsolidated, semi-rounded rock fragments larger than 2 millimeters (0.08 inches) and smaller than 75 millimeters (3 inches).*

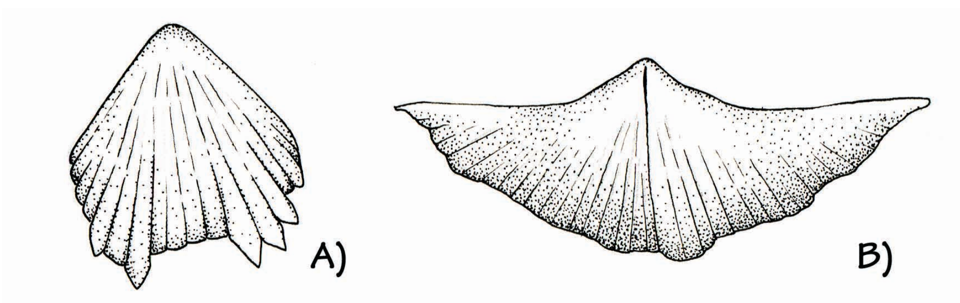


Figure 3.61: Paleozoic brachiopods of southeastern Idaho. A) Macropotamorhyncus insolitus. *B)* Prospira albapinensis. *Both about 2–4 centimeters (1–1.5 inches) wide.*

Southeastern Idaho also contains a thick sequence of early Triassic marine strata, and several horizons (especially the Thaynes and Dinwoody formations) contain biostratigraphically significant ammonoids. Overlying Jurassic rocks, especially the Twin Creek Limestone, contain well-preserved ammonoids and bivalves.

See Chapter 6: Glaciers to learn more about glacial lakes that formed during the last ice age.

Sand and **gravel** deposits in southeastern Idaho that were laid down in association with glacial Lake Bonneville have yielded fossils of Pleistocene bison (*see Figure 3.47*), camels, muskoxen, and horses.

State Fossils

Idaho
Equus simplicidens (horse, Neogene) (*Figure 3.60*).

Montana
Maiasaura peeblesorum (hadrosaur dinosaur; Cretaceous) (*Maiasaura Box, p. 112*).

Nebraska
Mammuthus columbi (Columbian mammoth; Neogene) (*Figure 3.49*).

North Dakota
Teredo Petrified Wood (petrified wood; Paleocene) (*Figure 3.37*).

South Dakota
Triceratops horridus (ceratopsian dinosaur; Cretaceous) (*Figure 3.34A*).

Wyoming
Knightia eocaena (fish; Eocene) (*Figure 3.57*).

Resources

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Benton, M. J., 2008, *The History of Life: A Very Short Introduction*, Oxford University Press, Oxford, UK, 170 pp.

Fenton, C. L., and M. A. Fenton, 1958, *The Fossil Book: A Record of Prehistoric Life*, Doubleday, Garden City, NY, 482 pp. (A well-illustrated classic.)

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Guides to Collecting and Identifying Fossils

Arduini, P., G. Teruzzi, and S. S. Horenstein, 1986, *Simon & Schuster's Guide to Fossils*, Simon & Schuster, New York, 317 pp.

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Benton, Rachel C., Dennis O. Terry Jr., Emmett Evanoff, and Hugh Gregory McDonald, 2015, *The White River Badlands: Geology and Paleontology*, Indiana University Press, Bloomington, IN, 240 pp.

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Fossils of the States of the Northwest Central

The Paleontology Portal, http://paleoportal.org/. (North American fossil record and geologic and climate histories, by state).

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Fossils in Idaho: Digital Atlas of Idaho, http://imnh.isu.edu/digitalatlas/geo/fossils/fossils.htm.

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Nebraska

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Ashfall Fossil Beds State Historical Park: Ashfall Animals, http://ashfall.unl.edu/ashfallanimals.html.
Discover your County's Fossils! A Virtual Journey Through the Paleontology Collections of the University of Nebraska State Museum, http://museum.unl.edu/research/vertpaleo/necounties/.
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North Dakota

North Dakota Geological Survey: Paleontology, https://www.dmr.nd.gov/ndfossil/. (Information on North Dakota's prehistoric life and environments, including some climate information.)

South Dakota

Badlands National Park, http://www.nps.gov/badl/index.htm.
The Fossils of the White River Badlands, by C. Ryan, http://whiteriver.weebly.com/.
Mammoth Site Geology, http://mammothsite.com/geology/.
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Wyoming

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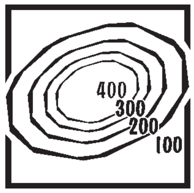

Chapter 4: Topography of the Northwest Central US

Does your region have rolling hills? Mountainous areas? Flat land where you never have to bike up a hill? The answers to these questions can help others understand the basic topography of your region. 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 occur over 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 the Northwest Central, topography is intimately tied to **weathering** and erosion as well as to the type and structure of the underlying bedrock, but it is also a story of **plate tectonics**, volcanoes, folding, **faulting**, **uplift**, and mountain building.

Weathering includes both the mechanical and chemical processes that break down a rock. There are two types of weathering: physical and chemical. Physical weathering describes the physical or mechanical breakdown of a rock during which the rock is broken into smaller pieces, but no chemical changes occur. **Wind**, water, temperature, and pressure are the main media by which physical weathering and erosion occur. Streams are constantly eroding their way down through bedrock to sea level, creating valleys in the process. Given sufficient time, streams can cut deeply and develop wide flat floodplains on valley floors. Streams, oceans, and ice also deposit the material they erode, creating new topographical features elsewhere. The pounding action of ocean waves on a coastline contributes to the erosion of coastal rocks and sediments, while the emptying of a river can lead to the building of a **delta**.

Pressure release can cause rocks to crack. Growing plant roots can exert many pounds per square inch of pressure on rocks—think of tree roots uplifting and cracking a sidewalk. Additionally, since rocks buried miles beneath the surface are under considerable pressure, if those rocks become exposed at the Earth's surface (where the rock is under less pressure), the rock may expand and crack in a process called **exfoliation** (*Figure 4.1*). Ice can also change the landscape due to frequent episodes of freezing and thawing, causing both temperature and pressure differentials within a rock. On a small scale, as water trapped in **fractures** within the rock freezes and thaws, the fractures continue to widen (*Figure 4.2*). This alone can induce significant breakdown of large rock bodies.

Working in conjunction with physical (mechanical) weathering, chemical weathering also helps to break down rocks through changes in the chemical composition of their constituent **minerals**. Some minerals contained in **igneous**

erosion *• the transport of weathered materials.*

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

plate tectonics *• the process by which the plates of the Earth's crust 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.*

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

delta *• a typically wedge-shaped deposit formed as sediment is eroded from mountains and transported by streams across lower elevations.*

CHAPTER AUTHORS

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Review

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.*

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

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

carbonate rocks *• rocks formed by accumulation of calcium carbonate, often made of the skeletons of aquatic organisms.*

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

cementation *• the precipitation of minerals that binds together particles of rock, bones, etc., to form a solid mass of sedimentary rock.*

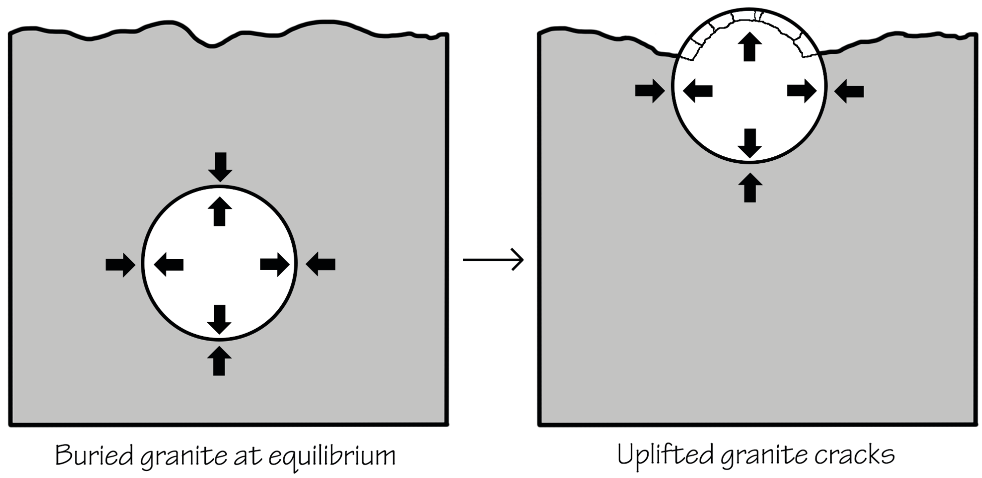


Figure 4.1: Exfoliation as a result of uplift and pressure release.

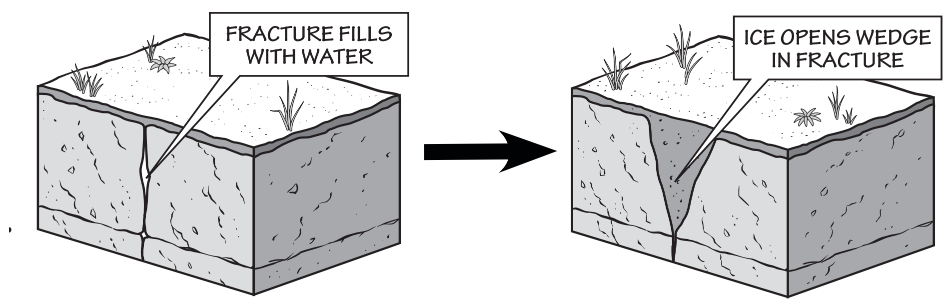


Figure 4.2: Physical weathering from a freeze-thaw cycle.

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 or placed in contact with water, where the temperature and pressure are considerably lower. Unstable minerals transition into more stable minerals, resulting in the breakup of rock. Weak acids, such as the carbonic acid found in rainwater, also promote the disintegration of certain types of rocks. **Limestone** and **marble** may be chemically broken down as carbonic acid reacts with the **carbonate** mineral composition of these rocks, forming cavities and caverns. Other **sedimentary rocks** held together by carbonate **cement** are also particularly susceptible to chemical weathering.

Glaciers have also contributed to the Northwest Central's topography. Ice sheets from the last glaciation covered part of this area, and mountain glaciers in the Rocky Mountains were considerably more extensive than they are at present. In mountainous areas, erosion by valley glaciers leaves behind jagged peaks, bowl-like depressions called **cirques**, and long U-shaped valleys with tributary **hanging valleys**. Glaciers can both erode and deposit material. As the ice melts, piles of sediment are left behind, forming structures such as moraines, **eskers**, and **drumlins**. Glacial lakes are common, as water from

Review

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

dike • *a sheet of intrusive igneous or sedimentary rock that fills a crack in a pre-existing rock body.*

tuff • *a pyroclastic rock made of consolidated volcanic ash.*

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

caldera • *a collapsed, cauldron-like volcanic crater formed by the collapse of land following a volcanic eruption.*

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

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

the melting ice readily fills depressions. The deposition of fine **silt** that has been ground from rock by glaciers can lead to the formation of wind-blown deposits called **loess**.

See Chapter 6: Glaciers to learn more about the ways in which glacial erosion alters the landscape .

Volcanic activity has shaped the land throughout the Northwest Central. Although there are no active volcanoes there today, evidence of past activity—such as volcanic cones and craters, lava flows, **dikes**, and sills—can be seen in a variety of locations, including **tuff** beds in western and central North Dakota, and the Shoshone lava field in Idaho. Evidence of hot rock and cooling **magma**, including igneous rocks (e.g., **basalt**, **andesite**, and **rhyolite**), hot springs, and **geysers**, can be found in the Yellowstone area, which contains the ancient **caldera** of a **supervolcano**. There has been no major volcanic activity in the Yellowstone area within recorded history; the most recent Yellowstone eruption occurred around 630,000 years ago. Nevertheless, there is concern that Yellowstone may erupt again in the future.

See Chapter 10: Earth Hazards to learn about supervolcanoes.

The specific rock type found at the surface has an important influence on a region's topography. 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, while surrounding layers of less resistant rock erode away. The great Western Interior Seaway of the **Cretaceous** collected and preserved sediments that became sedimentary rocks throughout the Great Plains and Central Lowland of Nebraska and the Dakotas. Sedimentary rocks weather and erode differently than do crystalline (and generally harder) igneous and metamorphic rocks, such as those found in the Rocky Mountains and the Black Hills. **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 even more resistant due to **recrystallization**. There are exceptions, however, such as **schist**, which is much weaker than its pre-metamorphic limestone or **sandstone** state.

The underlying structure of rock layers also plays an important role in surface topography. Sedimentary rocks are originally deposited in flat-lying layers that rest on top of one another. The movement of tectonic **plates** creates stress and tension within the **crust**, especially at plate boundaries. **Intrusions** beneath the surface may also cause deformation of the crust. All these different sources of geological stress can deform the flat sediment layers through folding, faulting, 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 brings layers of rock to the surface. Tilted rocks expose underlying layers. Faulting likewise exposes layers at the surface to erosion, due to the movement and tilting of blocks of crust along the fault plane. For example, the Basin and Range formed

Review

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

Laramide Orogeny *• a period of mountain building that began in the Late Cretaceous, and is responsible for the formation of the Rocky Mountains.*

physiography *• a subfield of geography that studies the Earth's physical processes and patterns.*

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

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).*

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

as a result of normal faulting (*Figure 4.3A*), which occurs due to extensional stresses that create uplifted ranges and downdropped basins. The Rocky Mountains provide another regional example of folding and faulting: this range formed as a result of uplift associated with **subduction** along the western edge of the North American plate. The shallow angle of the subducting plate generated thrust (reverse) faults (*Figure 4.3B*) and the onset of the **Laramide Orogeny**.

See Chapter 1: Geologic History to learn about the processes of subduction and uplift.

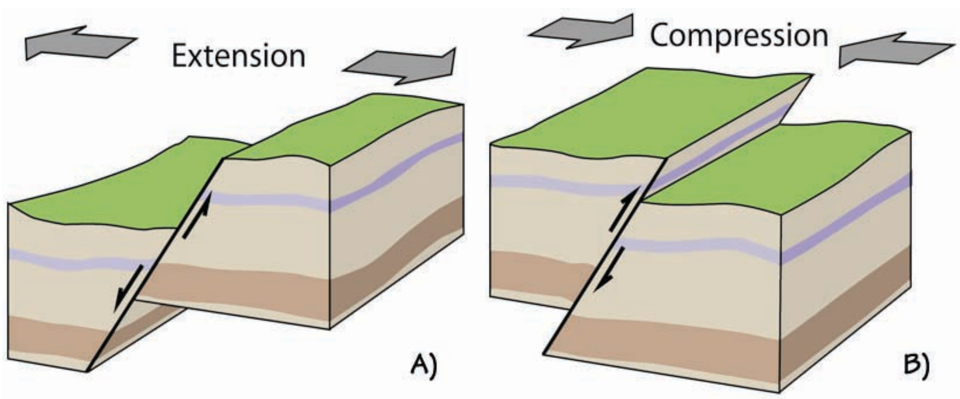


Figure 4.3: Normal faulting and thrust (reverse) faulting.

Just as we are able to make sense of the type of rocks in an area by knowing the geologic history of the Northwest Central US, we are able to make sense of its topography (*Figure 4.4*) based on rocks and structures resulting from past geologic events. Topography is a central element of the broader concepts of geomorphology or **physiography**, which also include consideration of the shape (not just the height) of land forms, as well as the bedrock, **soil**, water, vegetation, and **climate** of an area, and how they interacted in the past to form the landscape we see today. A physiographic province is an area in which these features are similar, in which these features are significantly different from those found in adjacent regions, and/or is an area that is separated from adjacent regions by major geological features. The "regions" of the Northwest Central that we use in this book are examples of major physiographic provinces.

Topography 4

Figure 4.4: Digital shaded relief map of the Northwest Central States.

Topography of the Central Lowland
Region 1

The Central Lowland is a flat-lying region located between the Appalachian Mountains to the east and the Great Plains to the west (*Figure 4.5*). It extends from the **Canadian Shield** in the north to the Atlantic Coastal Plain in the south and is part of the North American **craton** (the older, stable part of the continent).

The Central Lowland is composed of flat-lying **Precambrian** metamorphic and igneous rocks overlain by **Paleozoic** and **Mesozoic** sedimentary rocks. The Mesozoic sediments found in the region were eroded from the Rocky, Ozark, and Ouachita mountains, then carried to and deposited in the Western Interior Seaway that covered the area. Glacial erosion and deposition during the last **ice age** modified and smoothed much of the region's surface, leaving behind thick layers of **Cenozoic** sediment and **drift**. Today, rivers running through this region, including the Missouri and Red rivers, have contributed significantly to erosion.

See Chapter 1: Geologic History to learn more about the Western Interior Seaway.

The Central Lowland has a generally smooth and flat topography, generated by glacial **scouring** during the ice age, as well as by the presence of enormous glacial lakes and erosion from catastrophic outbursts of meltwater. During

Region 1

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).*

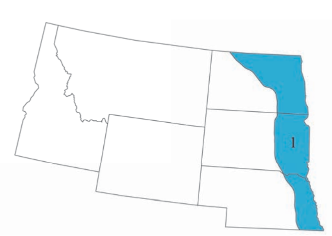
Paleozoic • *a geologic time interval that extends from 541 to 252 million years ago.*

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.*

drift • *unconsolidated debris transported and deposited by a glacier.*

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



Region 1

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

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).*

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

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

gravel *• unconsolidated, semi-rounded rock fragments larger than 2 millimeters (0.08 inches) and smaller than 75 millimeters (3 inches).*

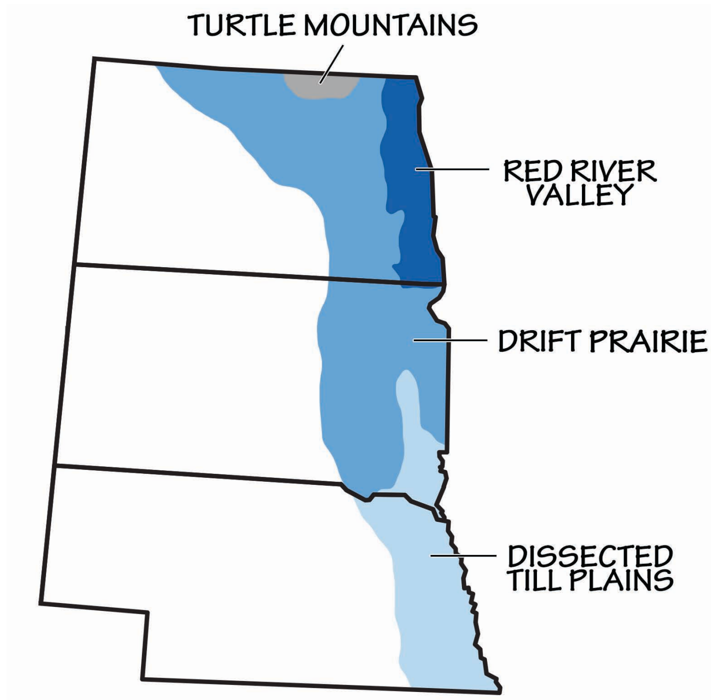


Figure 4.5: Physiographic divisions of the Central Lowland.

the **Quaternary**, a 152-meter-thick (500-foot-thick) **ice sheet** flattened the landscape, leaving behind the gently rolling hills and shallow lakes that spread throughout the Drift Prairie today (*Figure 4.6*). The ice sheet also left behind layers of **till**, **clay**, **gravel**, and wind-blown silt (loess), which contributed to the area's rich agricultural soils. The Red River Valley, directly to the east in North Dakota, is a flat lowland area that marks the former floor of glacial Lake Agassiz, which was once the largest freshwater lake in North America (*Figure 4.7*). About 160 kilometers (100 miles) west of the Red River Valley, the Missouri Escarpment—a ridge extending southeast from Canada to south-central South Dakota—separates the Drift Prairie from the Great Plains. The escarpment was formed when catastrophic floods at the end of the ice age carved a huge canyon, channeling future ice movements and flattening the surrounding area. The Missouri Escarpment is the remnant of this canyon's west and southwest wall.

See Chapter 6: Glaciers for more information about glacial landscapes and Lake Agassiz.

Escarpments **form when faulting or erosion acts to create a cliff or steep slope that separates two level or gently sloping topographical surfaces. Typically, cliffs created by faulting are called "scarps," while "escarpments" are those formed by the differential erosion of resistant layers that alternate with softer strata.**

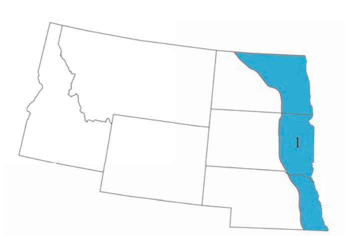
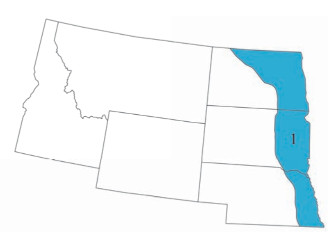


Figure 4.6: The Drift Prairie near Bottineau, North Dakota. The rolling landscape of the Turtle Mountains is visible in the far distance.

Figure 4.7: The extent of glacial Lake Agassiz during the Pleistocene. North Dakota's Red River Valley follows the bed of this ancient lake.



4

Topography

Region 1

Several landforms throughout North Dakota's Central Lowland were formed as ice-thrust features—the weight and pressure of the advancing glacier displaced large bedrock slabs, shoving and thrusting large masses of rock and sediment, and depositing them a short distance from their original position. Geologists speculate that ice-thrust features occur so prominently in central and eastern North Dakota because the region's water drains northward. Ice sheets advancing from the north prevented groundwater drainage, leading to increased pressure within the ground. Eventually, the weight of the glacier caused pieces of terrain to pop out of the ground, thrusting them a short distance forward and relieving the built-up pressure (*Figure 4.8*). Ice-thrust features are often accompanied by topographic depressions (usually lakes) located to the north, from which the material was displaced. Examples include Steele Lake near Anamoose, Medicine Lake and its adjacent Grasshopper Hills, and even Devils Lake, the largest natural lake in North Dakota. The Turtle Mountains of northernmost North Dakota, a plateau lying 600 meters (2000 feet) above sea level and 90–120 meters (300–400 feet) above the surrounding land, are another example of ice-thrust terrain that was later smoothed and rounded by further glacial erosion.

See Chapter 10: Earth Hazards to learn about flooding hazards at Devils Lake.

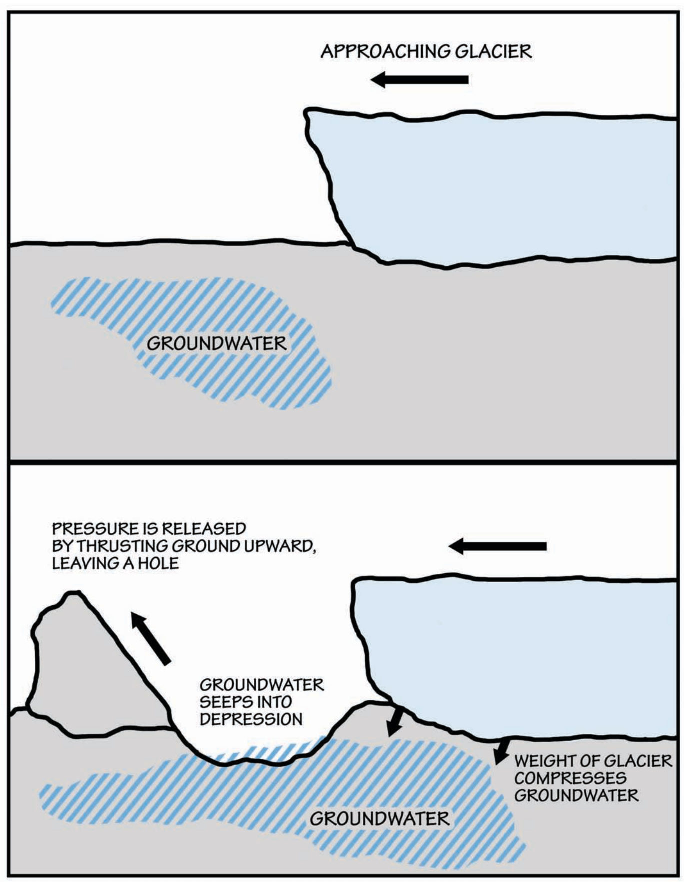
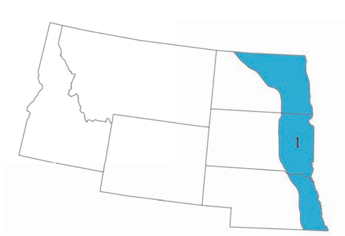


Figure 4.8: Ice-thrust features are created when pressure from the weight of an advancing glacier is released by thrusting a piece of terrain forward.



The Dissected Till Plains, extending from southeast South Dakota through Nebraska, are an area of rolling hills ripe with fertile soil. The area was initially scoured and flattened during the **pre-Illinoian** glacial stage; during the **Wisconsinian**, great quantities of loess accumulated there. Glacial runoff later led to erosion that sculpted the area into valleys and hills. Today, the Missouri River cuts across the plains at the border between Nebraska and South Dakota and runs south along Nebraska's eastern border, forming wide **floodplains** that support a complex environment of sandbars and wetlands (*Figure 4.9*).

Figure 4.9: Sandbars in the Missouri River, viewed from Mulberry Bend Scenic Outlook near Dixon, Nebraska.

pre-Illinoian glaciation *• a grouping of the Midwestern glacial periods that occurred before the Wisconsinian and Illinoian glaciations.*

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

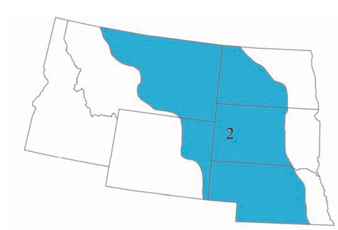
floodplain *• the land around a river that is prone to flooding.*

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

Topography of the Great Plains
Region 2

The Great Plains is a lowland area underlain by flat-lying sedimentary rocks, and located between the Central Lowland and Rocky Mountain regions. Despite its name, the Great Plains region is not entirely flat, changing in elevation from 1830 meters (6000 feet) on its western edge to 460 meters (1500 feet) on its eastern edge. The Black Hills and the Sand Hills are hilly areas in the western and southern parts of the Great Plains, and the Badlands (located in the central part of the Great Plains) contain tall cliffs, plateaus, and deep canyons. The Great Plains' physiographic subdivisions include the Missouri Plateau, the Black Hills, and the High Plains (*Figure 4.10*). The Missouri Plateau can be further divided into glaciated and unglaciated sections; the Plains Border, a subsection of the High Plains, extends from Nebraska into Kansas.

Similarly to the Central Lowland, the Great Plains region has a **basement** of flat-lying Precambrian metamorphic and igneous rocks, overlain by Paleozoic and Mesozoic sedimentary rocks. The Mesozoic sediments consist largely of materials eroded from the Rocky and Ozark mountains and deposited in the Western Interior Seaway, which covered this area during the Cretaceous. Today, the Missouri River runs through this region (*Figure 4.11*), where it both deposits



4

Topography

Region 2

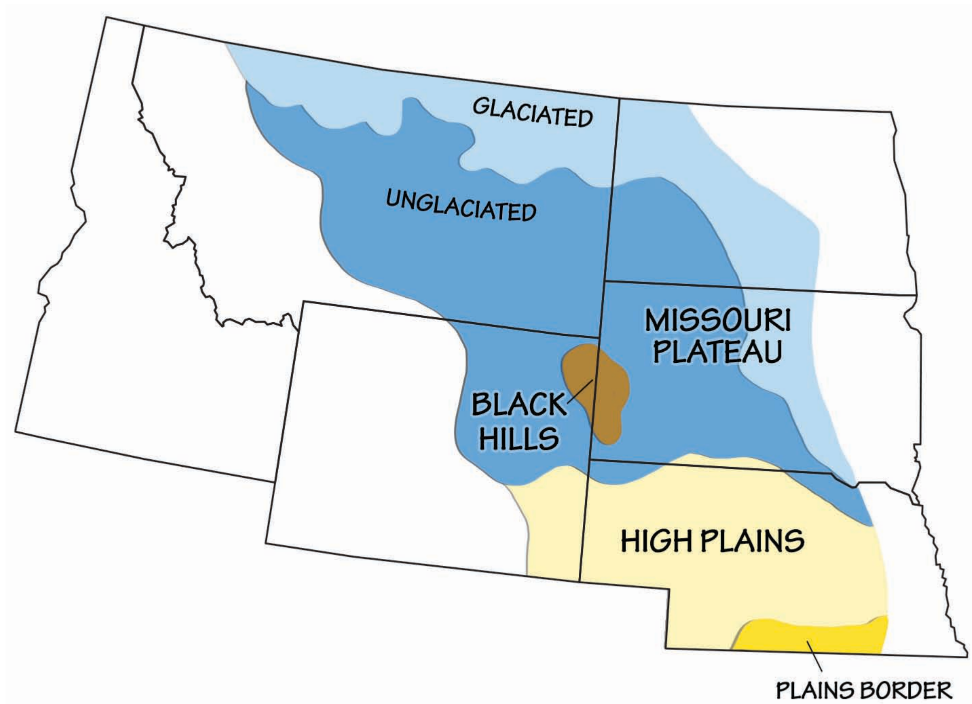
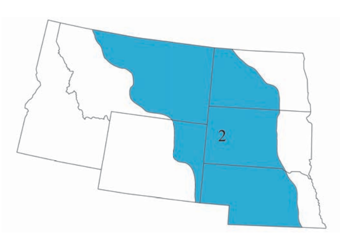


Figure 4.10: The physiographic regions of the Great Plains.

Figure 4.11: The Missouri River watershed. (See TFG website for full-color version.)



and erodes sediments. Glacial sediments can be found in the northern Great Plains, which was covered by ice sheets during the last glaciation. Additionally, some glacial sediment has been transported southward by the Missouri River and its tributaries.

The Missouri Plateau

The unglaciated portion of this area is a rugged expanse of semiarid terrain characterized by landforms sculpted from eroded sedimentary rock and glacial sediment, including **badlands** and dunes. Older surface features such as **buttes** and well-developed river systems also provide breaks in the generally flat topography. A butte can form when resistant **capstone** allows for the surrounding rock to be eroded away at a faster pace than the rock beneath the resistant layers (*Figure 4.12*). Over time, the differing rates of erosion will create a flat-topped hill with steep slopes. Such formations are a hallmark of an old erosional surface, since large buttes often take millions of years to form. On the Missouri Plateau, these topographical features are created from sedimentary rock that formed during erosional and depositional events associated with the uplift of the Rocky Mountains and the sedimentation of the Western Interior Seaway.

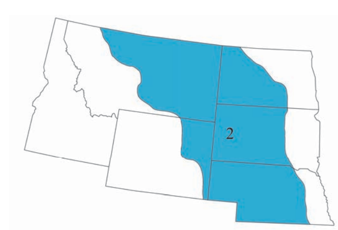
badlands • *a type of eroded topography that forms in semi-arid areas experiencing occasional periods of heavy rainfall.*

butte • *an isolated hill with steep, often vertical sides and a small, relatively flat top.*

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

Figure 4.12: Red Butte, near Casper, Wyoming, rises high above the easily erodible red Spearfish Shale thanks to a resistant capstone of white gypsum.

Badland topography forms in semiarid areas that experience occasional periods of heavy rainfall. Here, sloping ground composed of sandstones and calcareous sediments underlain by clay or other soft materials is eroded over time into an intricate series of gullies and ravines. Different layers of rock weather at different rates, resulting in a variety of sculpted spurs and buttresses. Harder layers crop out of softer sediments to form ledges, and isolated erosion-resistant patches



fossil • *preserved evidence of ancient life.*

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

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

porosity • *the percentage of openings in a body of rock such as pores, joints, channels, and other cavities, in which gases or liquids may be trapped or migrate through.*

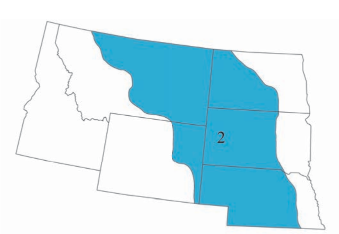
protect the sediments beneath, forming tall pillars of softer rock with a hard capstone. In the Northwest Central US, badlands can be found in Wyoming, Nebraska, Montana, and the western Dakotas, and are well known for their mammal **fossils**. Several scenic badlands areas have been set aside as protected land, including Theodore Roosevelt National Park in North Dakota (*Figure 4.13*), Badlands National Park in South Dakota (*Figure 4.14*), Makoshika State Park in Montana, and Toadstool Geologic Park in Nebraska.

See Chapter 3: Fossils for more information about the mammal fossils of the Great Plains.

Figure 4.13: Badlands in Theodore Roosevelt National Park, Billings and McKenzie counties, North Dakota.

The Sandhills of Nebraska are **sand** dunes that were created by wind-blown glacial material (*Figure 4.15*). During the last glaciation in the late **Pleistocene**, winds blowing along the edge of the ice sheet concentrated layers of sand and glacial loess in central Nebraska. This unique area, which covers 52,000 square kilometers (20,000 square miles), is the largest sand dune formation in the country. The dunes' **porous** composition allows them to absorb rainwater, helping to recharge the Ogalalla Aquifer that underlies the area and supplies fresh water to much of Nebraska.

See Chapter 10: Earth Hazards to learn about the effects of agriculture and drought on the Ogalalla Aquifer.



Region 2

Figure 4.14: Badlands National Park, near Jackson, South Dakota.

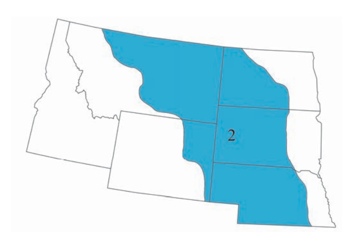
Figure 4.15: The Sandhills in Hooker County, Nebraska, as seen from Nebraska Highway 97.

The glaciated portion of the Missouri Plateau contains typical glacial features such as **moraines** and **kettle** ponds. The Prairie Pothole Region, an expanse of tallgrass prairie filled with thousands of shallow **pothole** wetlands (*Figure 4.16*), covers most of this area, extending from Alberta and Saskatchewan all the way down into Iowa. These potholes were formed as a result of glacial activity during the Wisconsinian glaciation, and the wetlands they support provide a haven for more than 50% of North America's migratory waterfowl. Today, however, more than half of the Prairie Pothole Region has been drained and converted for use in agriculture.

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

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

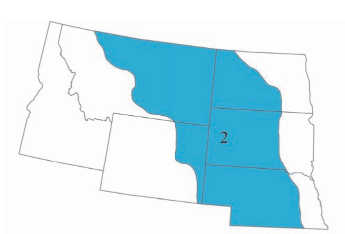
pothole *• a shallow, rounded depression eroded in bedrock by a glacier.*



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

Figure 4.16: Prairie pothole terrain near Wing, North Dakota.

Figure 4.17: The Black Hills of South Dakota, as viewed from Harney Peak.



The Black Hills

The Black Hills are an isolated mountain range that outcrops within western South Dakota and northeast Wyoming (*Figure 4.17*). The mountains contain a core of 1.8-billion-year-old Precambrian **granite**, generated during the formation of the North American craton. This core is surrounded by a ring of metamorphic

relief *• the change in elevation over a distance.*

compression *• flattening or squeezing as a result of forces acting on an object from all or most directions.*

Sevier Orogeny *• a mountain-building event resulting from subduction along the western edge of North America, occurring mainly during the Cretaceous.*

rock and layers of Paleozoic and Mesozoic sediment, including sandstone and limestone. The Black Hills were uplifted during the Cretaceous, as the Laramide Orogeny warped the landscape. Since then, the softer overlying sediment has been largely eroded, exposing remnants of the mountains' granitic core. This granite has been used as the base material for two notable sculptures: Mount Rushmore and the Crazy Horse Memorial. The highest elevation in the Black Hills is Harney Peak, which stands at 2208 meters (7244 feet) above sea level.

The High Plains

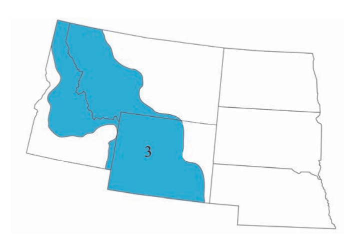
The High Plains, part of the vast North American Interior Plains, is a low area with flat **relief** that reflects 500 million years of cratonic stability in the continent's interior. Much of this area was submerged by the Cretaceous Western Interior Seaway, leading to the deposition of sediment that overlies the area's igneous and metamorphic core.

Topography of the Rocky Mountains

Region 3

The Rocky Mountain region, west of the Great Plains, is divided into the Northern, Middle, and Southern Rockies as well as the Wyoming Basin (*Figure 4.18*). The Rocky Mountains, which extend north into Canada and south into New Mexico, formed during the late Mesozoic when crustal **compression** led to deformation and thrust faulting. The mountains consist of igneous, sedimentary, and metamorphic rocks that were uplifted during the **Sevier** and Laramide orogenies, around 80 to 55 million years ago. Today, the tallest mountains in the Rockies are found in the state of Colorado, where over 50 mountains have an elevation greater than 4270 meters (14,000 feet). In the Northwest Central,

Figure 4.18: Physiographic subregions of the Rocky Mountains.



downwarp *• a segment of the Earth's crust that is broadly bent downward.*

intermontane *• between or among mountains.*

watershed *• an area of land from which all water under or on it drains to the same location.*

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

Figure 4.19: The Grand Tetons, some of the tallest mountains in Wyoming, as viewed from the Snake River Overlook. Grand Teton, the highest peak, is 4199 meters (13,775 feet) in elevation.

however, the tallest of the Rockies are located in Wyoming (*Figure 4.19*), where five peaks have an elevation of over 4000 meters (13,120 feet).

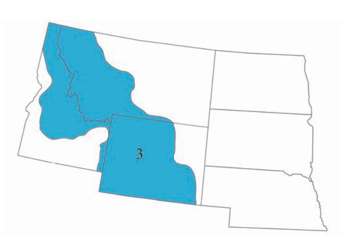
The Rocky Mountains have undergone extensive erosion thanks to the forces of weathering and glaciation. During the Cenozoic, thousands of feet of sediment were eroded from the Rockies and transported eastward into adjacent basins, which formed as a result of **downwarping** during the mountains' formation. The erosion of the Rockies has filled these basins, forming many flat-lying **intermontane** areas. Glacial erosion during the Quaternary created the jagged peaks and bowls that we see today.

The Continental Divide runs along the crest of the Rocky Mountains. It separates North America's **watersheds** into those that flow east and south into the Atlantic Ocean and the Gulf of Mexico, and those that flow west toward the Pacific Ocean.

A *hydrological divide* is a boundary between two drainage basins or watersheds.

The Northern Rocky Mountains

The Northern Rocky Mountains are found in northeastern Washington, northern Idaho, western Montana and northwestern Wyoming. These mountains are lower than those to the south, reaching heights of around 3660 meters (12,000 feet). In Idaho and western Montana, the Northern Rockies are composed of a series of mountain ranges, including the Clearwater, White Cloud, Salmon River, Sawtooth, and Lost River mountains. These ranges formed as a result of the uplift and erosion of the Idaho Batholith, a mass of granitic **plutons**



that formed during the Cretaceous when the oceanic Farallon plate subducted beneath the west coast of North America. The **batholith**, which underlies about 39,900 square kilometers (15,400 square miles) of central Idaho (*Figure 4.20*), was uplifted and exposed between 65 and 50 million years ago. Since then, weathering and erosion have sculpted the batholith's granitic rock into rough peaks (*Figure 4.21*).

batholith • *a large exposed structure of intrusive igneous rock that solidified at depth, and covers an area of over 100 square kilometers (40 square miles).*

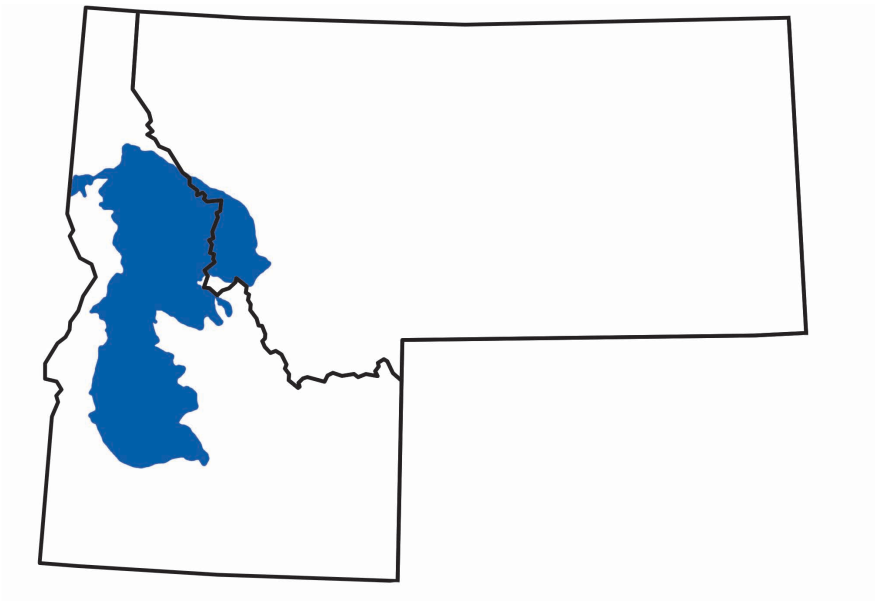


Figure 4.20: Extent of the Idaho Batholith.

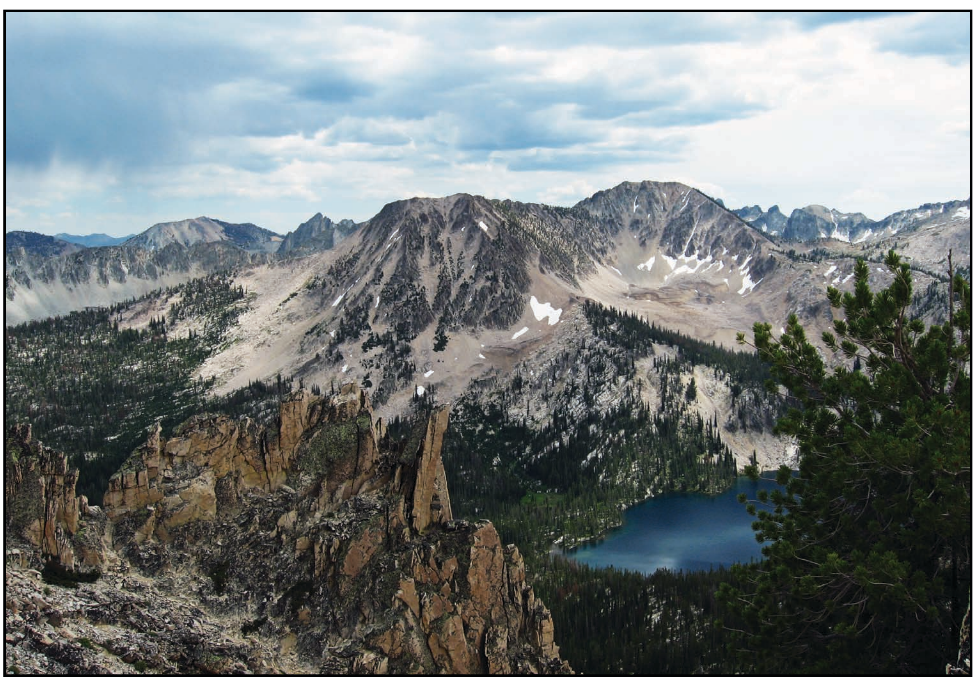
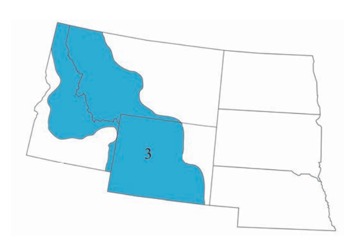


Figure 4.21: The Sawtooth Mountains above Toxaway Lake in the Sawtooth Wilderness, Idaho. These mountains are formed of granite from the Idaho Batholith.



The Northern Rocky Mountains of Montana are also home to the Cordilleran fold-and-thrust belt, an area of deformed rock created by crustal compression during the collision of the oceanic Farallon plate with the North American plate. Blocks of older rock were thrust forward on top of younger strata, resulting in the Lewis Overthrust, a 320-kilometer-long (200-mile-long) overthrust fault that extends from central Montana into southern Alberta, Canada. Glacier National Park in northern Montana contains many outcrops related to this fault belt, including the 2770-meter-high (9080-foot-high) Chief Mountain (*Figure 4.22*).

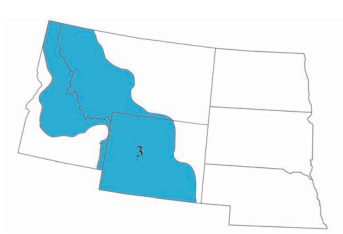
Figure 4.22: Chief Mountain, located in Montana's Glacier National Park, is a block of Precambrian rock that rests directly atop younger Cretaceous shales as a result of thrust faulting along the Lewis Overthrust. The surrounding thrust sheet has been eroded, leaving behind the mountain as an isolated block.

The Middle Rocky Mountains

The Middle Rocky Mountains consist of multiple mountain ranges, including the Wasatch, Teton, Absaroka, Bighorn, and Wind River mountains.

The Wasatch and Teton mountains were uplifted during the Cenozoic as a result of faulting, possibly due to processes related to extension in the Basin and Range region. Both ranges stretch in a north-south direction, and both border the Basin and Range: the Tetons stretch along the border of Wyoming and Idaho, and the Wasatch Range extends from the southeastern edge of Idaho down through Utah. The Wasatch Mountains (called the Bear River Mountains where they enter Idaho) formed from Cretaceous thrust faulting and the erosion of granitic batholiths followed by more recent uplift. The Teton Mountains are the

See Region 5: Basin and Range later in this chapter to learn more about the unique processes that formed its topography.



youngest range in the Rockies, formed as the rocks along one side of a normal fault were uplifted due to crustal extension between nine and six million years ago. Rocks along the other side of the fault were downdropped, creating a valley that is today known as Jackson Hole. Thanks to the fault at the base of the range, the Tetons lack foothills on their eastern side, and rise sharply up to 2100 meters (7000 feet) above the valley floor.

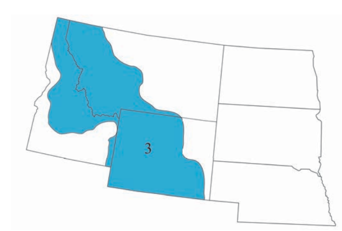
The Bighorn and Wind River mountains both have Precambrian rocks at their cores, with overlying Paleozoic and Mesozoic sedimentary rocks that were uplifted and exposed during the Cretaceous. The Wind River Mountains, formed by Mesozoic-Cenozoic thrust faulting, are the highest mountains in Wyoming with 40 peaks standing over 3960 meters (13,000 feet) high. Fault lines also cut through the flanks of the Bighorns, and the range's western face is pierced by gorges (*Figure 4.23*).

Figure 4.23: Tensleep Canyon, Washakie County, Wyoming.

The Absaroka Range stretches across the Montana-Wyoming border, and forms the eastern boundary of Yellowstone National Park. The Absarokas are the remnants of a 23,000-square-kilometer (9,000-square-mile) **Eocene** volcanic field filled with poorly consolidated volcanic debris, igneous intrusions, and tuffs. These volcanic rocks are not related to igneous activity at the Yellowstone **hot spot**, which occurred more recently. This largely looser material has been easily eroded over time, leading to the Absarokas' steep slopes and sharp, jagged topography (*Figure 4.24*). While much of the range was covered in ice during the last glaciation, weathering has destroyed most remnants of glacial landforms.

Eocene *• a geologic time period extending from 56 to 33 million years ago.*

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



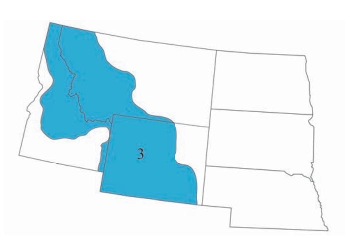
__mantle__ • the layer of the Earth between the crust and core.

__heat__ • a form of energy transferred from one body to another as a result of a difference in temperature or a change in phase.

Figure 4.24: An aerial view of the Absaroka Range near Livingston, Montana.

The Yellowstone Plateau is found in the Middle Rockies of western Wyoming, and is the location of Yellowstone National Park and the Yellowstone hot spot. Hot spots can occur under both continental and oceanic crust, and they provide evidence that the Earth's tectonic plates move. Since hot spots are nearly stationary in the **mantle**, they remain in place as the plates slowly move over them, forming a chain of volcanic features that increase in age as one moves away from the hot spot. North America first overlapped with the Yellowstone hot spot in what is now Washington State, where it is thought to have produced the Columbia River flood basalts. As the North American plate continued to move, the hot spot wound up beneath the current Oregon-Nevada border, and began to generate a succession of violent, caldera-producing explosions interspersed with calmer basalt flows. We can easily trace the continent's movement by following the path of calderas across Idaho to the northwestern corner of Wyoming and Yellowstone National Park (*Figure 4.25*). The most recent Yellowstone caldera was produced by an explosive volcanic eruption 630,000 years ago (*Figure 4.26*). Geothermal activity continues in the area today, as evidenced by geysers, hot springs, steam vents, and mud volcanoes.

Geysers and other water features form from the circulation of hot groundwater, channeled through fracture zones from the ancient Yellowstone eruptions. Magma from the Yellowstone hot spot heats up the overlying rocks and the water that flows through them. The fracture zones connect this underground **heat** source to the surface and produce geysers (*Figure 4.27*), hot springs (*Figure 4.28*), steam vents, and mud volcanoes.



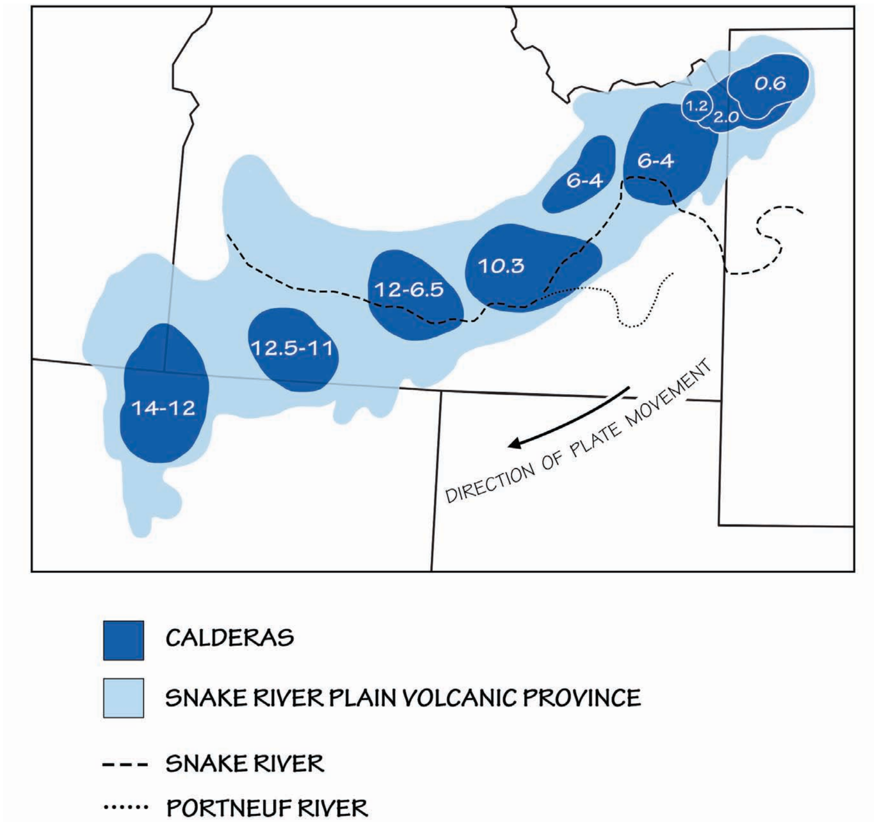
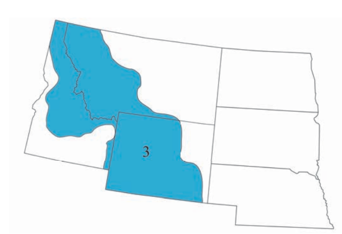


Figure 4.25: The path of the Yellowstone hot spot over the past 16 million years, including the Snake River Plain (part of the Columbia Plateau region) and Yellowstone National Park. During this time, the North American plate has been moving southwest over the hot spot.

system • *a set of connected things or parts forming a complex whole.*

How do geysers work?

When superheated water enters underground fractures, it becomes highly pressurized, preventing it from cooling. The fractures that create geysers contain a restriction near the surface that prevents water from circulating to the surface and diffusing heat, as in a hot spring. If a deep pocket of water begins to bubble, causing water to leak out of the fracture's mouth, pressure in the *system* is reduced. The water flashes into steam, and the geyser erupts; after the eruption is over, the process of pressurization begins again.



Topography

Region 3

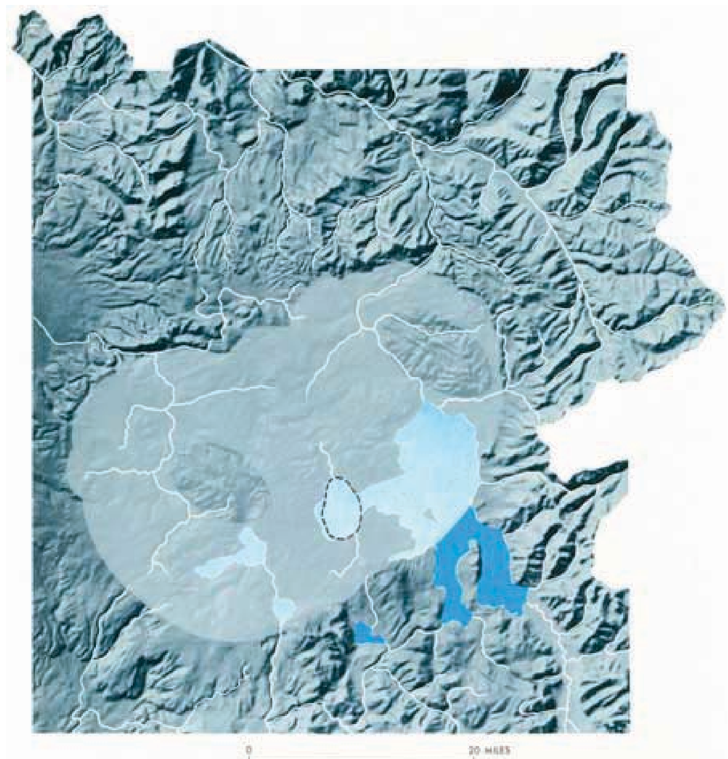
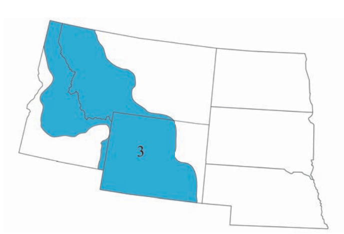


Figure 4.26: Extent of the Yellowstone caldera in Yellowstone National Park (Wyoming, overlapping into Montana and Idaho), created 630,000 years ago. The small area enclosed by the dotted line represents a small, younger caldera created during an eruption 174,000 years ago, and now filled by part of Yellowstone Lake.

Figure 4.27: Old Faithful geyser erupting at Yellowstone National Park. The geyser is one of the most predictable in the world, with intervals of 60 to 90 minutes between each eruption, which can shoot 32,000 liters (8400 gallons) of boiling water as high as 56 meters (185 feet) and last for up to five minutes.



Region 3

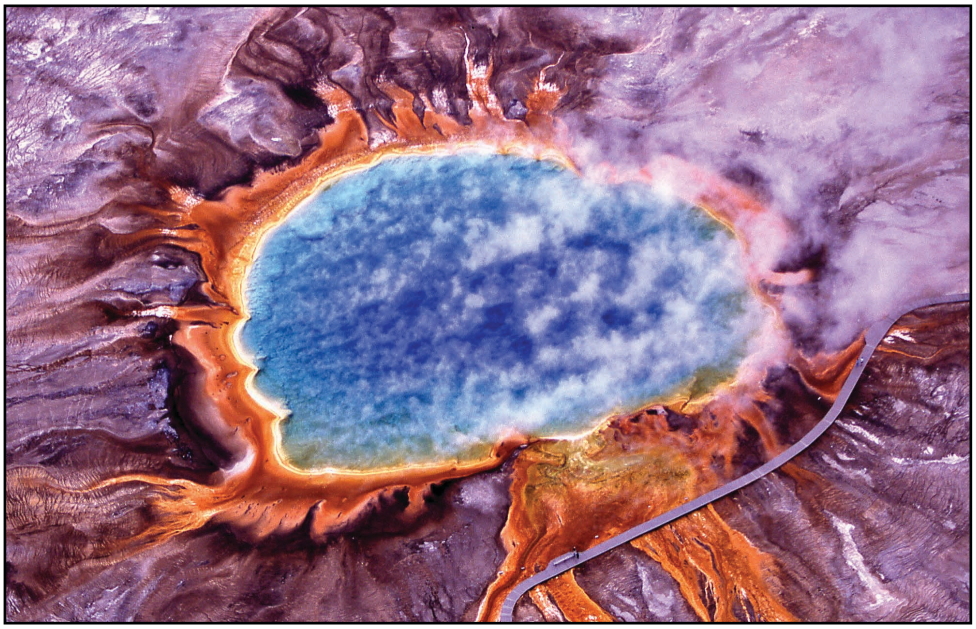


Figure 4.28: An aerial view of the Grand Prismatic Spring at Yellowstone National Park, the largest hot spring in North America, with an average diameter of 85 meters (275 feet). The spring's bright colors are caused by bacteria that live in the water.

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

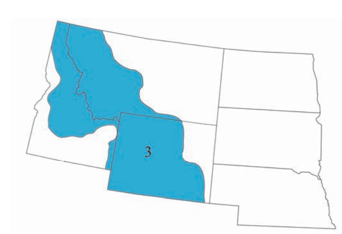
hectare *• a metric unit of area defined as 10,000 square meters.*

The Wyoming Basin

The Wyoming Basin is one of many intermontane basins that formed during the uplift of the Rocky Mountains. When the Rockies underwent weathering and erosion, layers of sediment thousands of feet thick were deposited in these basins.

The Wyoming Basin is particularly notable because it contains the Great Divide Basin—a major closed drainage basin, or area of land from which water does not drain into an ocean, but rather is retained and diffuses out by evaporation or seepage. This basin straddles the Continental Divide, and includes the Red Desert, an arid steppe and desert landscape encompassing 24,000 square kilometers (9320 square miles) of south central Wyoming. The desert receives only about 20 centimeters (8 inches) of annual precipitation, and most of its water comes from melting snowpack in the spring. This brief influx of moisture forms standing water that leads to temporary wetlands, intermittent streams, and mud flats in wet years, and which evaporates to form **salt** pans during drought. The Red Desert also contains the Killpecker Sand Dunes, one of North America's largest dune fields, spanning 44,110 **hectares** (109,000 acres) of the Great Divide Basin (*Figure 4.29*). The dunes formed from glacial sediments that collected along the banks of the Big Sandy and Little Sandy rivers to the northeast. Over the past 20,000 years, westerly winds have moved the sand toward its present location.

Winds are named for the direction from which they originate. For example, a "westerly wind" blows from the west and moves toward the east.



Regions 3–4

stromatolite • *regularly banded accumulations of sediment created by the trapping and cementation of sediment grains in bacterial mats.*

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

Figure 4.29: An aerial view of the Killpecker Sand Dunes in Wyoming.

The Southern Rocky Mountains

The bulk of the Southern Rockies are located in Colorado and New Mexico, and only three small prongs extend north into Wyoming, east of the Wyoming Basin. These are the Laramie Mountains, the Medicine Bow Mountains, and the Sierra Madre. All three ranges consist of a core of uplifted Precambrian metamorphic rock flanked by younger sedimentary strata. The Medicine Bow Mountains contain abundant **stromatolite** remains.

See Chapter 2: Rocks to learn more about stromatolites.

Topography of the Columbia Plateau
Region 4

The Columbia Plateau lies to the west of the Rocky Mountains in eastern Washington, Oregon, and Idaho. This region, also called the Columbia Basin, is a broad, volcanic plain composed of basalt. Basalt solidifies from **lavas** that are very fluid when hot, and the basalt lava in this area erupted along a series of fractures in eastern Oregon between 17 and 14 million years ago. The basalt was so voluminous and fluid that it completely filled the preexisting topography, forming a broad, flat plain that tilts downward to the west. Geologists believe that some of these lava flows were 30 meters (100 feet) high, and flowed at speeds of up to 5 kilometers (3 miles) per hour. The Columbia Plateau also includes an area of volcanic materials erupted from the Yellowstone hot spot onto the relatively flat Snake River Plain. In the Northwest Central, the Columbia Plateau can be divided into the Walla Walla Plateau, the Payette Section, and the Snake River Plain (*Figure 4.30*).

See Chapter 3: Fossils to learn more about the Clarkia Lake flora, a Columbia Plateau lagerstätte in Idaho.

cinder • *a type of pyroclastic particle in the form of gas-rich lava droplets that cool as they fall.*

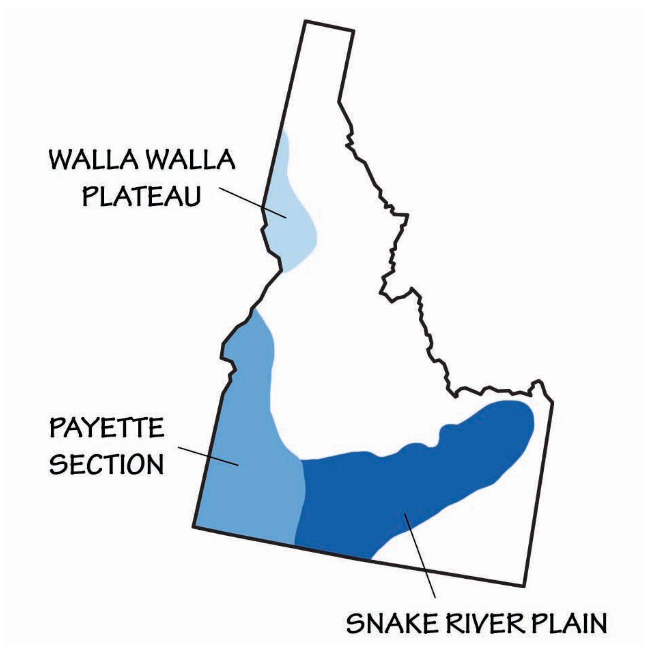


Figure 4.30: Physiographic subregions of the Columbia Plateau.

The Walla Walla Plateau is covered by flood basalt, and, in fact, one basalt flow in western Idaho, the Imnaha basalt, is 900 meters (2950 feet) thick. Some rivers were able to cut through the basalt, forming deep canyons (*Figure 4.31*). The presence and thickness of sediment varies on this plateau since some of the small rivers in this area were dammed by the basalt flows, forming lakes where sedimentation could occur. In some places, thick layers of wind-blown glacial sediment were deposited, eroding to form hills.

See Chapter 2: Rocks for more information about flood basalts.

The Payette Section is a flat-lying area dominated by the drainage basin of the Payette River (a tributary of the Snake River with two major tributaries of its own: the North and South forks). The Snake River Plain is a low-lying, relatively

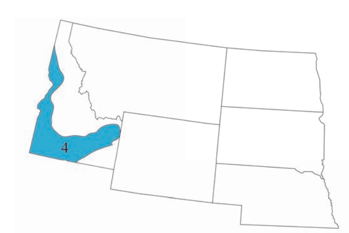


Figure 4.31: Hells Canyon, near Wallowa along the Oregon-Idaho border, cuts deeply through the Columbia Flood Basalt.

flat area underlain by volcanic rocks. This low-lying area, formed from eruptions of the Yellowstone hot spot as the North American plate moved westward (*see Figure 4.25*), forms an obvious feature on maps and satellite imagery. The majority of the features on the plain's surface are lava flows and **cinder** cones, with a few volcanic domes (*Figure 4.32*). As one moves toward the western edge of the Snake River Plain, ash flows and tuff become more common.

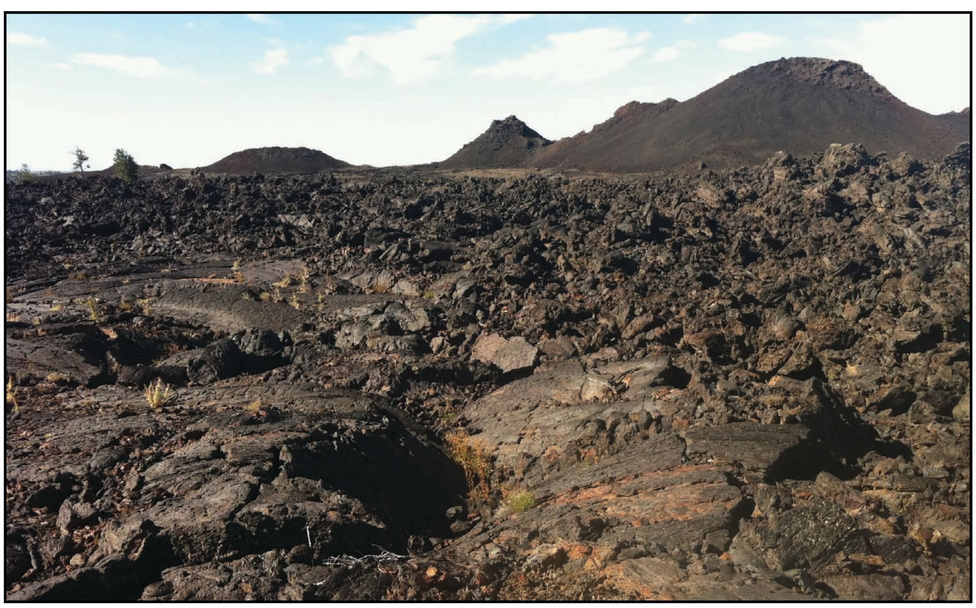


Figure 4.32: Craters of the Moon National Monument encompasses three major lava fields, spanning about 1000 square kilometers (400 square miles) along Idaho's Snake River Plain. The area's volcanic features include volcanic domes, basaltic flows, lava tubes, open rifts, and ash flows.

Region 5

Topography of the Basin and Range
Region 5

Only a small portion of the Basin and Range is found in the Northwest Central US, located in the southeastern corner of Idaho. The entire Basin and Range region stretches from Idaho through all of Nevada, southeastern California, and southeastern Oregon, and reaches as far as western Texas.

The Basin and Range is characterized by rapid changes in elevation alternating from flat and dry basins to narrow and faulted mountains. This pattern of many parallel, north-south mountain ranges found throughout the region inspired geologist Clarence Dutton to famously observe that the topography of the Basin and Range appeared "like an army of caterpillars crawling northward. "The formation of this topography is directly related to tectonic forces that led to crustal extension (pulling of the crust in opposite directions). After the Laramide Orogeny ended in the **Paleogene**, tectonic processes stretched and broke the crust, and the upward movement of magma weakened the **lithosphere** from underneath. Around 20 million years ago, the crust along the Basin and Range stretched, thinned, and faulted into some 400 mountain blocks. The pressure of the mantle below uplifted some blocks, creating elongated peaks and leaving the lower blocks below to form down-dropped valleys. The boundaries between the mountains and valleys are very sharp, both because of the straight faults between them and because many of those faults are still active.

These peaks and valleys are also called horst and graben landscapes (*Figure 4.33*). Such landscapes frequently appear in areas where crustal extension occurs, and the Basin and Range is often cited as a classic example thereof. In the Basin and Range, the crust has been stretched by up to 100% of its original width. As a result of this extension, the average crustal thickness of the

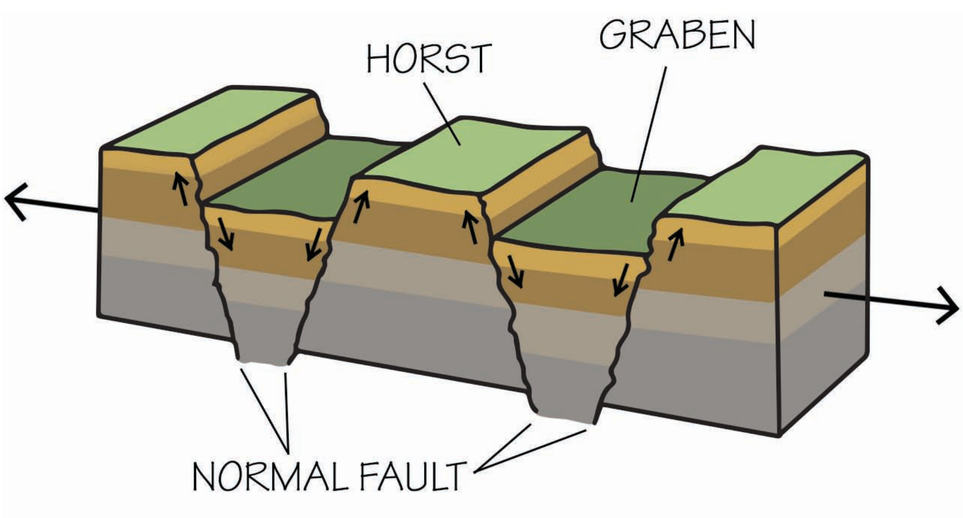


Figure 4.33: A horst and graben landscape occurs when the crust stretches, creating blocks of lithosphere that are uplifted at angled fault lines.

Paleogene *• the geologic time period extending from 66 to 23 million years ago.*

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

Elevations

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

magnitude (earthquake) • *a logarithmic scale used to measure the seismic energy released by an earthquake. Magnitudes range from 1 to 10, with M3 earthquakes classed as minor and earthquakes of M8 or greater being classified as great.*

Figure 4.34: The Portneuf Range, Bannock County, Idaho.

Basin and Range region is 30–35 kilometers (19–22 miles), compared with a worldwide average of around 40 kilometers (25 miles).

In Idaho, the Basin and Range encompasses long, parallel mountain ranges, including the Bannock and Portneuf ranges (*Figure 4.34*). The crustal extension of the Basin and Range has increased strain and tension throughout the region, leading to a dynamic variety of active fault zones that create an abundance of **earthquakes**.

See Chapter 10: Earth Hazards for more information about earthquakes in Idaho.

Highest and Lowest Elevations (by State)

Idaho

Idaho's highest point is Borah Peak, a 3861-meter-high (12,668-foot-high) mountain in the central Lost River Range, Custer County. The mountain was named in 1937 for Idaho senator William Borah, who had been in office for almost 27 years. In 2010, a **magnitude** 7.1 earthquake rocked Borah Peak, lifting it an additional two meters (seven feet) and scarring its west face. The Snake River in Nez Perce County is Idaho's lowest point, flowing at 216 meters (710 feet) above sea level.

Montana

At 3904 meters (12,807 feet) in elevation, Granite Peak is Montana's highest point and a popular mountain climbing destination. The mountain, part of the Beartooth range located 16 kilometers (10 miles) north of the Wyoming border, is considered the second most difficult state high point to climb. At the Montana-Idaho border, the Kootenai River tumbles over Kootenai Falls to land at an elevation of 555 meters (1820 feet), Montana's lowest point.

Elevations

Nebraska

Panorama Point, located near the juncture of Colorado, Nebraska, and Wyoming, is the state's highest point, with an elevation of 1655 meters (5,429 feet). Despite its name, this "point" is neither a peak nor a hill, but simply a rolling portion of the High Plains, marked only by an engraved stone and guest register. Nebraska's lowest point, at 256 meters (840 feet) above sea level, is located along the Missouri River in Richardson County.

North Dakota

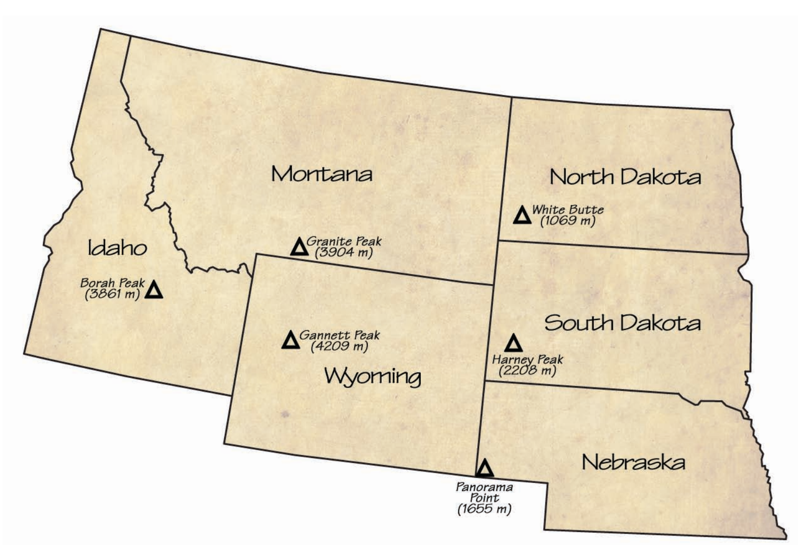
White Butte, located in North Dakota's southwestern badlands, is the highest point in the state, rising to 1069 meters (3506 feet) in elevation. The butte, about 10 kilometers (6.5 miles) south of the town of Amidon, is on privately owned land, but a trail allows visitors to access the landmark. The lowest part of North Dakota, at 229 meters (751 feet) in elevation, is found along the Red River where it flows into Manitoba.

South Dakota

South Dakota's highest point is Harney Peak, an exposed granitic edifice in the Black Hills just six kilometers (four miles) southwest of Mount Rushmore. The mountain, which has an elevation of 2208 meters (7244 feet), was first seen by European-Americans when General George Armstrong Custer climbed it in 1874. South Dakota's lowest point is Big Stone Lake, which lies at 294 meters (965 feet) above sea level and is located in the northeastern corner of the state on the Minnesota border.

Wyoming

Rising to an elevation of 4209 meters (13,809 feet) above sea level, Gannett Peak is the highest point in Wyoming—and the entire Northwest Central—as well as the highest mountain in the Rockies outside of Colorado. Gannett Glacier, the largest glacier in the American Rocky Mountains, flows from Gannett Peak's north slopes. The Belle Fourche River, which reaches an elevation of 945 meters (3099 feet) at the South Dakota border, is Wyoming's lowest point.



Resources

Books

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Trimble, D. E., 1980, *The Geologic Story of the Great Plain*, US Geological Survey Bulletin 1493, http://library.ndsu.edu/exhibits/text/greatplains/text.html.

Wyckoff, J., 1999, *Reading the Earth: Landforms in the Making*, Adastra West, Mahwah, NJ, 352 pp.

Maps

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

Topoquest, https://www.topoquest.com/.

Websites

Basin and Range Physiographic Province, National Park Service, http://www.nature.nps.gov/geology/education/concepts/concepts_basinrange.cfm. (Includes Idaho.)

Colorado Plateaus Province, National Park Service, http://www.nature.nps.gov/geology/education/concepts/concepts_coloradoplateau.cfm.

OpenLandform Catalog, Education Resources, OpenTopography, http://www.opentopography.org/index.php/resources/lidarlandforms. (High resolution topographic images that may be useful in teaching.)

Rocky Mountain System Physiographic Provinces, National Park Service, http://www.nature.nps.gov/geology/education/concepts/concepts_rockies.cfm.

South Dakota's Physiographic Regions, by Douglas Malo, http://www3.northern.edu/natsource/EARTH/Physio1.htm.

Teaching Geomorphology in the 21st Century, On the Cutting Edge, Strong Undergraduate Geoscience Teaching, SERC, http://serc.carleton.edu/NAGTWorkshops/geomorph/index.html. (A set of resources for college level, some of which may be adaptable to secondary education.)

Teaching with Google Earth, On the Cutting Edge, Starting Point: Teaching Entry Level Geoscience, SERC, http://serc.carleton.edu/introgeo/google_earth/index.html.

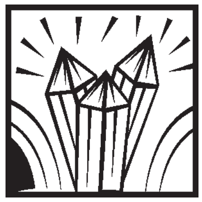
United States Geography, by S. S. Birdsall & J. Florin, http://countrystudies.us/united-states/geography.htm.

State-based Resources

No Ordinary Plain: North Dakota's Physiography and Landforms, by John Bluemle and Bob Biek, 2007, North Dakota Geological Survey Notes 1, https://www.dmr.nd.gov/ndgs/ndnotes/ndn1.asp.

North Dakota's Mountainous Areas: The Killdeer Mountains and the Turtle Mountains, by John Bluemle, 2002, North Dakota Geological Survey Notes 15, https://www.dmr.nd.gov/ndgs/ndnotes/ndn15-h.htm.

The Origin of Landscape: A Guide to Wyoming's Cultural Geology, http://www.wsgs.wyo.gov/public-info/cultural-geology.



Chapter 5: Mineral Resources of the Northwest Central US

What is a mineral?

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

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. In contrast, **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**.

Several thousand minerals have been discovered and classified according to their chemical composition. Most of them are **silicates** (representing approximately a thousand different minerals, of which quartz and feldspar are two of the most common and familiar), which are made of silicon and oxygen combined with other elements (with the exception of quartz, SiO_2). **Carbonate rocks** are made of carbon and oxygen combined with a metallic element; **calcium carbonate** ($CaCO_3$) is the most common example, and most of it today originates as skeletal material precipitated by organisms. Other mineral categories include native elements (such as gold), oxides and **sulfur**-bearing minerals, and **salts**.

Metallic minerals are vital to the machinery and technology of modern civilization. However, many metals occur in the **crust** in amounts that can only be measured in parts per million (ppm) or parts per billion (ppb). A mineral is called an **ore** when one or more of its elements can be profitably removed, and it is almost always necessary to process ore minerals in order to isolate the useful element. 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. Ores are not uniformly distributed in the crust of the Earth, but instead occur in localized areas where they are concentrated in amounts sufficient for being economically extracted by mining.

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.*

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

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

cementation • *the precipitation of minerals that binds together particles of rock, bones, etc., to form a solid mass of sedimentary rock.*

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

silica • *a chemical compound also known as silicon dioxide (SiO_2).*

CHAPTER AUTHORS

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

gold • *a soft, yellow, corrosion-resistant element (Au), which is the most malleable and ductile metal on Earth.*

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

silver • *a metallic chemical element (Ag).*

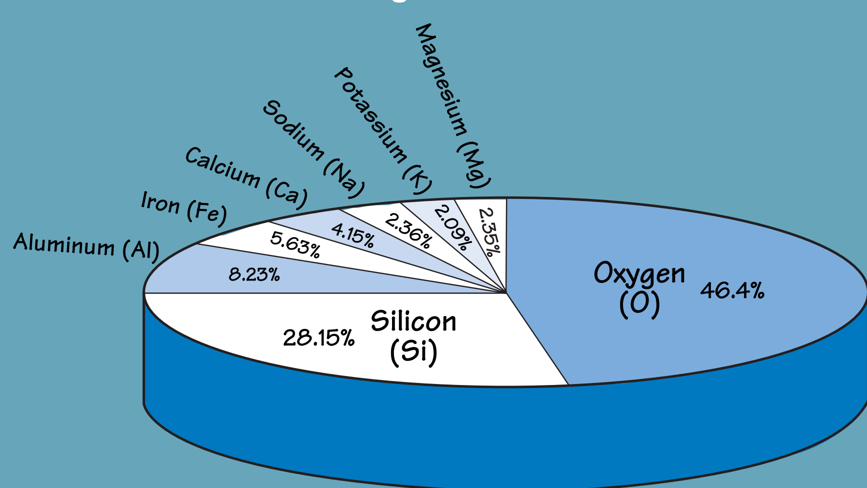
feldspar • *an extremely common, rock-forming mineral found in igneous, metamorphic and sedimentary rocks.*

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.*

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, and, in turn, is also a major component of many rocks. Most minerals present in nature are not composed of a single element, though there are exceptions such as *gold*. Elements such as *copper* (Cu), lead (Pb), zinc (Zn), and even *silver* (Ag), gold (Au), and diamond (C) are not rare, but they are usually widely dispersed through the rocks and occur at very low average concentrations. Eight elements make up (by weight) 99% of the Earth's crust, with oxygen being 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. Since silicon (Si) and oxygen (O) are the most abundant elements in the crust by mass, it makes sense for silicates (e.g., *feldspar*, quartz, and garnet) to be some of the most common minerals in the Earth's crust and to therefore be found throughout the Northwest Central.



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** ($CaSO \cdot 2H_2O$). Generally much lighter in color than metals, 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 determined when identifying a mineral, with each such property eliminating possible alternatives.

Hardness is a very useful property for identification, as a given mineral can only exhibit a narrow range of hardnesses, and since it is easily testable, this property can be used to quickly and simply minimize 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 the mineral **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 calcite. Quartz is a very common mineral in the Earth's crust, and it is quite resistant due to its hardness and relative insolubility. Thus, quartz grains are the dominant mineral type in nearly all types of **sand**.

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 the Mohs scale of hardness, and it remains very useful as a means for identifying minerals or for quickly determining their hardness. Everyday items can be used to determine hardness if the minerals in the scale are not available. These include a streak plate or piece of unglazed porcelain (hardness 7), a piece of glass (hardness 5), a penny (hardness 3), and a fingernail (hardness 2).

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

Color is helpful in identifying some minerals such as sulfur, but it is uninformative or even misleading in others such as garnet. **Luster** describes how light is reflected from a mineral's surface, and it can range from adamantine, seen in diamonds, to dull or earthy (effectively no luster), such as in **kaolinite**. **Crystal form**, if visible, can also 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, but instead display **fracture** when broken. For example, mica

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hardness • *a physical property of minerals, specifying how hard the mineral is.*

erosion • *the transport of weathered materials.*

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

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

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

color (mineral) • *a physical property determined by the presence and intensity of certain elements within the mineral.*

kaolinite • *a silicate clay mineral, also known as china clay.*

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

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 **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 Are Minerals Used For?

Mineral resources fall into many different categories, including industrial minerals, construction materials, **gemstones**, and metallic and non-metallic ores. Some minerals and rocks are abundant and are used in the construction industry or in the manufacturing of many of the products we commonly find in stores. Construction materials include **dimension stone** (e.g., sandstone, limestone, and granite), which is used for the exterior or interior of structures.

Minerals used in manufacturing include kaolinite for ceramics, gypsum for wallboard, fluorite for the fluoride in toothpaste, and halite for common table and rock salt. We also seek out specific rock types and sediment to use in the construction of buildings, highways, and bridges. Many of the statues in museums are commonly made of **marble**, **jade**, or **soapstone**. Granite, travertine, and other decorative stones are increasingly used to beautify our

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

luminescence • *the emission of light.*

radioactivity • *the emission of radiation by an unstable atom.*

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.*

gemstone • *a mineral that has been cut and polished for use as an ornament.*

dimension stone • *the commercial term applied to quarried blocks of rock cut to specific dimensions.*

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

home interiors and to make art, in addition to being used in public buildings. Some minerals are considered to be precious or semi-precious and are used in jewelry, including diamond and some crystalline forms of quartz.

What distinguishes a regular mineral from a gem?

Minerals are assigned to the category of gemstones based primarily on our interpretation of what has value. Typically, the 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. Not all gems are prized for these reasons; for example, scarcity may be artificially inflated, or a mineral may be valued for its unusual color.

Gemstones can be further categorized as precious or semi-precious stones. Precious stones, including diamond, topaz, and sapphire, are rare and translucent to light. They are more durable because they are hard, making them scratch resistant. On the Mohs scale of hardness, the majority of precious gemstones have values greater than 7. Semi-precious stones are generally softer, with hardness scale values between 5 and 7. The minerals peridot, jade, garnet, amethyst, citrine, rose quartz, tourmaline, and turquoise are examples of semi-precious stones that can be cut and used in jewelry.

Gems may have common names that differ from their geological ones, and these names may be dependent on mineral color. For example, the mineral *beryl* is also referred to as emerald, aquamarine, or morganite depending on its color. Corundum can also be called sapphire or ruby, and peridot is another name for *olivine*.

Metallic minerals have many applications and are used to manufacture many of the items we see and use every day. For example, iron comes from **hematite** and **magnetite**, and from it we make steel. **Lead**, from the mineral **galena**, is used in the manufacture of batteries and in the solder found in electronic devices. **Titanium**, from the mineral **ilmenite**, is used in airplanes, spacecraft, and even white nail polish. **Aluminum** comes from **bauxite** and is known for being both lightweight and strong—many of the parts that make up today's

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jade • *a word applied to two green minerals that look similar and have similar properties: jadeite (a kind of pyroxene) and nephrite (a kind of amphibole).*

soapstone • *a metamorphic schistose rock composed mostly of talc.*

beryl • *a white, blue, yellow, green, or pink mineral, found in coarse granites and igneous rocks.*

olivine • *an iron-magnesium silicate mineral ($(Mg,Fe)_2SiO_4$) that is a common constituent of magnesium-rich, silica-poor igneous rocks.*

hematite • *a mineral form of iron oxide (Fe_2O_3), with vivid red pigments that make it valuable as a commercial pigment.*

magnetite • *a mineral form of iron oxide (Fe_3O_4) with naturally occurring magnetic properties.*

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

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__magma__ • molten rock located below the surface of the Earth.

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

__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.

__felsic__ • igneous rocks with high silica content and low iron and magnesium content.

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

__mafic__ • igneous rocks that contain a group of dark-colored minerals, with relatively high concentrations of magnesium and iron.

automobiles are made of this metal. Copper comes from a variety of copper-bearing minerals, including chalcopyrite, and is used to make electrical wire, tubing, and pipe.

Mineral Formation

Economically recoverable mineral deposits are formed by geologic processes that can selectively concentrate desirable elements in a relatively small area. These processes may be physical or chemical, and they fall into four categories:

Magmatic processes separate minor elements of **magma** from the major elements and concentrate them in a small volume of rock. This may involve either the early crystallization of ore minerals from the magma while most other components remain molten or late crystallization after most other components have crystallized. Magmatic processes responsible for the formation of mineral deposits are usually associated with igneous **intrusions** (formed during mountain building events, **rifting**, and **volcanic** activity), which can range in composition from granite (**felsic**) to **gabbro** (**mafic**). **Metamorphism** may also cause **recrystallization** of minerals and concentration of rare elements. Under conditions of extreme high-temperature metamorphism, minerals with the lowest melting temperatures in the crust may melt to form small quantities of **pegmatite** magmas.

Hydrothermal processes involve **hydrothermal solutions** that dissolve minor elements dispersed through large volumes of rock, transport them to a new location, and precipitate them in a small area at a much higher concentration. Hydrothermal solutions are commonly salty, acidic, and range in temperature from over 600°C (~1100°F) to less than 60°C (140°F). Some of these fluids may travel very long distances through **permeable sedimentary rock**. Eventually, the hydrothermal fluids precipitate their highly dissolved load of elements, creating concentrated deposits.

Sedimentary processes gather elements dispersed through large volumes of water and precipitate them in a sedimentary environment, such as in sedimentary layers on the ocean floor or on lakebeds. Sedimentary mineral deposits form by direct precipitation from the water.

Weathering and erosion break down large volumes of rock by physical and chemical means and gather previously dispersed elements or minerals into highly concentrated deposits. **Residual weathering deposits** are mineral

A mineral is not necessarily restricted to one method of concentration or environment of formation. For example, economically important deposits of gypsum may form as a precipitate from evaporating water. However, gypsum formation may also be associated with volcanic regions where limestone and sulfur gases from the volcano have interacted, or from other areas as a product of the chemical weathering of *pyrite*.

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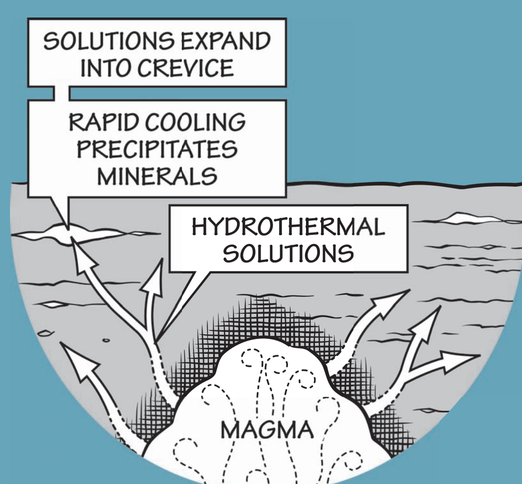
What are hydrothermal solutions?

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 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.

Hot water brines can have varying origins. Most bodies of magma contain mineral-enriched, superheated water, which is released into the surrounding rock as the magma cools. Rainwater can become a hydrothermal solution as it filters through rocks and picks up soluble materials along its path. 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.

Hydrothermal solutions move away from their source of heating through cracks, faults, and solution channels into the adjacent cooler rocks. As the water moves quickly through fractures and openings in the rock (where it experiences changes in pressure or composition and dilution with groundwater), it can cool rapidly. This rapid cooling over short distances allows concentrations of minerals to be deposited. When a hydrothermal solution cools sufficiently, the dissolved salts form a precipitate, leaving behind minerals in a vein or strata-bound deposit.



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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.

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

pegmatite • a very coarse-grained igneous rock that formed below the surface.

permeability • a capacity for fluids and gas to move through fractures within a rock, or the spaces between its grains.

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

pyrite • the iron sulfide mineral (FeS_2) with a superficial resemblance to gold, known commpnly as "fool's gold."

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

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Regions 1–2

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

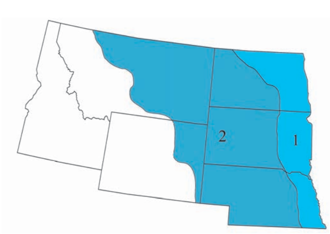
nuclear • *pertaining to a reaction, as in fission, fusion, or radioactive decay, that alters the energy, composition, or structure of an atomic nucleus.*

energy • *the power derived from the use of physical or chemical resources.*

rare earth elements • *a set of 17 heavy, lustrous elements with similar properties, some of which have technological applications.*

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

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



deposits formed through the concentration of a weathering-resistant mineral, as a result of surrounding minerals being eroded and dissolved. In contrast, mineral deposits formed by the concentration of minerals in moving waters are called **placer deposits**.

Minerals in the Northwest Central

The Northwest Central States are major contributors to the production of mineral resources in the US. In some cases, these states produce the majority of certain minerals used in the US, and they also have the largest deposits of particular mineral types in the world. The Northwest Central provides significant **fossil fuel** resources, along with uranium, which is mined for **nuclear energy**. Several Northwest Central States are also emerging as contributors of **rare earth elements** vital to developing technologies. These valuable metals are useful in a range of technological industries, with applications ranging from manufacturing processes to use in electronics such as HDTVs, computers, hybrid and electric vehicles, solar and **wind power** generators, compact fluorescent lamps, and LEDs.

See Chapter 7: Energy to learn about fossil fuel resources in the Northwest Central.

Each region of the Northwest Central US contains significant economic mineral deposits. Mineral resources reflect not only the type of deposit, but also the geological processes that control how and when the minerals were emplaced. Because some geologic events influence more than one region, associated mineral deposits may also cut across regions. In this chapter, the Great Plains and Central Lowland regions have been combined because of similarities in the types of resources found throughout.

Mineral Resources of the Central Lowland and Great Plains

Regions 1 and 2

The Great Plains and Central Lowland compose a **topographically** flat expanse that slopes gently eastward toward the mid-continent. Once partly glaciated, these regions are now characterized by rolling, grassy plains and farmland. The land is interrupted only by river and stream valleys and other erosional features formed during the **Holocene**, with the exception of the Black Hills of Wyoming and South Dakota, and a few outlying **Precambrian** rocks that protrude through the **Quaternary** sedimentary cover. Geologically, the Black Hills are the easternmost outpost of the Rocky Mountains and account for considerable mineral wealth in the Great Plains region (*Figure 5.1*). Beneath the surface cover of **Neogene-** and late Quaternary-aged sediments lies a series of sedimentary and structural basins formed during the **Laramide Orogeny** (about 70 to 40 million years ago) and earlier tectonic events preceding the Laramide.

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Regions 1–2

See Chapter 1: Geologic History to learn about the Laramide Orogeny and other tectonic events that shaped the face of North America.

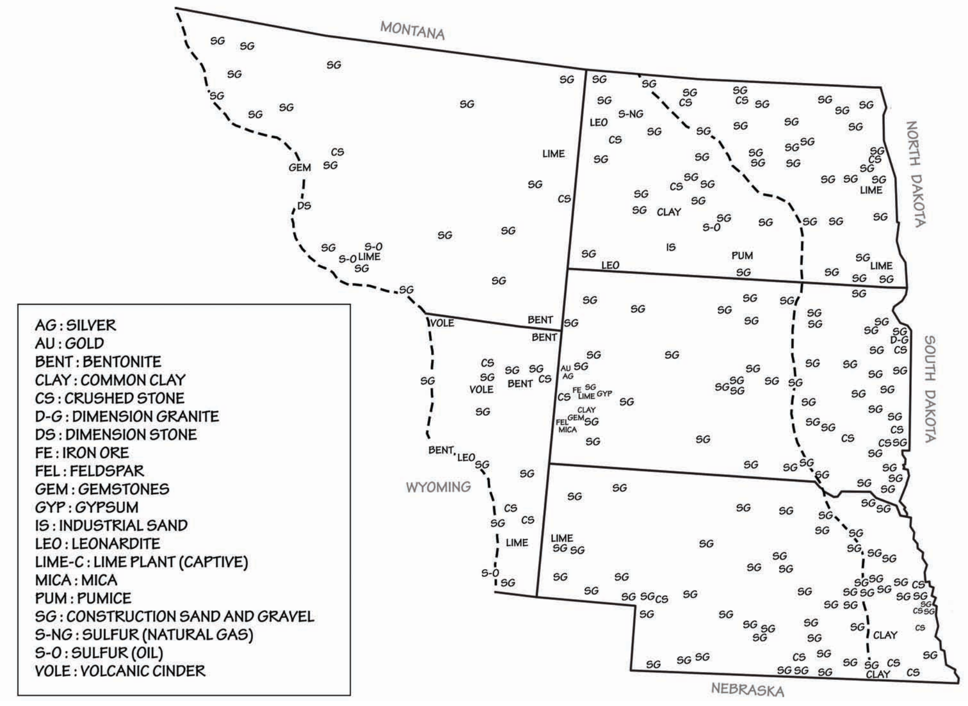


Figure 5.1: Principal mineral resources of the Great Plains and Central Lowland.

Large halite deposits that formed nearly 400 million years ago in the warm, evaporating seas of the **Devonian** are found deep beneath the Williston Basin of North Dakota and Montana. These salt beds represent a massive resource of **potash**, a name used for a variety of salts containing potassium, with mined potash being primarily potassium chloride. The majority of potash is used as fertilizer, but an increasing amount is being used in a variety of other ways: for water softening, for snow melting, in a variety of industrial processes, as a medicine, and to produce potassium carbonate.

Several saline lakes (*Figure 5.2*) on the northern and northwestern plains of North Dakota are "mined" for salts such as sodium sulfate ($NaSO_4$), often in the form of **mirabilite** (also known as "Glauber salts" in its processed form) (*Figure 5.3*). This mineral is used in the manufacture of detergents, paper, and chemical processing, especially in the production of hydrochloric and sulfuric acids. The **playa lakes** that produce these salts were originally **potholes** created during the last glaciation of North Dakota.

See Chapter 6: Glaciers for more about the effect of glaciers on Great Plains topography.

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

Holocene • *the most recent portion of the Quaternary, beginning about 11,700 years ago and continuing to the present.*

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).*

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

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

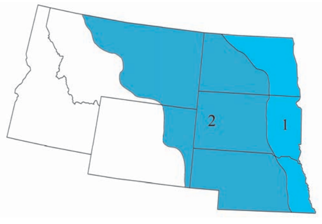
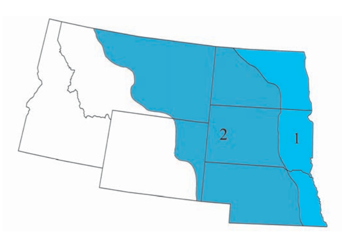


Figure 5.2: A white ring of salt can be seen around the outer rim of this evaporating playa lake in North Dakota. Typically, these shallow lakes fill up with about a foot of water during the spring and slowly dry throughout the summer, depositing layers of evaporite minerals such as halite as they diminish.

Figure 5.3: A crystal of mirabilite.



Halite is mined in two ways. When deposited in thick beds, this 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, where the water is then removed, leaving the salt behind. 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*).

***solution mining** • the extraction of soluble minerals from subsurface strata by the injection of fluids.*

***brine** • see hydrothermal solution; hot, salty water moving through rocks.*

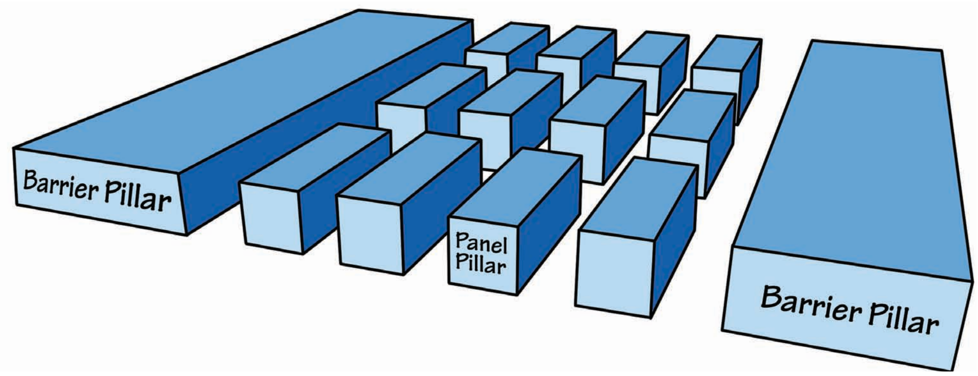


Figure 5.4: In pillar and room mining, the mine is divided up into smaller areas called "panels." Groups of panels are separated from one another by extra-large (barrier) pillars that are designed to prevent total mine collapse in the event of the failure of one or more regular-sized (panel) pillars.

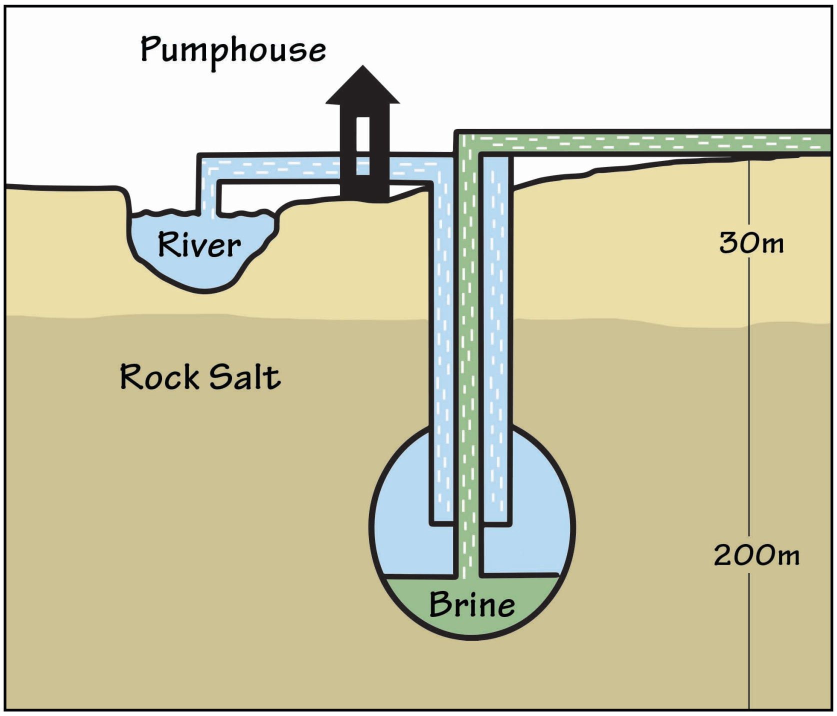
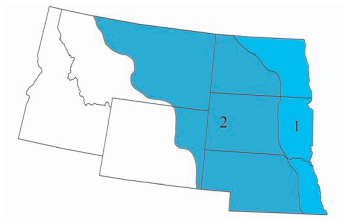


Figure 5.5: An example of solution mining that involves the pumping of fresh water through a borehole drilled into a subterranean salt deposit.



5 Mineral Resources

Regions 1–2

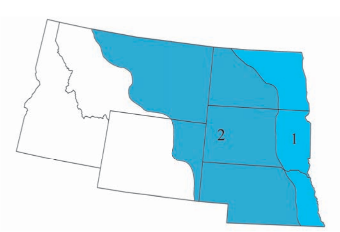
gravel • *unconsolidated, semi-rounded rock fragments larger than 2 millimeters (0.08 inches) and smaller than 75 millimeters (3 inches).*

lime • *an inorganic white or grayish-white compound made by roasting limestone (calcium carbonate, $CaCO_3$) until all the carbon dioxide (CO_2) is driven off.*

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.*

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

agate • *a crystalline silicate rock with a colorful banded pattern. It is a variety of chalcedony.*



The Great Plains region also produces numerous industrial minerals. These include sand and **gravel**, cement and **lime**, dimension stone, and **leonardite**, a mineral found in association with **lignitic coals** and used as a source of humic acid for agriculture and remediation of polluted water sources. Gravel, sand, and other construction materials are mined extensively throughout the Dakotas and Nebraska.

The gravels of the Great Plains' streams and valleys, especially those of Montana, yield numerous gemstones. The origins of these stones, including one of Montana's state gemstones, the Montana **agate** (*Figure 5.6*), lie in older igneous material worn down by **Pleistocene glaciers** and then redeposited as glacial sediments.

Figure 5.6: The Montana agate or moss agate formed after silica-laden water infiltrated cavities in a volcanic ash bed laid down by an eruption of the Yellowstone hot spot.

In addition, catlinite, a metamorphosed mudstone that is usually reddish in color and also known as "pipestone" or "pipe clay," is found in the 1.7-billion-year-old Sioux Quartzite of southeastern South Dakota. This material has long been used by Native Americans and artists to make sacred pipes and sculptures.

See Chapter 2: Rocks to learn more about pipestone and the Sioux Quartzite.

Mineral Resources 5

Regions 1–2

Outcroppings of **Proterozoic** and **Archean** granites and metamorphic rocks in Wyoming's Hartville Uplift are similar in nature to those found in the adjacent Laramie Mountains of the Southern Rockies, and are located on the divide that marks the northern end of the Denver Basin. Ores of tin (such as the simple **oxide** cassiterite, SnO_2, *Figure 5.7*), iron (as hematite), copper, silver, uranium, and gold were emplaced here through hydrothermal processes during the late **Cretaceous** to **Paleogene** periods.

Figure 5.7: Bipyramidal crystals of cassiterite (SnO_2, tin oxide). Each crystal in the photo is approximately 30 millimeters (1.1 inches) across.

The Great Plains of Nebraska is home to the largest known deposit of the rare earth metal niobium, found near Elk Creek. Over 100 million tons of this **heat**-resistant element was emplaced here in a 545-million-year-old (late Precambrian) deposit of carbonatite (a type of a carbonate-rich igneous and volcanic rock), intruded into 1.8-billion-year-old metamorphic **gneisses**, **schists**, and granites. Niobium is often used in steel alloys, rocket engines, and the manufacture of superconducting materials, such as superconducting magnets for MRI scanners.

Economic deposits of uranium and **vanadium** are found in **Paleocene** and **Eocene** sediments of the southern Powder River Basin of Wyoming, and in the **Oligocene** rocks of northwest Nebraska at the Crow Butte mine. In 2013, extraction plants in Wyoming alone provided 81% of the nation's total uranium production. The lignitic coals of North Dakota also contain significant uranium content, and economic quantities of uranium have been produced from these coals. Uranium is primarily used for nuclear power, while vanadium's main use is in the production of specialty steel alloys.

See Chapter 7: Energy for more information on uranium and other energy resources found in the Northwest Central.

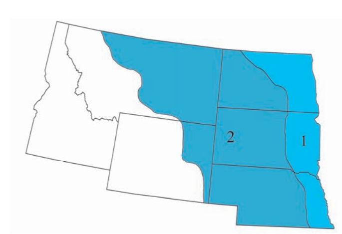
Pleistocene • *a subset of the Quaternary, lasting from 2.5 million to about 11,700 years ago.*

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

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

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

oxidation • *a chemical reaction involving the loss of at least one electron when two substances interact.*



5 Mineral Resources

Regions 1–2

physiography *• a subfield of geography that studies the Earth's physical processes and patterns.*

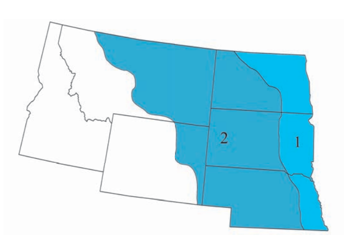
uplift *• upward movement of the crust due to compression, subduction, or mountain building.*

molybdenum *• a metallic chemical element (Mo) which has the sixth-highest melting point of any element.*

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

thorium *• a radioactive rare earth element.*

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



The Black Hills of South Dakota and Wyoming represent an anomaly with respect to Great Plains **physiography**: they share their geologic history with the ranges of the Rocky Mountain region farther west, and thus are often considered to be the easternmost outpost of the Rockies. The Black Hills are an eroded, dome-shaped **uplift** that formed during the Laramide Orogeny, near the end of the Cretaceous or early Paleogene. Standing roughly 900 meters (3000 feet) above the rest of the Great Plains, they contain an exposed core of Archean and Proterozoic metamorphic, granitic, and pegmatitic rocks. The Archean rocks are approximately 2.5 to 2.7 billion years old, while the Proterozoic granites are roughly 1.7 billion years old. A sequence of sedimentary rocks, covering more than 400 million years of Earth's history, is also exposed in these hills. Numerous mineral deposits occur in the Black Hills, the exploration and development of which led to the area's settlement. In 1874, General George Armstrong Custer's expedition discovered placer gold in Black Hills streams, just two years before the Battle of the Little Bighorn. Minerals containing gold, silver, **molybdenum**, tin, iron, copper, lead, uranium, vanadium, and rare earth elements are found in rocks ranging from Proterozoic through Quaternary in age.

Much of the gold produced in the Black Hills came from the Homestake Mine in Lead (pronounced "leed"), South Dakota, where it is found in late Cretaceous to **Cenozoic** veins that were intruded into early Proterozoic rocks during the Laramide Orogeny. Homestake was originally an underground mine that reached a depth of over 2400 meters (8000 feet), and it was once ranked as the deepest mine in the Western Hemisphere. Considered a "world-class" gold deposit, the mine was discovered in 1876 and sold in 1877 for the 2014 equivalent of $1.5 million dollars. It was later developed as an open pit operation (*Figure 5.8*). Before its eventual closure in 2002, the Homestake Mine produced over 1.1 billion grams (40 million ounces) of gold—worth over $50 billion in today's gold prices! Outside of the Homestake area, a number of Paleocene and Eocene-aged igneous intrusions occur in the northern Black Hills. These also carry gold, sometimes in commercial quantities.

On the northwestern edge of the Black Hills, deposits of **thorium**, a radioactive rare earth element, have been found in the Bear Lodge Mountains near the town of Sundance, Wyoming. These Eocene-aged deposits are intruded into **Paleozoic** and **Mesozoic** sedimentary rocks. Thorium is considered to be a "critical" rare earth element, meaning one in limited supply. It has potential applications in next-generation nuclear reactors that could be safer and more environmentally friendly than current uranium reactors.

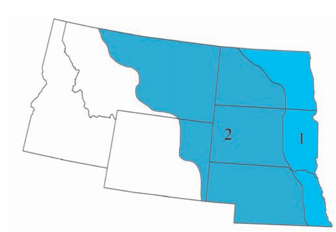
The Black Hills are also well known for deposits of beryllium, lithium, tin, tungsten, and potassium-bearing minerals. These minerals are found in early Proterozoic pegmatites, some of which contain giant crystals of **spodumene** (lithium aluminum inosilicate, *Figure 5.9*). Lithium is important to the manufacture of modern batteries, especially those used in computers, cell phones, and electric and hybrid vehicles.

Figure 5.8: Gold veins are visible in the Homestake Mine open pit, Lead, South Dakota.

Figure 5.9: Giant spodumene crystals in the pit wall of Etta Mine, Keystone, South Dakota, in 1916. Note miner (right) for scale.

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

spodumene • *a translucent pyroxene mineral (lithium aluminum inosilicate) occurring in prismatic crystals, and a primary source of lithium.*



Mineral Resources of the Rocky Mountains
Region 3

The Rocky Mountain region is somewhat discontinuous, containing a scattered collection of mountain ranges and rocks of varying geologic origins and ages. The region's mineral resources are found within its four physiographic subregions: the Northern, Middle, and Southern Rockies, as well as the Wyoming Basin (*Figure 5.10*).

See Chapter 4: Topography for more information about the physiographic subregions of the Rocky Mountains.

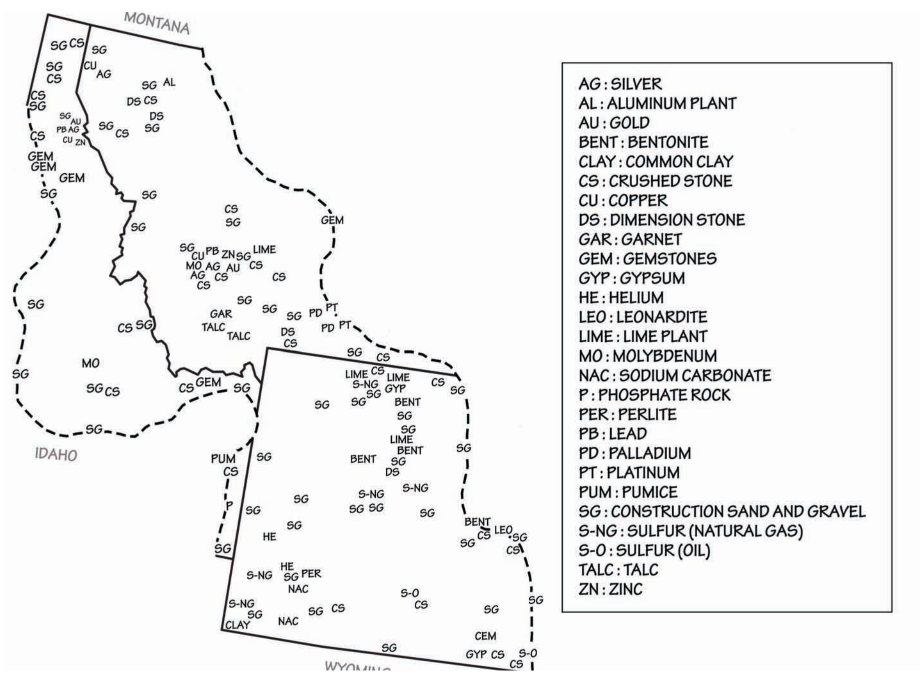
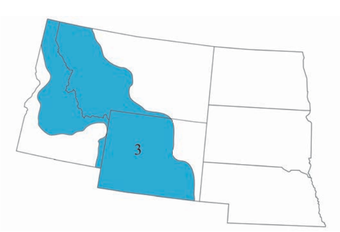


Figure 5.10: Principal mineral resources of the Rocky Mountains region.

The Northern Rocky Mountains

The Northern Rockies subregion is located primarily in western Montana and eastern Idaho, and includes the massive Idaho Batholith, the Boulder Batholith, the Stillwater Igneous Complex at Nye, Montana, and the famous Coeur d'Alene mining district in the metamorphosed Precambrian

See Chapter 2: Rocks to learn more about Belt Series rocks from the Belt and Snowy Pass supergroups.



sediments of northernmost Idaho. Many of the area's mineral resources are concentrated within its **batholiths**, igneous complexes, and Precambrian sedimentary "Belt Series" rocks.

The Boulder Batholith, a **pluton** emplaced during the early Laramide Orogeny at Butte, Montana, has been called "the richest hill on Earth," and it was a major producer of copper from about 1880 until 2004. The mines at Butte produced over 9.5 billion kilograms (21 billion pounds) of copper along with considerable quantities of **zinc**, lead, **manganese**, silver, gold, and molybdenum. The Berkeley Pit, one of Butte's major open pit mines, produced about 450,000 kilograms (one billion pounds) of copper, silver, and gold during its operation from 1955 to 1982 (*Figure 5.11*). Today, the pit is classified as a Superfund site due to the infiltration of groundwater that has become highly acidic and laden with heavy metals and dangerous chemicals leached from the surrounding rock.

A Superfund site is a heavily polluted location, designated by the government to receive a long-term clean-up response in order to remove environmental hazards and contamination.

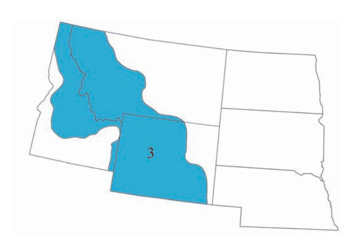
Figure 5.11: The Berkeley Pit and associated tailings pond. This open pit copper mine reaches a depth of about 540 meters (1780 feet), and is filled to a depth of about 270 meters (900 feet) with metal-laden acidic water. The mine is 1.6 kilometers (1 mile) long and 0.8 kilometers (0.5 miles) wide.

batholith *• a large exposed structure of intrusive igneous rock that solidified at depth, and covers an area of over 100 square kilometers (40 square miles).*

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

zinc *• a metallic chemical element (Zn, atomic number 30).*

manganese *• a metallic chemical element (Mn).*



5 Mineral Resources

Region 3

chromium *• a lustrous, hard, steel-gray metallic element (Cr), resistant to tarnish and corrosion.*

fuel *• a material substance that possesses internal energy that can be transferred to the surroundings for specific uses.*

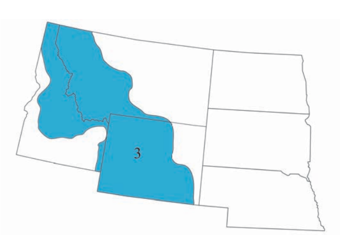
nickel *• a ductile, silvery-white metallic element (Ni) generally found in combination with iron.*

Mining

Mining is a profit-focused undertaking. The profitability of mining minerals or rocks depends on a number of factors, including the concentrations of recoverable elements or material contained in the deposit; the anticipated amount of the deposit that can be mined; its accessibility using current mining methods and technologies; its marketability; and lastly the cost of returning the site to its original state once the extraction phase of mining has ended (reclamation). All these factors determine the choice of mining method. Types of mining include underground (tunnel or shaft), surface (open pit or quarry), hydraulic operations (placer), solution using hot water, and seawater evaporation ponds. Once a mineral resource has been removed from the ground, the next step is to process it in order to recover its useful elements or to transform it so that it can be used in manufacturing or other industrial processes.

Modern mining is accomplished in three phases: exploration, extraction, and reclamation. Exploration is performed to determine the extent of the mineral resource and usually involves extensive use of drilling and geophysical techniques to determine the shape, size, and quality of the resource. Extraction involves removing the mineral resource from the ground. Reclamation is undertaken when mining ceases and is designed to restore the land to a condition where it can be used for other purposes. This last phase usually involves removing sources of contamination, which can be considerable depending on the scope of the mining activity.

The Stillwater Complex in the Beartooth Mountains northeast of Yellowstone is a 2.7-billion-year-old layered mafic intrusion, an inverted umbrella-shaped intrusive body that contains distinct layers. It is a major producer of **chromium** and the rare precious metals palladium, platinum, and other associated metal ores. Platinum group metals are used in many industrial applications, including the manufacture of catalytic converters for vehicles, data storage devices, anti-cancer drugs, fiber optic cables, gasoline additives, and **fuel** cells. Quantities of gold, silver, copper, and **nickel** are also recovered from this complex.



The Idaho Batholith, which was emplaced in multiple phases during the **Sevier Orogeny**, has three major lobes: the Atlanta lobe (100 to 75 million years ago), the Kiniksu Lobe (94 million years ago), and the Bitterroot Lobe (85 to 65 million years ago). Several million ounces of gold and silver, along with quantities of lead, zinc, and **antimony** in the form of the mineral stibnite (antimony sulfide, Sb_2S_3), have been mined from this batholith.

The Coeur d'Alene (Silver Valley) mining district of Idaho occurs within 1.4-billion-year-old metamorphosed sediments. These rocks are interpreted by some as having been deposited in a failed **rift basin** in the continental crust, probably similar to, but less developed than, the East African rift zone. Gold was discovered on the Coeur d'Alene River in 1874, which led to a short-lived gold rush. In 1884, the first major discovery of lead-zinc-silver ores was made, and within a year several major mines were in operation. The district has produced over 51 billion grams (1.8 billion ounces) of silver, 2.7 million metric tons (3 million tons) of zinc, and 7.3 metric tons (8 million tons) of lead from 90 mines, some of which reach a depth of roughly 2400 meters (8000 feet). Two or three of these mines still produce today. The area is also famous for its many large specimens of pyromorphite, a crystalline lead **phosphate** mineral (*Figure 5.12*)

See Chapter 1: Geologic History for more about rifting and failed rifts.

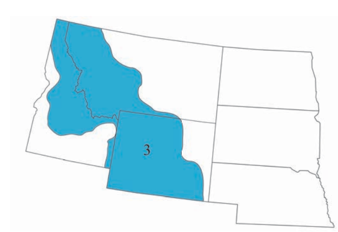
Figure 5.12: Pyromorphite from the Bunker Hill Mine, Coeur d'Alene mining district, Idaho. This mineral is found in association with lead-rich ores.

Sevier Orogeny • *a mountain-building event resulting from subduction along the western edge of North America, occurring mainly during the Cretaceous.*

antimony • *a lustrous gray metallic element (Sb), mainly found in nature as the sulfide mineral stibnite (Sb_2S_3).*

rift basin • *a topographic depression caused by subsidence within a rift.*

phosphate • *an inorganic salt of phosphoric acid, and a nutrient vital to biological life.*



5

Mineral Resources

Region 3

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.*

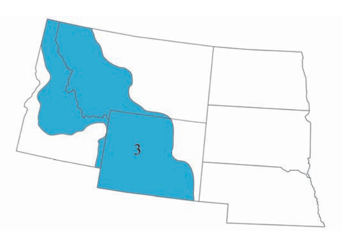
Miocene *• a geological time unit extending from 23 to 5 million years ago.*

Pliocene *• a geologic time interval extending from roughly 5 to 2.5 million years ago.*

corundum *• an aluminum oxide mineral (Al_2O_3) that is, after diamond, the hardest known natural substance.*

dike *• a sheet of intrusive igneous or sedimentary rock that fills a crack in a pre-existing rock body.*

opal *• a silicate gemstone lacking a rigid crystalline structure.*



Mining Districts

Mines in the American West are grouped into "mining districts," defined by their mineral resources as well as by natural boundaries such as rivers. Districts were originally defined informally by miners, but in the late 19th century the US federal government developed regulations for staking claims, property ownership, and mining itself. Some districts have been defined by political boundaries.

In Lemhi County, Idaho, the most important mineral districts produce or have produced gold, silver, lead, copper, cobalt, nickel, tungsten, and molybdenum (*Figure 5.13*). The Lemhi Pass area of Idaho and Montana is also one of the principal US sources of rare earth elements, including thorium. The area's complex geology contains elements of crustal extension as well as thrust **faulting** associated with mountain building. The eastern portion of this area is dominated by "thin-skinned" thrusts (low-angle faults through surface sedimentary layers) that appear to contain controlled ore emplacement that occurred in two different phases. The first phase corresponds with the Sevier Orogeny (about 140 to 50 million years ago) and overlaps the Laramide Orogeny (about 70 to 40 million years ago). The second phase of emplacement began in the **Miocene** and **Pliocene**, corresponding to later phases of the formation of the Basin and Range (about 35 to 12 million years ago or later).

The Northern Rockies also produce high-quality gemstones. One of the area's more famous gemstone localities is the Yogo Sapphire deposit in the Little Belt Mountains of Montana. Sapphire is otherwise known as the mineral **corundum** (Al_2O_3). Discovered in 1876, the Yogo mine was not recognized as a sapphire deposit until 1895, when Tiffany's of New York pronounced Yogo sapphires to be "the finest precious gemstones" in the United States. Yogo sapphires, produced from greenish colored, igneous **dikes** called lamprophyres, range in color from cornflower blue to purple. Their coloring is due to traces of iron and titanium in the corundum's crystal lattice. Montana also produces sapphires from three other major areas: the Missouri River area, which has yielded large blue-green sapphires of up to twenty carats in size, and the Rock Creek and Dry Cottonwood areas, which yield smaller, rounded gems that come in a variety of intense colors, from green and blue to pink and yellow (*Figure 5.14*). The abundance of sapphires and other gem and mineral resources found in Montana has led to it being nicknamed the "Treasure State."

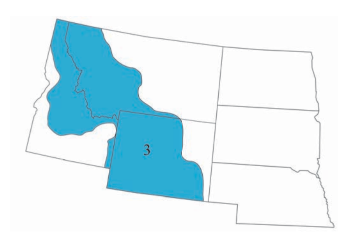
The Rocky Mountains of Idaho are also renowned for their production of gemstones, including garnets, **opal**, topaz, jade, zircon, agate, and tourmaline. Idaho, as the "Gem State," is especially famous for its gem-quality star garnets (*Figure 5.15*), an extremely rare form of garnet that is found in commercial

Figure 5.13: The Thompson Creek Molybdenum Pit Mine in Custer, Idaho. The mill here processes about 27,200 metric tons (30,000 tons) of ore per day, producing molybdenum sulfide concentrate that is later converted to specialty materials.

Figure 5.14: A variety of cut sapphires from Montana.

quantity in only two places in the world, Idaho and India. Idaho's garnets are found in pegmatites, schist, and other metamorphic rocks; although they can be removed from these rocks or the surrounding **soil**, they are most often collected from placer deposits in streams. Additionally, opals are produced in commercial quantities from mines near Spencer, Idaho.

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



5 Mineral Resources

Region 3

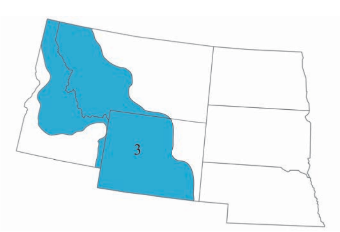
Figure 5.15: The star garnet, Idaho's state gem, is a rare garnet that refracts light in the shape of a 4- or 6-pointed star when polished.

The Middle Rocky Mountains

Geologically, the Middle Rockies subregion represents a somewhat scattered and discontinuous collection of mountain ranges that vary in geologic origin and age. Many of these ranges formed during various intervals from the Cretaceous to the Miocene, and have Archean rocks at their core. They contain faults ranging from low-angle thrust faults to Basin and Range-type block faulting. At least one range owes its origin to volcanic and igneous activity rather than uplift.

See Chapter 4: Topography to learn about the formation of the various mountain ranges and geologic features in the Middle Rocky Mountains.

The Teton Range near Jackson Hole, Wyoming is composed largely of Archean gneisses and has not yielded significant mineral deposits. The area, protected as part of Grand Teton National Park, formed around nine to six million years ago through Basin and Range-type extension. Southeast of Jackson Hole lie the Gros Ventre Range, the Wind River Range, and the Granite Mountains. These mountains contain some of the oldest known rocks exposed on the North



American continent. Archean granitic gneisses in these ranges have been dated at up to approximately 3.8 to 3.65 billion years old, along with metamorphosed sediments and volcanics (**greenstone belts**) at roughly 3.3 to 2.6 billion years old. Mining districts developed on these **terranes** yield gold, copper, and minor silver. To the north of the Wind River Range and east of Yellowstone National Park and the Tetons is the Absaroka Volcanic Plateau, which formed some 50 to 34 million years ago during the Eocene. The volcanics of this range are unrelated to those of the nearby and much younger Yellowstone Plateau (about 2 to 0.6 million years old) and are home to several mining districts that have yielded copper, molybdenum, lead, zinc, gold, and silver from what are known as copper-gold **porphyry** complexes. The Sunlight, New World, Kirwin, and Stinking Water districts in the Absaroka Mountains all contain placer gold deposits that can be recovered by panning, sluicing, and dredging (*Figures 5.16, 5.17*). Although limited commercial efforts have been put into this area, gold prospecting is a popular recreational activity here.

The Bighorn Mountains, which lie east of the Absarokas and the Bighorn Basin, were uplifted during the Laramide Orogeny and contain Archean rocks at their core. The area has thus far proven somewhat uneconomically viable, although gold is known here, and placer deposits were likely mined by the Spanish in the 1700s and by Native Americans prior to the arrival of the Spaniards. The

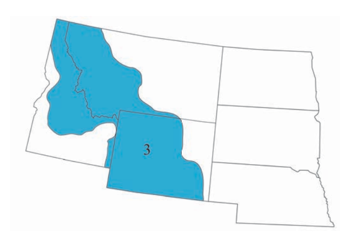
How is gold mined?

Gold can be extracted using a wide variety of methods. *Placer mining* searches stream bed deposits for minerals moved from their original source by water. Placer deposits can be mined in several different ways: *panning*, which uses a small, hand-held pan to manually sort the gold from sand and rock fragments; *sluicing*, in which water is sent through a man-made stepped channel that traps particles of gold; or *dredging*, where a large machine uses mechanical conveyors or suction to pull loads of material from the river bottom and then dump smaller fragments into a sluice box. Gold that is trapped in layers of rock may be excavated through *underground mining*, where tunnels or shafts are used to locate the ore, or by *open pit mining*, which is used when deposits are relatively close to the surface.

greenstone belt • *a series of interlayered volcanic and sedimentary rocks that have been metamorphosed into meta-sedimentary rocks and amphibolite.*

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

porphyry • *an igneous rock consisting of large grained crystals, or phenocrysts, cemented in a fine-grained matrix.*



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

pyroxene • *dark-colored rock-forming silicate minerals containing iron and magnesium.*

inclusion • *a fragment of older rock located within a body of igneous rock.*

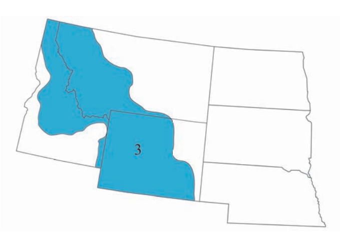
Figure 5.16: Gold dust (placer gold) found near Cody, Wyoming.

area also contains a relatively large deposit of rare earth elements—including dysprosium, used in high-performance magnets and compact fluorescent bulbs—and minor amounts of uranium have also been produced in the Bighorns.

The Middle Rockies of Wyoming, especially the Granite and Seminole Mountains, are famous for "Wyoming Jade," otherwise known as nephrite jade (the mineral nephrite, an **amphibole** group mineral), which is highly prized for its deep apple-green color and transparency and is considered to be some of the finest nephrite in the world (*Figure 5.18*). It ranges in color from deep green to a light yellowish variety known as "mutton fat." Nephrite jade should not be confused with the pale green "true" jade (the mineral jadeite of the **pyroxene** mineral group). These two minerals are so similar that they were not distinguished from one another until 1863. Both minerals are formed during metamorphism, and Wyoming Jade is found within granites and gneisses where amphibole **inclusions** were altered by hydrothermal fluids.

The Wyoming Basin

The Wyoming Basin subregion covers most of southwestern Wyoming, and it effectively separates the Southern Rockies from the Middle Rockies. The



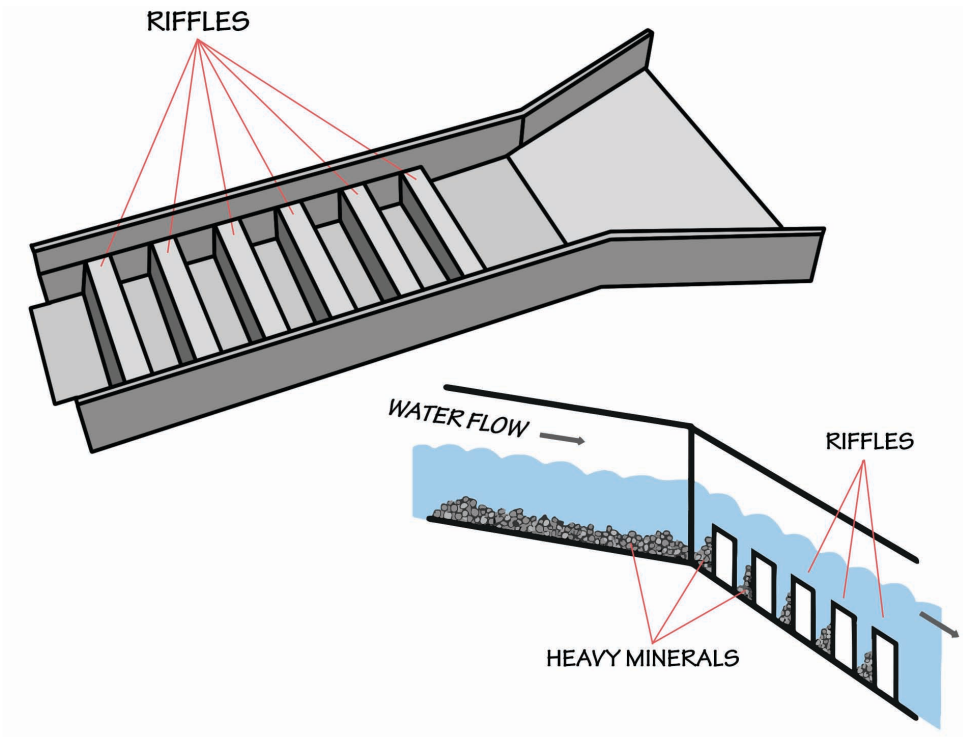
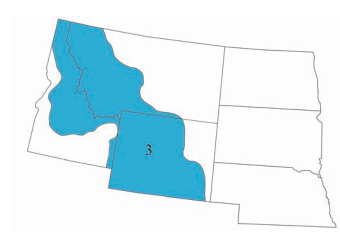


Figure 5.17: A sluice is a long tray through which water that contains gold is directed. The sluice box contains riffles, or raised segments, which create eddies in the water flow. Larger and heavier particles, such as gold, are trapped by the eddies and sink behind the riffles where they can later be collected.

Figure 5.18: Nephrite jade from Crooks Mountain, central Wyoming.



lamproite • *an ultramafic volcanic (extrusive) rock with high levels of potassium and magnesium that contains coarse crystals.*

accretion • *the process by which a body of rock increases in size due to the addition of further sedimentary particles or of large chunks of land.*

craton • *the old, underlying portion of a continent that is geologically stable relative to surrounding areas.*

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

breccia • *a pyroclastic rock composed of volcanic fragments from an explosive eruption.*

Leucite Hills, at the northeast end of the Rock Springs Uplift, have yielded potassium- and magnesium-rich minerals as well as rare earth elements from young (about 1-million-year-old) **lamproites**. These rocks are rare and sometimes include diamond-bearing igneous rocks chemically similar to kimberlites; only 25 such occurrences are known worldwide. In the southwest part of the Wyoming Basin, indicator minerals associated with diamond-bearing kimberlites have been found in surface sediments. The presence of indicator minerals suggests the presence of diamond pipes beneath the sedimentary cover in this area. A number of uranium deposits are found in the northeastern part (Great Divide Basin) of the Wyoming Basin, where several new mines are in the process of receiving permits.

The Green River Basin in Wyoming is home to the world's largest deposit of trona, a non-marine evaporite mineral that is mined as a primary source of sodium carbonate. The layered deposits in Wyoming, which lie 240 to 490 meters (800 to 1600 feet) below ground, were deposited in a lake during the Paleogene. Trona is a common food additive and water softener, and it also has applications in the manufacturing of paper, textiles, glass, and detergents.

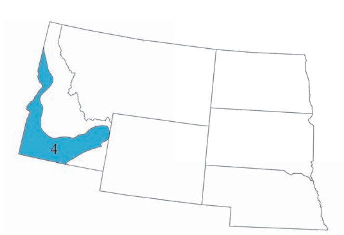
The Southern Rocky Mountains

In Wyoming, this subregion is defined by the Laramie and Medicine Bow mountains, and the Sierra Madre. Within this area lies the geologic boundary between early **accreted** terranes of the Proterozoic, at 1.9 to 1.8 billion years old, and very old (2.4- to 2.2-billion-year-old) early Proterozoic metamorphic rocks originally deposited as **cratonic** sediments. The Southern Rockies of Wyoming have produced gemstones as well as precious and base metals. Iron and diamond-bearing kimberlites are found in the Laramie Range and the State Line District, spanning the Wyoming-Colorado border. More than 130,000 diamonds have been recovered since they were first discovered here in 1975.

Gold and silver have been mined in the Gold Hill District and other parts of the Medicine Bow Mountains, and also in the Purgatory Gulch area of the Sierra Madre west of the Medicine Bows (*Figure 5.19*). These mountains were prospected extensively from the 1800s up through the Great Depression, when metal prices dropped to the point at which mining was no longer profitable. Rich copper deposits are found in the Ferris-Haggerty District of the Sierra Madre where massive chalcocite (copper sulfide, Cu_2S) and (minor) chalcopyrite (copper-iron sulfide, $CuFeS_2$) ores are found in **quartzite breccia**. Uranium is produced from the Shirley Basin immediately west of the Laramie Range.

Mineral Resources of the Columbia Plateau

Region 4



The Columbia Plateau, dominated by the Miocene-aged Columbia Flood Basalts, is present in only a small area of the Northwest Central US, in far west-central Idaho. This area does not contain any mineral occurrences of note. The

Figure 5.19: The Carissa Gold Mine, which operated from 1867 to 1954. In 2003, the state of Wyoming restored the mine and mill as a historic attraction.

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

jasper • *a speckled or patterned silicate stone that appears in a wide range of colors.*

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

Snake River Plain of southern and central Idaho, which marks the movement of the North American plate over the Yellowstone **hot spot**, has only a few small associated gold placers. However, the volcanic and igneous activity associated with the formation of this feature may have contributed to the formation of hydrothermal gold deposits in nearby mining districts. Gold and other precious metals, as hydrothermal deposits, are also found in the hot springs of the Yellowstone Plateau, which is the terminus of the Snake River Plain (*Figure 5.20*).

See Chapter 2: Rocks to find out how the Columbia Flood Basalts were formed.

The most notable mineral deposit near the Snake River Plain is the Silver City-De Lamar District, a remote area in southwestern Idaho. This district has produced over 28 million grams (1 million ounces) of gold and more than 910 million grams (32 million ounces) of silver from selenium-rich ores emplaced about 16 million years ago in the middle Miocene. Common minerals and metals found here include gold, silver, naumannite, aguilarite, and argentite, and the ruby silver minerals cerargyrite and acanthite. Today, De Lamar and Silver City are both ghost towns, largely abandoned after their nearby mines were depleted.

Bruneau Canyon, in Owyhee County, southwestern Idaho, produces large quantities of **jasper**. This silicate mineral precipitated within the cavities and fractures of **rhyolite** flows, and it ranges in color from brown to reddish cream.

5 Mineral Resources

Regions 4–5

zeolites *• porous alumino-silicate minerals, often formed some time after sedimentary layers have been deposited, or where volcanic rocks and ash react with alkaline groundwater.*

pumice *• a pyroclastic rock that forms as frothing and sputtering magmatic foam cools and solidifies.*

obsidian *• a glassy volcanic rock, formed when felsic lava cools rapidly.*

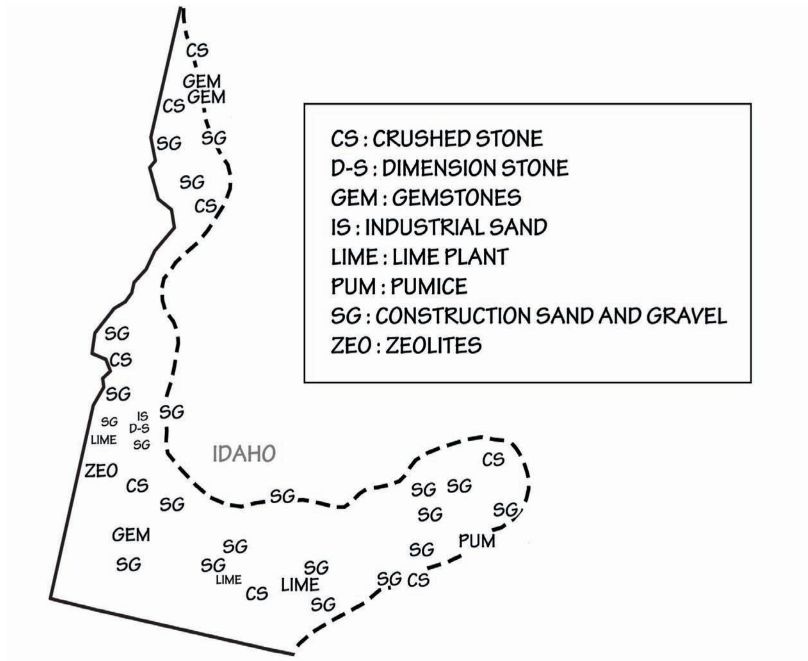
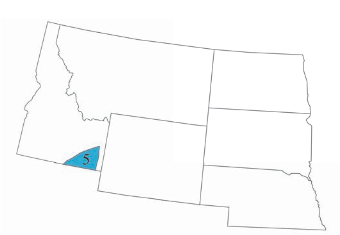


Figure 5.20: Principal mineral resources of the Columbia Plateau.

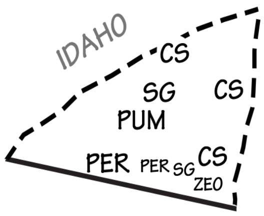
Zeolites—porous alumino-silicate minerals with cation-exchange properties that can transform hard water into soft water—are mined along the Idaho-Oregon border. These deposits were created from alkaline volcanic ejecta that was deposited into a fresh or salt water source.

Mineral Resources of the Basin and Range
Region 5

The Basin and Range region, with its distinctive horst and graben features formed by extensional tectonics, is present only in southeastern and east-central Idaho. Aside from a few gold placer deposits associated with the southern margin of the Snake River Plain, the Basin and Range region in Idaho contains only one metallic ore deposit of even marginal significance: the Mount Pigsah District in the Caribou Mountains, which produced some 454,000 grams (16,000 ounces) of gold from ore bodies intruded into Mesozoic sediments. In addition, this area produces industrial minerals such as **pumice** and phosphate for use in fertilizer and the making of phosphoric acid and dimension stone (*Figure 5.21*). It also produces perlite, an amorphous hydrated volcanic glass often found ias small hollow spheres embedded within **obsidian** (*Figure 5.22*). Perlite is used in horticulture, water filters, lime, and cement.



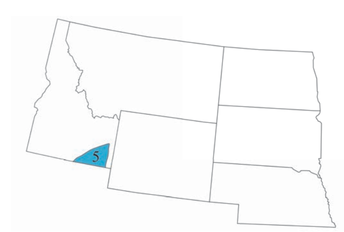
See Chapter 4: Topography for more about horst and graben landscapes.



CS : CRUSHED STONE
PUM : PUMICE
PER : PERLITE
SG : CONSTRUCTION SAND AND GRAVEL
ZEO : ZEOLITES

Figure 5.21: Principal mineral resources of the Basin and Range.

Figure 5.22: An outcrop of flow-banded perlite (amorphous hydrated volcanic glass) in obsidian. Perlite occurs as small hollow spheres called "spheruloids."



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Mineral Resources

5

Resources

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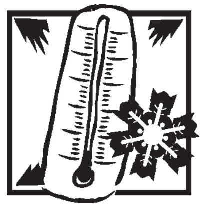

Chapter 6: Glaciers in the Northwest Central US

Glaciers have had a profound impact on the Northwest Central's scenery, geology, and water resources. Today, small **cirque** glaciers and larger valley glaciers are found largely in the mountains of Wyoming and Montana, while a few small glaciers and **perennial** snowfields can be seen in Idaho. Ongoing research into how these glaciers have changed since the last major **ice age** is proving invaluable to our understanding of **climate change**.

What is a glacier?

A **glacier** is a large mass of ice (usually covered by snow) that is heavy enough to flow like a very thick fluid. Glaciers form in areas where more snow accumulates than is lost each year. As new snow accumulates, it buries and **compresses** old snow, transforming it from a fluffy mass of snowflakes into ice crystals with the appearance of wet sugar, known as **firn**. As this firn is buried yet deeper, it coalesces into a mass of hard, dense ice that is riddled with air bubbles. Much of this transformation takes place in the high part of a glacier where annual snow accumulation outpaces snow loss—a place called the **accumulation zone***.* 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 (*Figure 6.1*). Once the ice becomes thick enough, it flows outward to the **ablation zone***,* where the ice is lost due to melting and **calving** (*Figure 6.2*). The boundary between these two zones, the equilibrium line, is where annual ice accumulation equals annual ice loss. Because the altitude of this line is dependent on local temperature and precipitation, glaciologists frequently use it to assess the impact of climate change on glaciers.

Most broadly, there are two types of glaciers: smaller alpine glaciers and larger continental glaciers. Found in mountainous areas, alpine glaciers have a shape and motion that is largely controlled by **topography**, and they naturally flow from higher to lower altitudes. Glaciers confined to valleys are called valley glaciers, while bowl-shaped depressions called cirques are located in mountainous areas. Continental glaciers are much larger, and they are less controlled by the landscape, tending to flow outward from their center of accumulation. **Ice sheets** are large masses of ice that cover continents (such as those found in Greenland) or smaller masses that cover large parts of mountain ranges (**ice fields**). Because ice fields often appear to be crowning a mountain range, they are sometimes called **ice caps** as well. Mountains fringing the ice sheets cause the descending ice to break up into outlet glaciers (streams of ice resembling alpine glaciers) or broad tongues of ice called piedmont glaciers**.**

cirque *• a large bowl-shaped depression carved by glacial erosion and located in mountainous regions.*

perennial *• continuous; year-round or occurring on a yearly basis.*

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

compression *• flattening or squeezing as a result of forces acting on an object from all or most directions.*

calving *• the process by which ice breaks off from the end of a glacier.*

CHAPTER AUTHOR

Libby Prueher

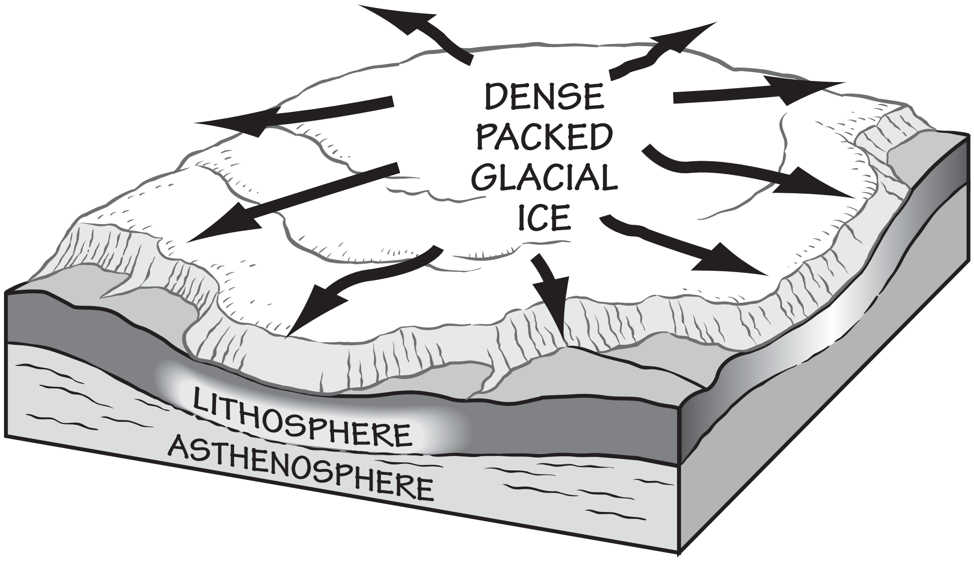

Figure 6.1: As dense glacial ice piles up, a glacier is formed. The ice begins to move under its own weight and pressure.

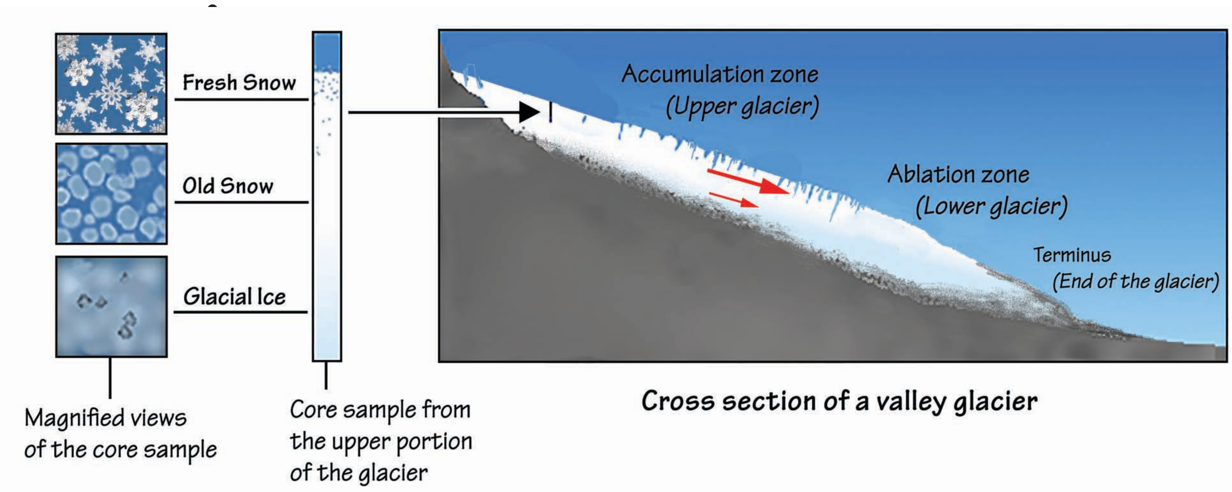

Figure 6.2: Cross-section of an alpine (valley) glacier, showing snow being converted into glacial ice and the two major zones of a glacier's surface. The red arrows show the direction and relative speed of different parts of the glacier. The longer the arrow, the faster the ice is moving.

While only the two broadest categories of glaciers are discussed here, glaciers exist in a variety of forms. Even these broadest of distinctions are not quite so clear-cut (e.g., continental glaciers often have tongues that feed into valleys, which may become alpine glaciers).

In summary, glaciers grow when it is cool enough for an 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 that reached the Northwest Central States flowed from centers of accumulation far to the north (in what is now Canada), and glacial growth southward through the Midwest was more a result of this lateral flow than of direct precipitation from falling snow. By 18,000 years ago, the ice was in retreat due to a slight warming of the **climate**—it was not actually flowing backward, but melting faster than it was accumulating and advancing.

Glacial Landscapes

The interaction of glaciers with the landscape is a complex process. Glaciers alter landscapes by **eroding**, transporting, and depositing rock and sediment. **Scouring** abrades bedrock and removes sediment, while melting causes the ice to deposit sediment.

See Chapter 4: Topography to learn more about the marks left by glaciers on the Northwest Central's landscape.

Continental glaciers also affect the landscape by depressing the Earth's **crust** with their enormous mass, just as a person standing on a trampoline will cause the center to bulge downwards. The effect is quite substantial, with surfaces being lowered by hundreds of meters. Of course, this means that when the glacier retreats and the mass is removed, the crust will rise to its former height in a process known as **isostasy** (*Figure 6.3*). Dramatic results include marine **reefs** lifted high above sea level and marine sediments composing coastal bluffs.

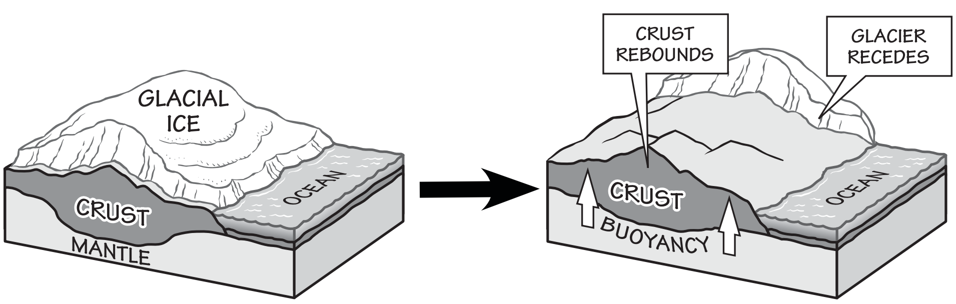

Figure 6.3: Isostatic rebound resulting from glacial retreat.

Glacial erosion can produce rugged mountainous areas with knife-edge ridges (**arêtes**), pointed rocky peaks (**horns**), and bowl-shaped depressions (cirques). These landscape features are most visible in areas where glaciers have retreated (*Figure 6.4*).

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).*

erosion • *the transport of weathered materials.*

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

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

isostasy • *an equilibrium between the weight of the crust and the buoyancy of the mantle.*

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.*

arête • *a thin ridge of rock with an almost knife-like edge, formed when two glaciers erode parallel valleys.*

Glaciers

Landscapes

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

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

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

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

rock flour • *very fine sediments and clay resulting from the grinding action of glaciers.*

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

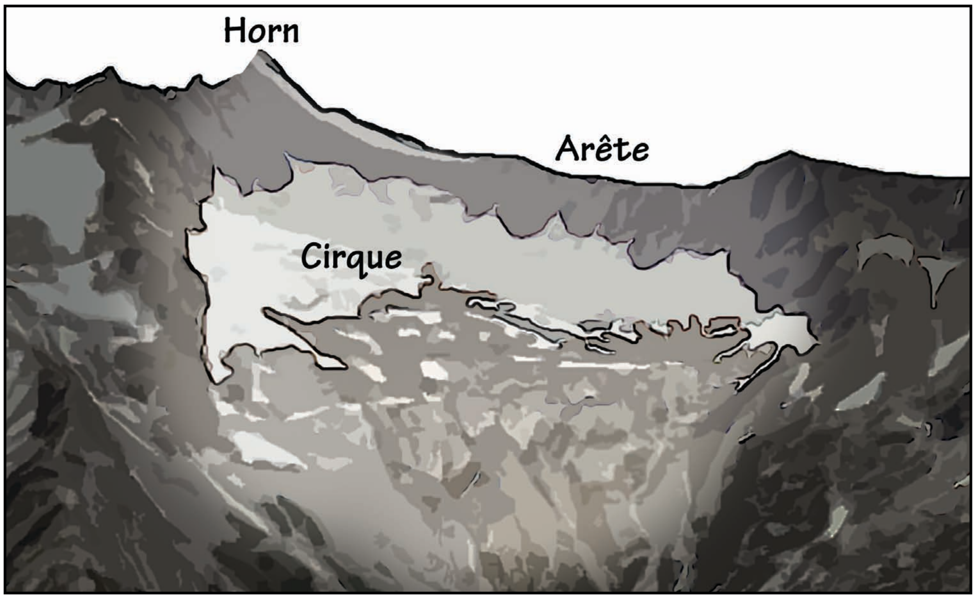

Figure 6.4: Common alpine glacial landscape features.

Erosion

Thousands of years of scraping by ice can have dramatic, and sometimes dramatically varied, effects on a landscape. Glaciers erode the land they flow over via abrasion and **plucking**. 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. Abrasion, or scouring, occurs when rock fragments in the ice erode bedrock as the glacier moves over it. Plucking involves glaciers literally pulling rock from underlying bedrock. 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 less resistant rock over which glaciers move is often eroded and ground-up into very fine **sand** and **clay** (called **rock flour**). Once eroded, this material is carried away by the ice and deposited wherever it melts out (*Figure 6.5*).

More resistant **igneous** and **metamorphic rock** is often polished and scratched by the grinding action of sediments trapped 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 **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 some of the distinctive landforms found in the Dakotas and Montana today.

The nature of the glacier causing the erosion is also crucial. Because continental glaciers spread from a central accumulation zone, they cannot 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

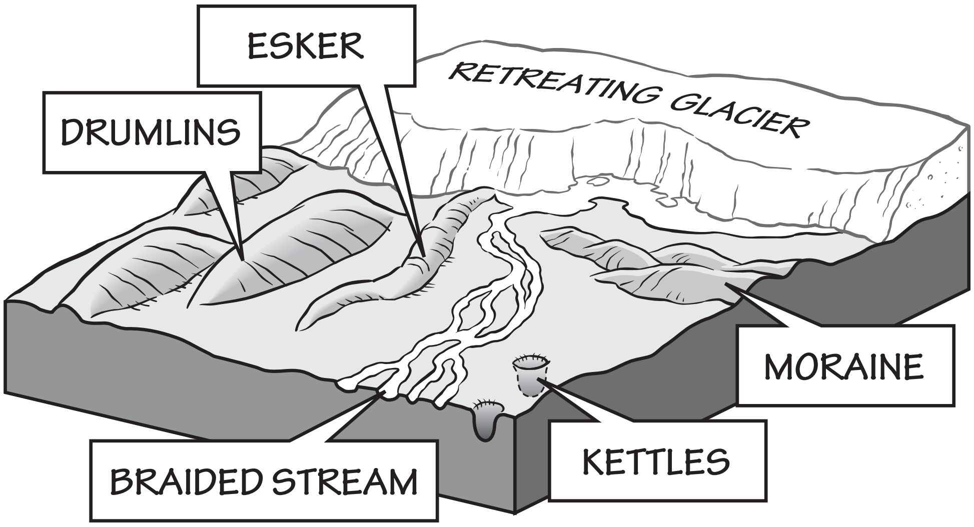

Figure 6.5: Common erosional glacial landscape features.

the existing topography, flowing downhill. This frequently causes them to scour existing low points, 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 (*Figure 6.6*).

Figure 6.6: A glacially carved valley in Glacier National Park, Montana.

Landscapes

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.*

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.*

relief *• the change in elevation over a distance.*

gravel • *unconsolidated, semi-rounded rock fragments larger than 2 millimeters (0.08 inches) and smaller than 75 millimeters (3 inches).*

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 deposited by glaciers as they recede.*

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

drift • *unconsolidated debris transported and deposited by a glacier.*

outwash plain • *large sandy flats created by sediment-laden water deposited when a glacier melts.*

Deposition

As glaciers scrape over the earth, sediment is incorporated into or shoved ahead of the advancing ice. 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. In places 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, marking the farthest extent of the glacier's margin, or terminus. A ridge of till formed this way is called a terminal **moraine**, and it may range in length from hundreds to thousands of meters. Moraines can also form when till is pushed to the sides of an advancing glacier (*Figure 6.7*).

Figure 6.7: The snakelike ridge in the foreground is a now-forested lateral moraine deposited by a valley glacier. Today, it curves along the left side of Mission Reservoir, located about 48 kilometers (30 miles) north of Missoula, Montana.

Drift-covered plains with lakes and low ridges and hills appear near the terminus of a glacier as dwindling ice leaves behind glacial till. Beyond the terminus, meltwater streams leave more orderly deposits of sediment, creating an **outwash plain** where the finest sediments are farthest from the terminus, while cobbles and boulders are found much closer. Spoon- or teardrop-shaped hills called **drumlins** (*Figure 6.8*) are composed largely of till that was trapped beneath a glacier and streamlined in the direction of the flow of ice moving over it. The elongation of a drumlin provides an excellent clue to the direction of flow during an ice sheet's most recent advance and reflects the final flow direction before the glacier receded.

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 so that even they are dropped. In other words, the faster the water is moving, the coarser the sediment deposited (*Figure 6.9*). 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, and when an ice sheet retreats, these snaking ridges of stream deposits, known as **eskers**, are left behind (*Figure 6.10*).

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 6.11*). 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. 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 6.12*). Often, kettles and kames occur near one another.

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

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

Figure 6.8: The Eureka Drumlin Field, near Eureka, Montana. These drumlins are arranged in a north-south orientation, indicating the direction of ice flow.

Erratics are rocks that the ice sheet picked up and transported farther south, sometimes hundreds of kilometers (miles) from their origin. They are often distinctive because they are a different type of rock than that making up the bedrock in the area to which they have 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. The pink-colored

Landscapes

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

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

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

aeolian • *pertaining to, caused by, or carried by the wind.*

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.*

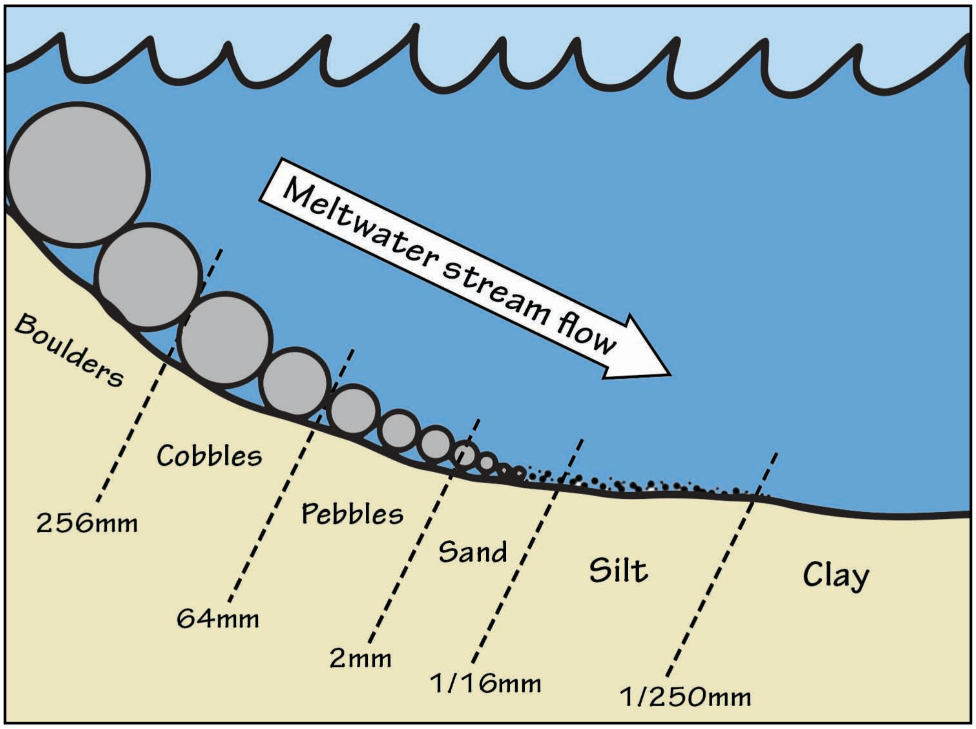

Figure 6.9: Moving water deposits sediment in what is known as a horizontally sorted pattern. As water slows (i.e., loses energy) with decreased gradient, it deposits the large particles first. The sizes in the figure represent the boundaries between categories of sediment type.

Sioux **quartzite**, which originates in southeastern South Dakota as well as northeastern Nebraska and several of the Midwestern states, is one such example. Erratics from this **Proterozoic** outcrop are found across much of northwestern Kansas and north-central Iowa, carried there by ice during the **Quaternary**.

See Chapter 2: Rocks to learn more about the Sioux Quartzite.

Periglacial Environments

Though a large portion of the Northwest Central was covered by ice, even unglaciated areas felt its effects. The land covered by the ice sheet was scoured and covered with glacial deposits, while the area south of the ice sheet developed its own distinctive landscape and features due to its proximity to the ice margin. This unglaciated but still affected area is called a **periglacial zone**.

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, such as those found in the Sandhills of Nebraska and Wyoming's Red Desert, are found in former periglacial areas of the Northwest Central. The **permafrost** associated with

Figure 6.10: Eskers are sinuous deposits composed of sand and gravel deposited by streams that once flowed under the ice.

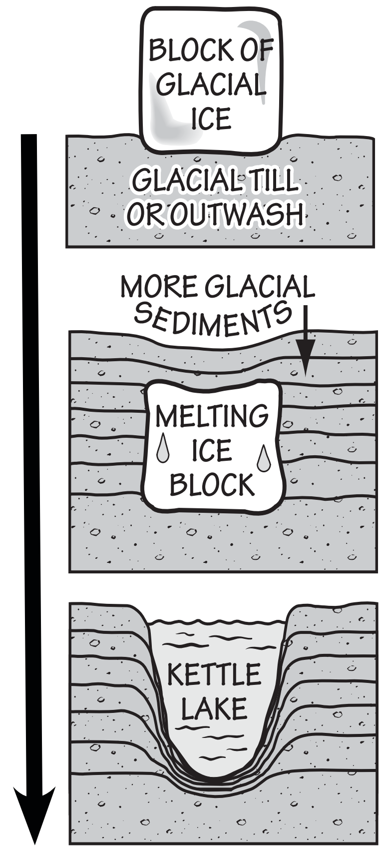

Figure 6.11: Kettle lakes form where large, isolated blocks of ice become separated from the retreating ice sheet. The weight of the ice leaves a shallow depression in the landscape that persists as a small lake.

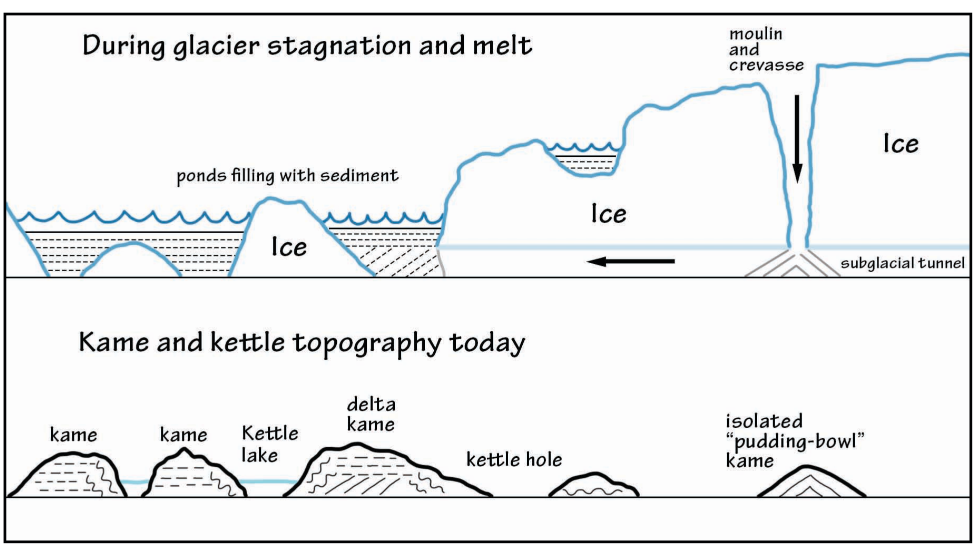

Figure 6.12: Glacial sediment deposits and the resulting hills called kames.

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.*

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

fracture *• a physical property of minerals, formed when a mineral crystal breaks.*

joint *• a surface or plane of fracture within a rock.*

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

Laurentide Ice Sheet *• an ice sheet that covered most of Canada during the last major glaciation.*

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 downhill 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 cracks and fissures in the ground and subsequently freezes, the ice wedges the cracks farther and farther apart (*Figure 6.13*). Freeze-thaw is important in any climate that cycles 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 **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, and evidence for them can be seen all along the glacial margin of the **Laurentide Ice Sheet**, from Nebraska to Idaho.

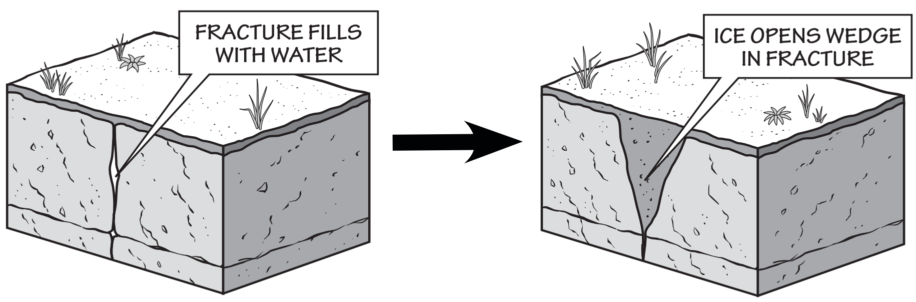

Figure 6.13: Physical weathering from a freeze-thaw cycle.

Glaciers and Climate

Glaciers are sometimes called the "canary in the coal mine" when it comes to climate change. This is because alpine glaciers are highly sensitive to changes in climate. For instance, a glacier grows (advances) when it accumulates more ice than it loses from melting or calving. Advances tend to happen when cold, wet years dominate the local climate. On the other hand, a glacier will shrink (retreat) during warm, dry periods as it loses more ice than it gains each year.

As discussed in the chapter on 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." Based on this definition, we

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are living in an ice age right now! The current ice age began about 34 million years ago when ice sheets first began forming on Antarctica, followed by their appearance on 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** during which much of North America and Europe covered in ice thousands of meters (feet) thick and many kinds of large, wooly mammals roamed the unfrozen portions of those continents.

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—the beginning of the **Holocene**. During the Pleistocene, there were several dozen intervals of glaciation separated by warmer **interglacial** intervals characterized by glacial retreat. In North America, these cycles are known as the **pre-Illinoian** (1.8 million to 302,000 years ago), **Illinoian** (191,000–131,000 years ago), Sangamonian (131,000–85,000 years ago), and **Wisconsinan** (85,000–11,000 years ago). The Illinoian and Wisconsinian were cooler periods that saw glaciers advance, while the Sangamonian was a warm interglacial period.

Age of the Quaternary

In 2009, scientists at the International Commission on Stratigraphy voted to move the beginning of the Quaternary period to 2.6 million years ago, shifting it 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 start date was based on data that reflected climatic cooling that was only local to the region in Italy where it was first observed. In contrast, 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 having it divided between the Quaternary and the earlier *Neogene* period.

The pre-Illinoian glaciation included many glacial and interglacial periods that were once subdivided into the Nebraskan, Aftonian, Kansan, and Yarmouthian ages. New data and numerical age dates suggest that the deposits are considerably more complicated; they are now lumped together into a single period. Most of the glacial features in the Northwest Central were created in the Pleistocene, during the Wisconsinian glaciation.

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.*

Holocene • *the most recent portion of the Quaternary, beginning about 11,700 years ago and continuing to the present.*

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

pre-Illinoian glaciation • *a grouping of the Midwestern glacial periods that occurred before the Wisconsinian and Illinoian glaciations.*

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

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Milankovitch cycle • *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.*

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

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

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 and are 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 during which the Northern Hemisphere experiences summer. When the cycles interact such that there is milder seasonality (cooler summers and warmer winters) at high latitudes in the Northern Hemisphere, less snow melts in summer, which allows glaciers to grow. 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 approach Kansas and Missouri 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 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.

Seeking Detailed Records of Glacial-Interglacial Cycles

While glaciers have advanced over central North America and retreated again dozens of times during the Quaternary, each advance scrapes away and reworks much of what was previously left behind, making it difficult to reconstruct the precise course of events. Therefore, to investigate the details of any associated climate change we must seek environments that record climate change and are preserved in the geologic record. 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 6.14*). In the 1980s, coring of ice sheets in Greenland and Antarctica provided similar high-resolution data on atmospheric composition and temperature back nearly one million years (*Figure 6.15*). The data from these programs have revealed that the Earth experienced dozens of warming and cooling cycles over the course of the Quaternary period. Traces of the earlier and less extensive Pleistocene glacial advances that must have occurred have been completely erased on land, so these advances were unknown before records from deep-sea cores and ice cores revealed them.

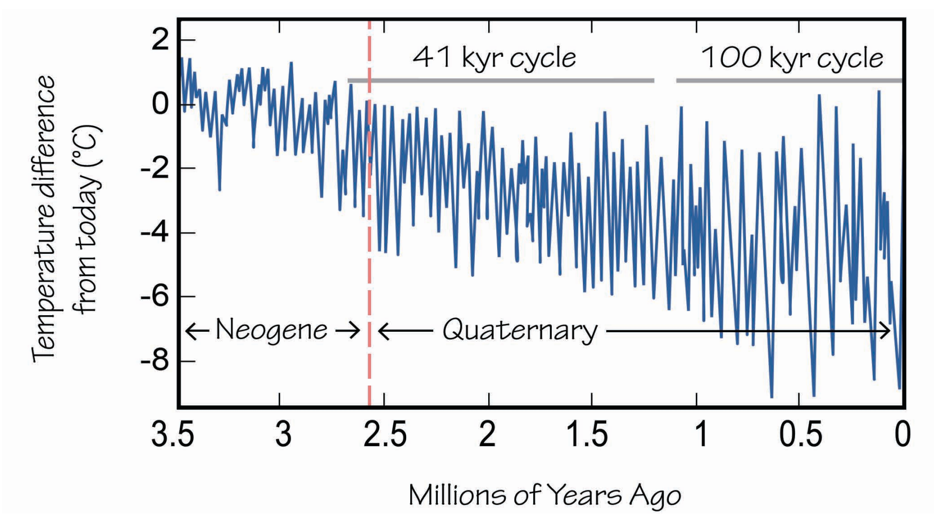

Figure 6.14: Ocean bottom temperatures from 3.6 million years ago to present, based on chemical analyses of foraminifera shells. Notice how the amplitude of glacial-interglacial variations increases through time, and how the length of cycles changes.

A large proportion of glacier and climate research involves making regular inventories of existing glaciers and their characteristics to determine how they are impacted by global, regional, and local climate changes. Equally important is determining the impact of changing glaciers on seasonal streamflow. Glaciers act as water reservoirs where winter snowfall is released as meltwater during summer, when precipitation is low. This characteristic is particularly important to farms and fisheries in areas downslope from glaciated mountains like the Northern Rockies.

tree • *any woody perennial plant with a central trunk.*

system • *a set of connected things or parts forming a complex whole.*

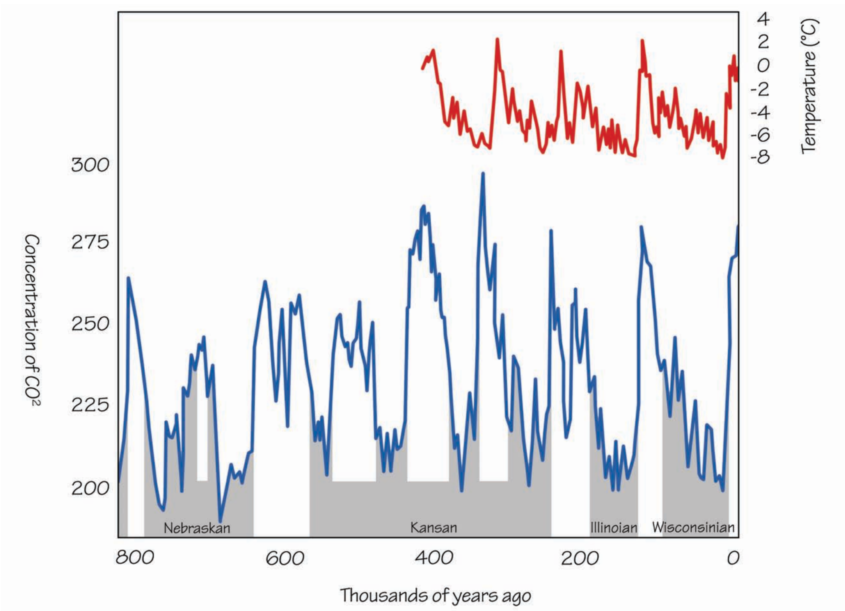

Figure 6.15: Ice core atmospheric temperature and carbon dioxide concentrations from an ice core taken in Vostok in Antarctica along with CO_2 data from several cores in Greenland give a record of glacial advances over the past 800,000 years. Note that Kansan and Nebraskan deposits represent more than one glacial advance.

In addition to investigating present-day glacier behavior, researchers use clues from the landscape to reconstruct ancient glaciers. This information, along with climate evidence from **tree** rings and lake sediments, provides a long view of climate change that has done much to improve our understanding of how climate **systems** work, and what the future might have in store for us.

As the last Pleistocene ice age came to a close, the Laurentide Ice Sheet and alpine ice caps throughout the Rockies retreated, leaving behind rugged mountain ranges, deep glacial valleys, and plains covered with thick deposits of

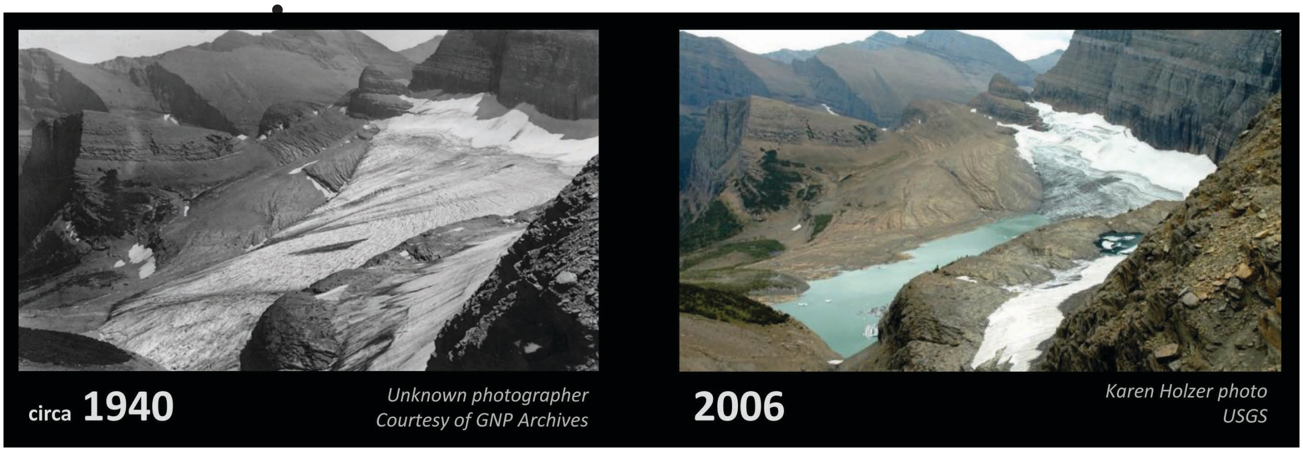

Figure 6.16: An example of glacial recession in Glacier National Park: Grinnell Glacier, as seen in 1940 and 2006.

glacial sediment. The time from the end of the Pleistocene to now is regarded as an interglacial period (a warm spell with diminished glaciers), but it has not been without its minor ice ages. The most recent of these, the Little Ice Age, began somewhere between 1300 and 1500 CE and ended by the late 19th century. Presently, the continental ice sheets and ice caps of the Pleistocene are gone, but some 150,000 alpine glaciers remain worldwide, and the impact of the ancient ice sheets and caps can be seen in nearly every region of the Northwest Central States.

Today's warming climate is having a profound impact on the glaciers that still exist in the Northwest Central. For example, Glacier National Park in Montana contained 150 named glaciers in 1850, but thanks to the effects of climate change, today only 26 of these glaciers remain. Scientists estimate that all of the park's glaciers will have vanished by 2030 (*Figure 6.16*).

loess • *very fine grained, wind-blown sediment, usually rock flour left behind by the grinding action of flowing glaciers.*

The Impact of Glaciation in the Northwest Central

During the Pleistocene, continental glaciers covered much of Canada, Alaska, and the northern edge of the continental United States (*Figure 6.17*). Continental ice sheets blanketed the Central Lowland and the northern Great Plains, scraping away rock and overlying sediment. When the glaciers retreated, glacial drift and till were deposited. Today, large swaths of the Dakotas and Nebraska are covered in glacial debris. Besides carving vast sections of the northern landscape and depositing huge quantities of sediment in low-lying areas, the glaciers' impact was felt throughout the landscape as glacial outburst floods carved into Idaho and winds laden with glacial **loess** reached deep into Nebraska and Wyoming.

Glacial Erosion and Deposition in the Northwest Central

The Drift Prairie, a relatively flat area consisting of glacial drift, is located in North and South Dakota. In some areas, there are small hills or ridges underlain by glacial debris. The Glaciated Missouri Plateau, also called the Missouri Coteau, is another hilly area underlain by glacial moraines and containing many small, closed kettle lakes. The eastern edge of the plateau, extending north and south across both Dakotas, is marked by a gentle slope that exhibits topographical relief from moraines and pre-existing river valleys. It marks the western extent of glacial ice coverage in the Dakotas during the Wisconsinian glaciation, and is also the boundary between the Central Lowland to the east and the Great Basin to the west.

See Chapter 4: Topography for more about the features of the Drift Prairie and other glaciated areas.

Eastern Nebraska is covered by glacial till, indicating that glaciers covered that portion of the state. Deposits of loess—silt-sized windblown material that is

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

Figure 6.17: Extent of glaciation over North America during the last glacial maximum.

commonly associated with continental ice sheets—are also common throughout Nebraska (*Figure 6.18*). Strong winds blowing off of the ice sheet deposited sand, silt, and other glacial debris over the landscape to create relatively flat areas as well as forming hills and dunes (such as the Sandhills). In northwest Idaho, the Columbia River Basalts are also covered by loess. Because the sediment was not deposited evenly over the **basalts**, the area is characterized by hummocky terrain.

The drainage of rivers and streams was also changed by the Pleistocene glaciation (*Figure 6.19*). Prior to the ice age, North Dakota's water—including the Missouri River—drained to the north, into Hudson Bay. During the ice age, glaciers created dams that diverted rivers to the south and formed lakes such as Glacial Lake Agassiz (*Figure 6.20*). This enormous lake, stretching from Saskatchewan down into Minnesota and eastern North Dakota, was formed by water that accumulated in front of the Laurentide Ice Sheet. Most of the area

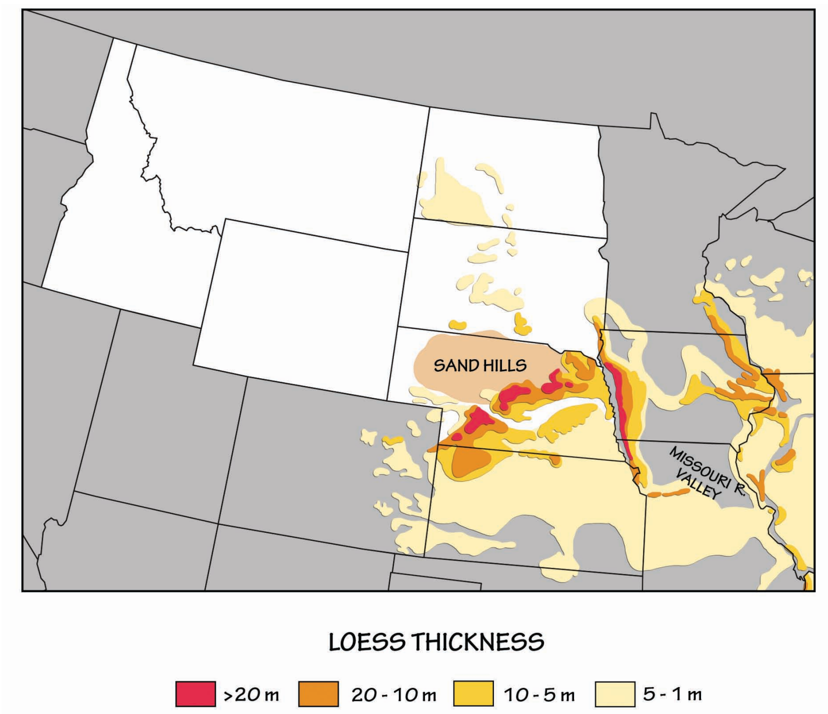

Figure 6.18: Loess deposits in Nebraska and surrounding states. (See TFG website for full-color version.)

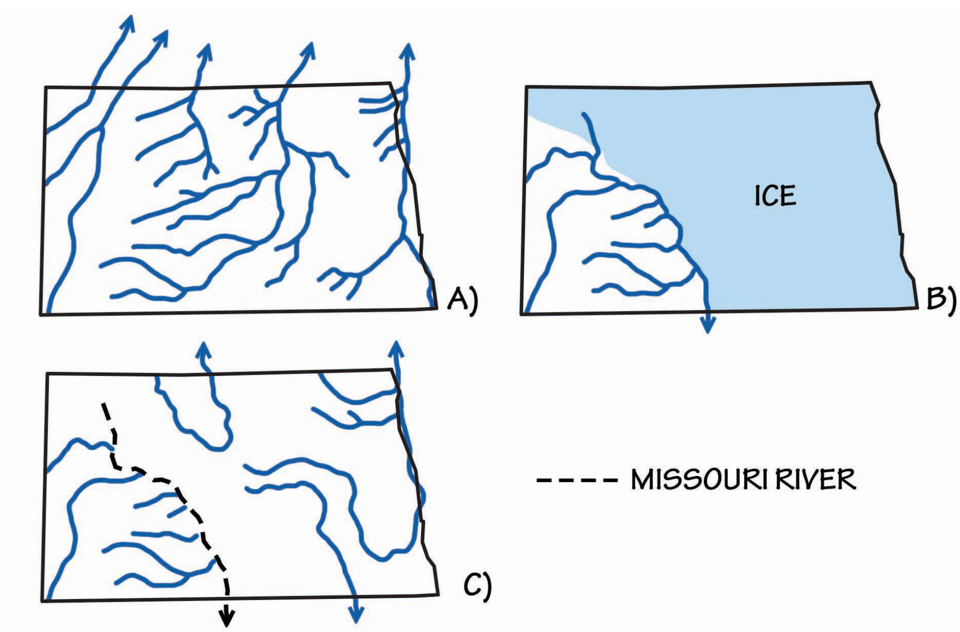

Figure 6.19: Drainage valleys of North Dakota. A) Pre-glacial river valleys drained into the Hudson Bay. B) Ice coverage and drainage during the Pleistocene. Water flowed along the margins of the ice to the south. C) After the Pleistocene, the Missouri river flowed south through the channel created during glaciation. Note that a few of the pre-glacial valleys became river valleys once more, after the glaciers retreated.

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ice lobe *• a broad, rounded section of a continental glacier that flows out near the glacier's terminus.*

Figure 6.20: The maximum extent of Glacial Lake Agassiz.

that is now eastern North Dakota would have been close to the shoreline of Lake Agassiz, and waves along its coastline modified the area. Today, the Red River Valley in North Dakota marks the extent to which Lake Agassiz covered the state. The James River Valley, extending from central North Dakota across South Dakota to the Mississippi River, was also carved by a **lobe** that extended from the ice sheet.

Glacial Lake Missoula, another massive glacial lake located in Montana, was created when the Clark Fork River in Idaho was dammed by ice over 610 meters (2000 feet) high. As the lake grew deeper and higher, waves eroded the ground along the shoreline (*Figure 6.21*), and water pressure against the ice dam increased, eventually causing catastrophic failure of the dam. Water flowed out of the dam at a calculated speed of 105 kilometers (65 miles) per hour, allowing the lake to drain in a few days. Along with water, ice and glacial debris were carried to the west as the lake drained. This event carved the Channeled Scablands, a barren, scoured landscape that extends from Idaho through Washington and Oregon (*Figure 6.22*).

Figure 6.21: Wave-cut terraces along Mt. Jumbo near Missoula, Montana mark the ancient lakeshore of Lake Missoula.

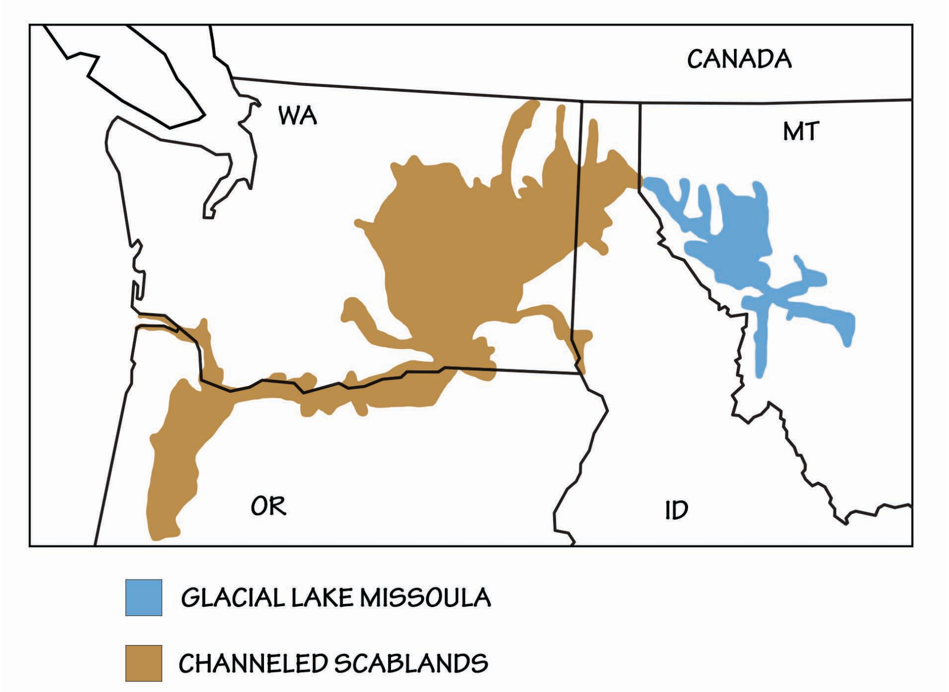

Figure 6.22: Glacial Lake Missoula and the extent of the Channeled Scablands. (See TFG website for full-color version.)

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Impact

hanging valley *• a tributary valley that drops abruptly into a much larger and deeper valley.*

Alpine Glaciers in the Northwest Central States

One of the hallmarks of alpine glaciers in the Northwest Central States is the rugged mountain terrain they carve. The stunning characteristics of the Rocky Mountains—from jagged peaks and bowls to glacial valleys and high meadows—are largely a result of glacial erosion and deposition during the Pleistocene. In several cases, these glaciers coalesced into ice caps covering entire mountain ranges. In other instances, they merged with advancing continental ice sheets, eventually becoming indistinguishable as separate glaciers, only to regain their distinctiveness as the ice sheets retreated. As these glaciers retreated, they not only exposed characteristic U-shaped valleys, but they also revealed a diverse collection of peaks, bowls, ridges, and lakes scraped into the bedrock (*Figures 6.23, 6.24*).

For instance, in the Wind River Mountains of Wyoming, the Beartooth-Absaroka Range in Montana, and the Sawtooth Mountains of Idaho, glaciers have carved a series of horns, arêtes, and cirques. Below these prominent features, we often find chains of lakes that form when meltwater pools behind lateral and terminal moraines. Likewise, in and around Yellowstone National Park and the Teton Mountains of Wyoming, a network of small Pleistocene glaciers merged like streams flowing into a large river. As the glaciers retreated, they left behind a collection of smaller U-shaped valleys (known as **hanging valleys**) that drop abruptly into a much larger valley. This phenomenon is responsible for the formation of spectacular waterfalls like Tower Fall (*Figure 6.25*)

Figure 6.24: Glacial meltwater lakes near Yellowstone National Park in Wyoming.

Figure 6.23: Glacially sculpted mountain ranges with horns, arêtes, and cirques are common in Glacier National Park, Montana.

Figure 6.25: Tower Fall, Yellowstone National Park.

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Chapter 7: Energy in the Northwest Central 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 power 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 for 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.

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, it produced more than 120 million MWh—more than 1000% growth in ten years! That aspect of change stands in contrast to our

***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 2000 years ago.**

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.

energy • *the power derived from the use of physical or chemical resources.*

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

heat • *a form of energy transferred 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.*

system • *a set of connected things or parts forming a complex whole.*

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

CHAPTER AUTHORS

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long-lasting reliance on **fossil fuels**, such as **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.

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

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 roughly 1055 **joules**, or the amount of energy released by burning a single wooden match. A joule is the energy expended (or work done) to apply a force of one newton over a distance of one meter. Since a typical apple weighs about one newton, lifting an apple one meter requires about a joule of energy. That means that one Btu—the energy contained in a wooden match—is equivalent to the total amount of energy required to lift an apple 1000 meters, or one kilometer.

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.

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

Another measure of energy, the kilowatt-hour (kWh), represents 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.

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

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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.*

natural gas • *a hydrocarbon gas mixture composed primarily of methane (CH4), but also small quantites of hydrocarbons such as ethane and propane.*

joule • *the energy expended (or work done) to apply a force of one newton over a distance of one meter.*

kinetic energy • *the energy of a body in motion.*

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 7

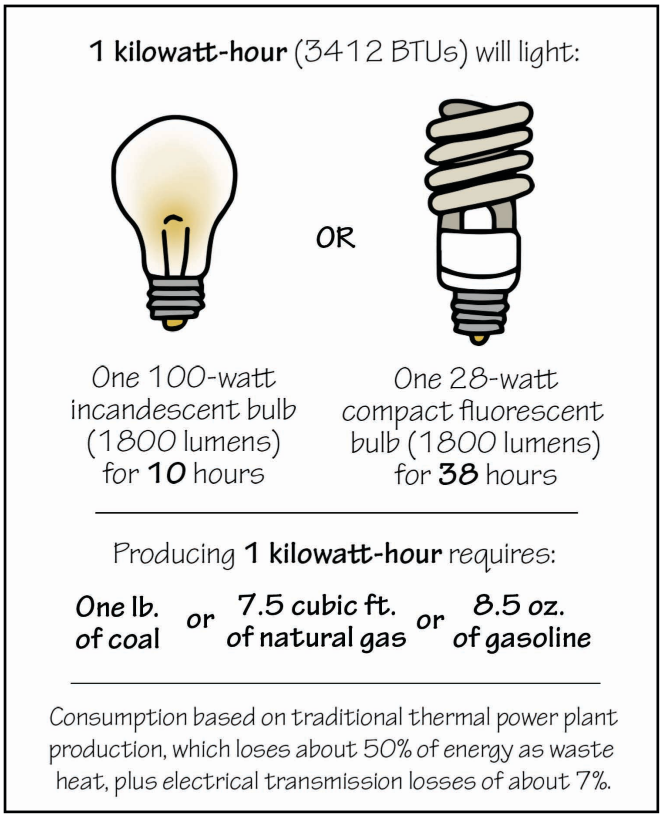


Figure 7.1: Examples of uses and sources of one kilowatt-hour.

greater distances). Especially as the global population grows and standards of living increase in some parts of the world, so too does global energy demand continue to grow.

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

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 • *pertaining to a reaction, as in fission, fusion, or radioactive decay, that alters the energy, composition, or structure of an atomic nucleus.*

7

Energy

Review

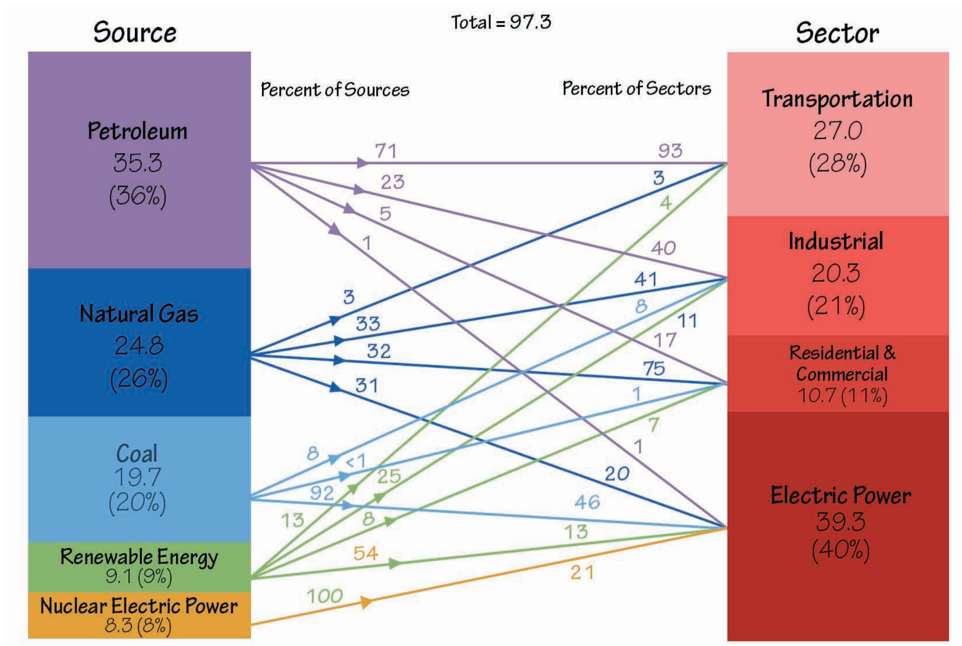


Figure 7.2. US energy production sources and use sectors for 2011. Petroleum provides more energy than any other source, and most of it is used for transportation. More energy is used to generate electricity than for any other use, and electricity is generated by all five energy sources. Nuclear is unique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

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 listed in the following chart.

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.**

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 7

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.**

Energy in the Northwest Central Regions

The Northwest Central US is rich in energy production, but varies significantly in the types of production among its regions. Some of the nation's largest coal and petroleum reserves exist in the Great Plains and Rocky Mountains, thanks to the extensive geologic basins found within these regions (*Figures 7.3–7.5*). A substantial quantity of corn for **biofuel** comes from the Central Lowland, because the region's **topography**, **soils**, and **climate** make it appropriate for large-scale agriculture. Large wind farms exist in the Great Plains where high wind speeds can develop over relatively flat lands with low surface friction. Large hydroelectric plants associated with the Snake River and its tributaries exist in the Basin and Range and Columbia Plateau. Even uranium for nuclear energy is mined in the Northwest Central US, primarily from basins in the Rocky Mountains. In each case, the energy developed is a function of the area's past geologic history and the economic viability of developing its resources. While fossil fuel development and use still dwarfs that of alternative energy sources, renewable energies continue to grow quickly.

Of the Northwest Central States, Idaho, Nebraska, and South Dakota produce more energy from "clean" sources (including biomass, nuclear, and renewables) than they do from fossil fuels. Idaho is especially rich in geothermal resources, and almost all energy produced there is generated from renewables and biofuels, which provide for nearly 80% of the state's total power consumption.

Regions

biofuel • *carbon-based fuel produced from renewable sources of biomass like plants and garbage.*

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

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

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).*

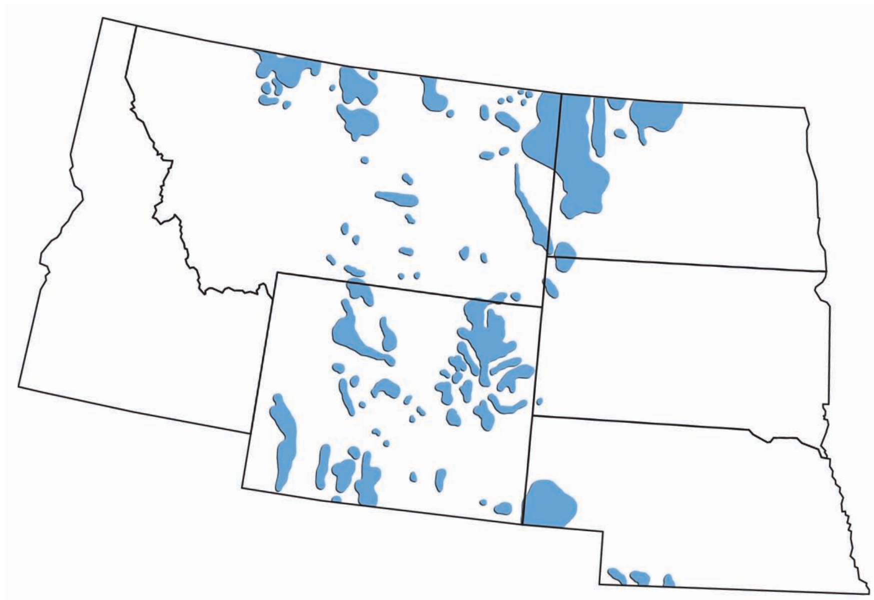


Figure 7.3: Petroleum-producing regions of the Northwest Central US.

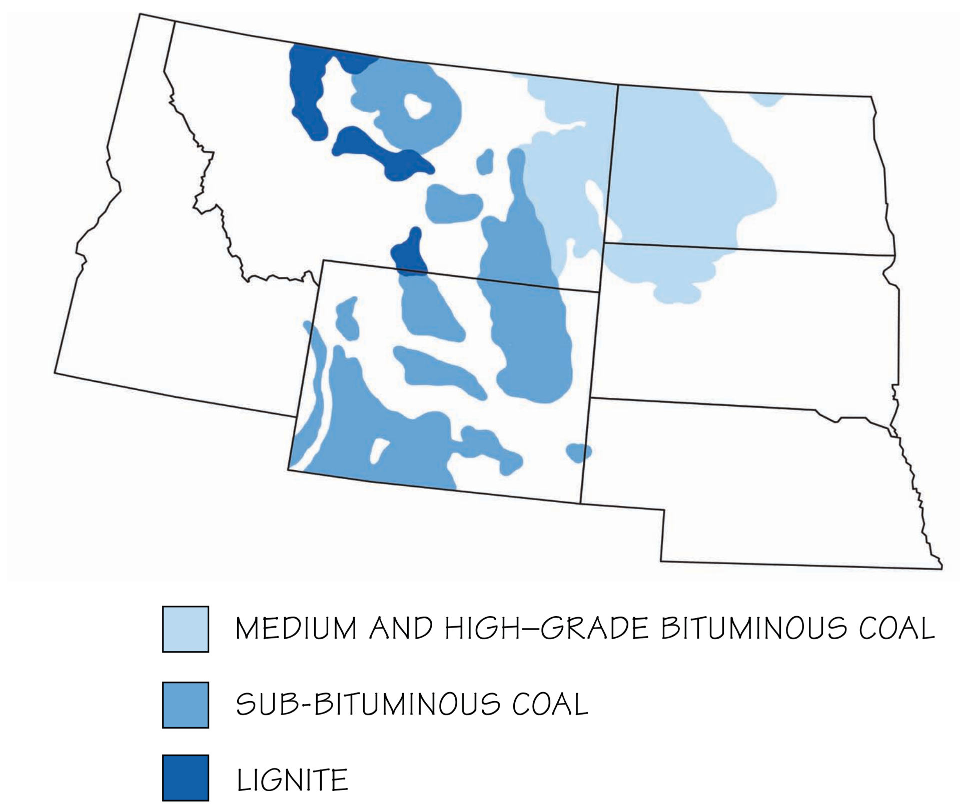


Figure 7.4: Coal-producing regions of the Northwest Central US. The Great Plains is a particularly significant coal producing area.

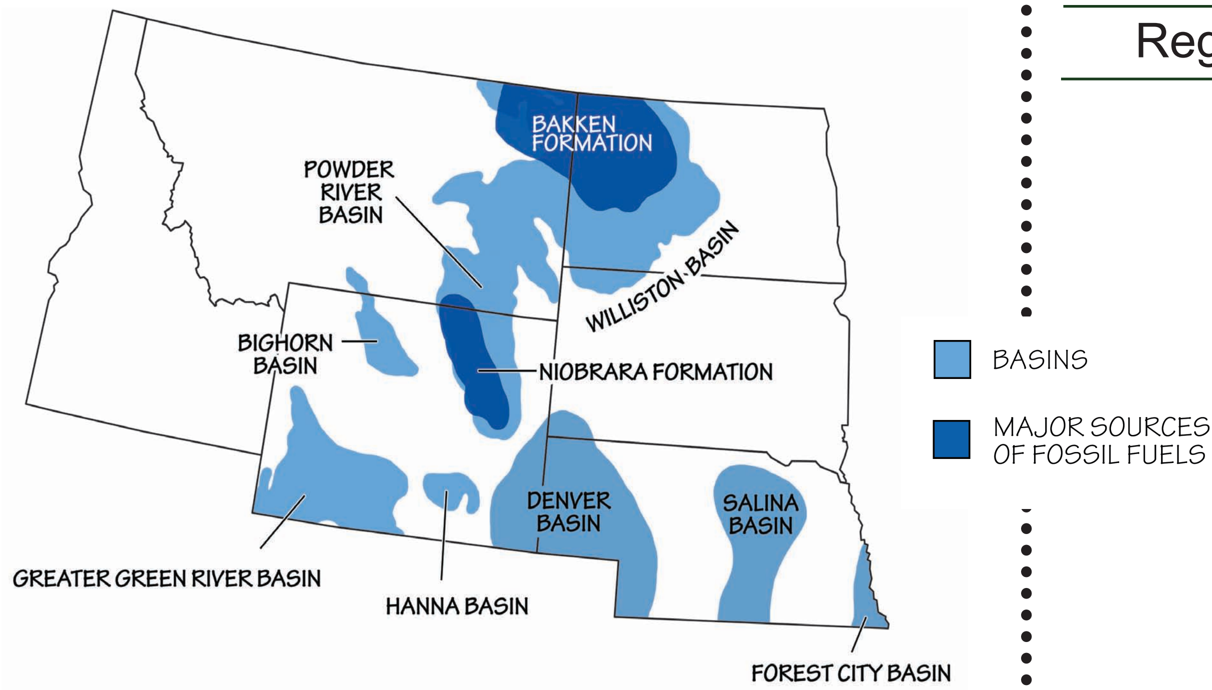
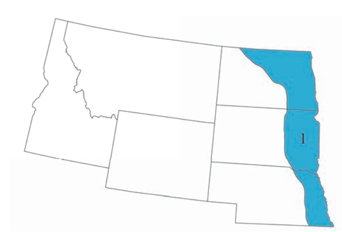


Figure 7.5: Sedimentary basins containing significant fossil fuel accumulations in the Northwest Central US.

Energy in the Central Lowland

Region 1



Due to its geological history, the Central Lowland is not a major producer of fossil fuels, but in recent years the region's energy production has increased for two energy sources related to its topography: wind energy and corn-based ethanol. Even given these new sources, the Central Lowland of the Northwest Central is not considered a center of production. Wind energy potential is even higher to the west in the Great Plains, and the bulk of corn production for ethanol occurs to the east, in the Midwestern US.

Fossil Fuels

Fossil fuel production in the Central Lowland is primarily limited to a small part of the Forest City Basin in the southeast corner of Nebraska and the Salina Basin in south-central Nebraska, also known as the Central Nebraska Basin (*see Figure 7.5*). The Salina Basin in Nebraska did not experience the appropriate combination of heat, pressure, and organic matter to generate a large petroleum potential.

7

Energy

Region 1

Fossil Fuels

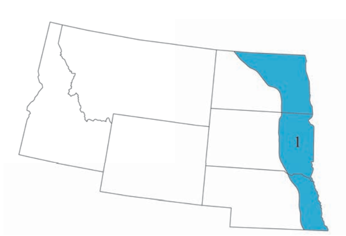
Fossil fuels—oil, natural gas, and coal—are made of the preserved organic remains of ancient organisms. Coal and lignite result from the burial, compaction, and heating of preserved plant matter, whereas petroleum and natural gas originate deep underground through a slow process involving the low-grade heating of sedimentary source rocks that contain an abundance of organic matter. In either case, organic matter is only preserved when the rate of accumulation is higher than 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.

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.

Alternative Energy

Much of the Central Lowland is part of the "corn belt," the largest corn-producing area in the US, which supports over a hundred-billion-dollar-a-year industry that helps feed the world but that also produces plastics, biofuel, and livestock feed. In the Northwest Central, this region has become a leading area for the production of corn-based biofuels (*Figure 7.6*). In fact, the processing and production of crops for biofuel has been expanding here since the 1980s. Corn ethanol is the most common liquid biofuel in the United States, with the majority blended into gasoline for use in passenger vehicles. About 40% of US-grown corn is now used to produce ethanol.

See Chapter 8: Soils for more information about the Central Lowland's fertile agricultural soils.



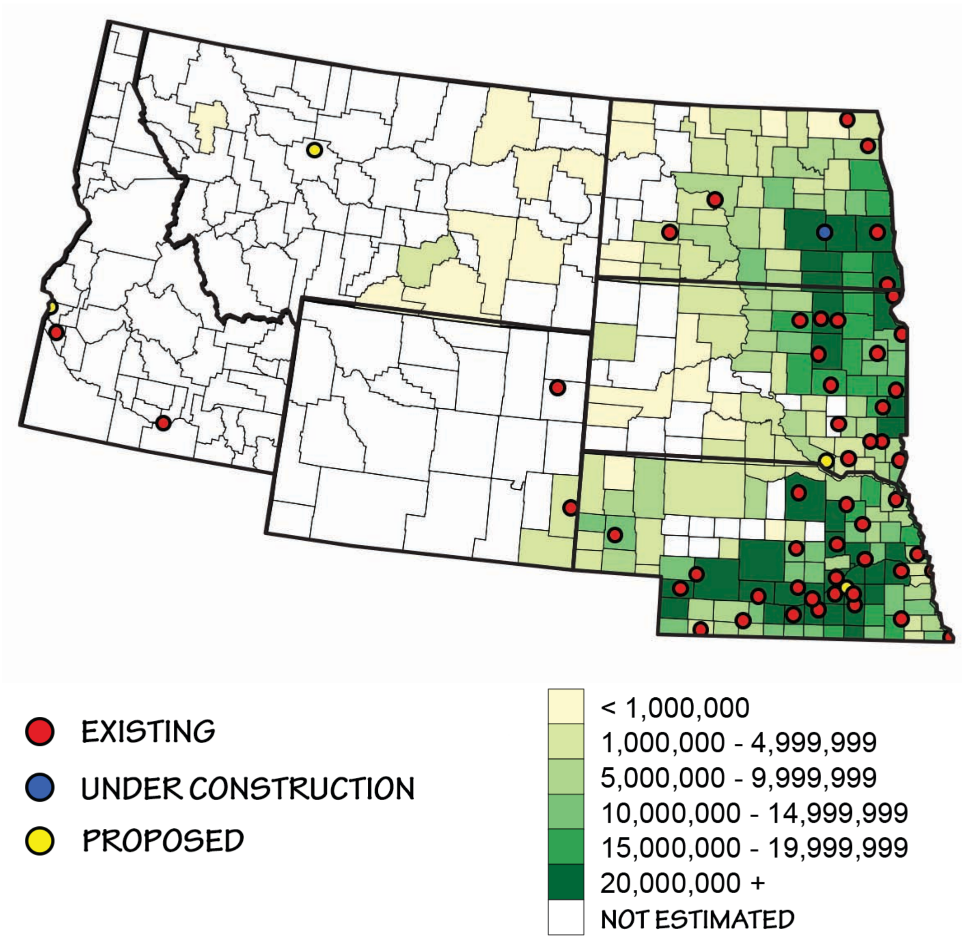
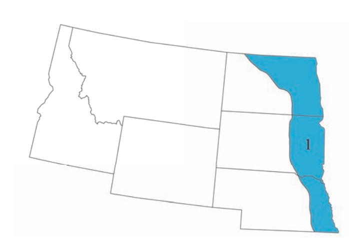


Figure 7.6: Corn production (bushels) and locations of ethanol plants in the Northwest Central US by county and location (as of 2013).

Two nuclear power plants are present in the Central Lowland, both in Nebraska. The Cooper Nuclear Station and the Fort Calhoun Nuclear Generating Station are both located along the Missouri River, and they produce a combined 1244.6 megawatts of power.

See Chapter 10: Earth Hazards to learn about major Missouri River floods that endangered Nebraska's nuclear power plants.

The Central Lowland and adjacent Great Plains regions, with their broad and flat topography, have become major sources of wind energy. North Dakota produces nearly two gigawatts of wind power, and its low population grants it the highest per capita generation of wind power in the country. Most of the state's wind power is located in the Great Plains, which is discussed in greater detail in the next section of this chapter.



7 Energy

Region 2

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

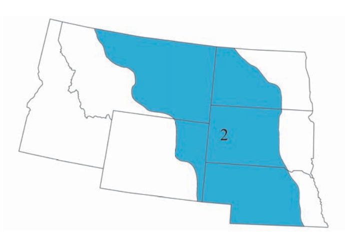
Cenozoic • *the geologic time period spanning from 66 million years ago to the present.*

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.*

Paleocene • *a geologic time interval spanning from about 66 to 56 million years ago.*

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

fuel • *a material substance that possesses internal energy that can be transferred to the surroundings for specific uses.*



Energy in the Great Plains

Region 2

The Great Plains region is a broad expanse of flat land underlain by thick sequences of **sedimentary rock** and primarily covered in grassland and prairie. Ancient sedimentation patterns and tectonic activity have favored the placement of widespread fossil fuel resources in this region. Organic-rich sediments were deposited in **inland seas** that spread across much of the region, and **Cenozoic** swamps contributed plant matter to form thick beds of coal. The Great Plains' sedimentary basins contain vast oil, gas, and coal reserves that dominate energy production here (*see Figure 7.5*), but the area's topography and climate also make it appropriate for large wind farms.

Coal

The world's largest known **lignite** coal deposit, weighing in at an estimated 351 billion tons, is found in western North Dakota's Williston Basin. This area is known as the Fort Union coal region, named after the Fort Union Formation, a thick sequence of **Paleocene**-aged coal deposits lying above **Cretaceous**-aged marine sediments from the Western Interior Seaway. North Dakota's supply of lignite is estimated to last more than 800 years, and the deposits are used for synthetic **fuels** (made of carbon monoxide and hydrogen) as well as fuel for nearby power plants. Coal mining in this area began in the 1870s, when small seasonal mines sprung up along the main routes of transportation in the area. Over 250 mines were in operation by the 1920s. Today, there are only six large coal mines in western North Dakota, from which 32 million tons of coal are extracted annually. One of these, the Freedom Mine, is the 12th largest coal mine in the US.

In Wyoming, great quantities of coal are produced annually from the Powder River Basin (*see Figure 7.4*). Like the Williston Basin, the Powder River Basin contains a thick sequence of Cretaceous marine **shales** and **sandstones** formed in the Western Interior Seaway, overlain by Paleocene-aged coals of the Fort Union Formation. These coals have experienced greater heat and pressure from burial than those in the Williston Basin, and thus are higher-grade sub-**bituminous** coals. In fact, the Powder River Basin contains the largest resources of low-**sulfur**, low-ash, sub-bituminous coal in the US. These deposits provide more than 40% of the US coal supply, making Wyoming the largest coal-producing state (*Figure 7.7*). The Black Thunder Coal Mine is currently the most productive coal mine in the US, providing 8% of the country's coal and 20% of Wyoming's total coal production. This mine utilizes the world's largest dragline excavator, employed to strip the overlying rock and sediment and expose the underlying coal seams.

The Great Plains of Montana also produce sub-bituminous coal from the northern extension of the Powder River Basin and lignite from the western extension of Williston Basin deposits (*see Figure 7.4*). Montana ranks 6th in the nation among coal-producing states. Considerably more coal resources lie below currently mineable depths, that is, below about 150 meters (500 feet). Not surprisingly, these zones are being considered for potential underground

Figure 7.7: Coal mining in Wyoming. Mining of thick sub-bituminous coal beds in the Paleocene Fort Union and other formations make Wyoming the largest coal-producing state in America.

coal gasification projects that would convert coal to gas below the surface and then bring the gas to the surface through wells.

Oil and Gas

Oil deposits from the Great Plains region are also among the largest in the US. It is possible to make sense of why we find petroleum and natural gas in these areas by understanding the history of marine environments. Mud with relatively high organic matter content tends to accumulate in shallow continental seas and in coastal marine environments. The Northwest Central has been home to both types of environments throughout its geologic past.

See Chapter 1: Geologic History to learn more about the changing face of the Northwest Central through geologic time.

Conventionally, finding oil and gas has not been as simple as finding organic-rich rock layers. Oil and gas can flow both within and between rock layers, wherever the number and size of paths between pores, **fractures**, and other spaces (**permeability**) is large enough. Because oil and gas are under pressure, they will move gradually upward to areas of lower pressure and will rise all the way to seeps at the surface unless they are blocked by a **caprock**—that is, one or more layers with permeability so low that they effectively block the flow of liquids and gases. If the fossil fuel happens to rise beneath a caprock in the shape of a concave surface (such as an **anticline** or certain **faults**), the

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

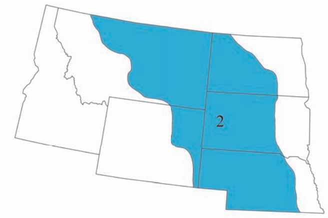
sandstone • *sedimentary rock formed by cementing together grains of sand.*

bituminous coal • *a relatively soft coal containing a tarlike substance called bitumen, which is usually formed as a result of high pressure on lignite.*

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

fracture • *a physical property of minerals, formed when a mineral crystal breaks.*

permeability • *a capacity for fluids and gas to move through fractures within a rock, or the spaces between its grains.*



Energy

Region 2

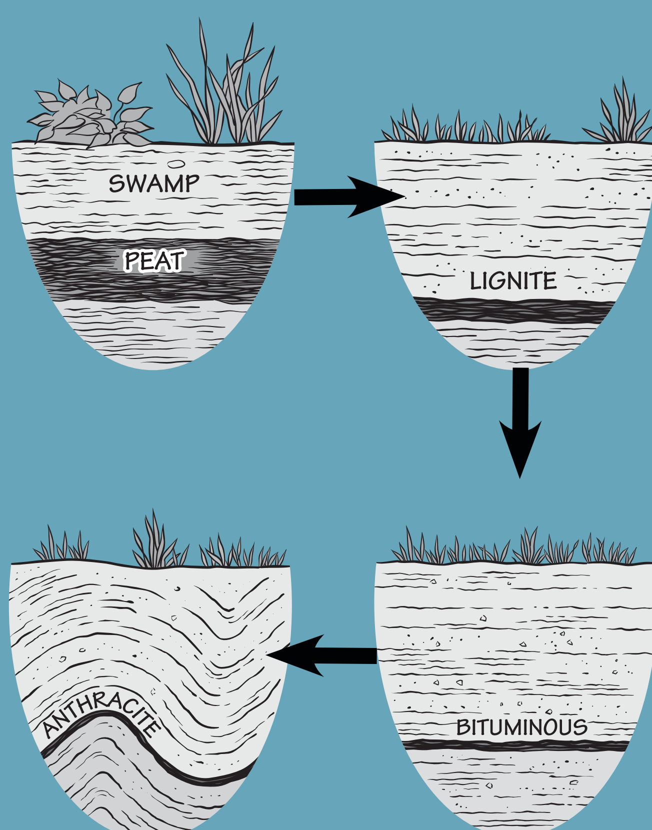
anthracite • *a dense, shiny coal that has a high carbon content and little volatile matter.*

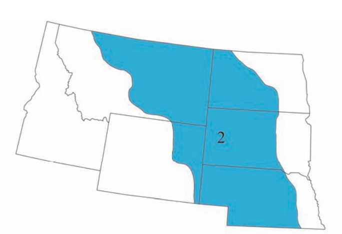
Carboniferous • *a geologic time period that extends from 359 to 299 million years ago.*

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. Globally, a remarkable amount of today's coal formed from the plants of the Carboniferous, which included thick forests of trees with woody vascular tissues. However, in the Northwest Central US most coal is from plants of the Paleocene and Eocene epochs.

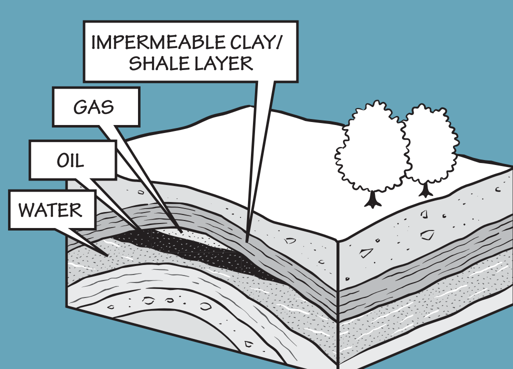




Oil and Gas

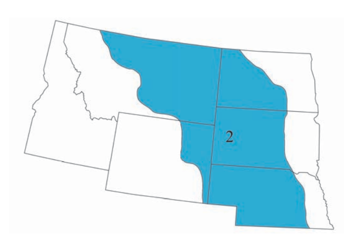
Oil and gas form from organic matter in the pores of sediments subjected to heat and pressure. The organic matter is primarily composed of photosynthetic plankton that die and sink in vast numbers to the bottom of large water bodies. Shale in particular is often organic rich, because organic matter settles and accumulates in the same places that mud (*clay* and *silt* particles) settles out of the water. In most environments, organic matter is recycled by bacteria before it can be buried, but the quiet waters where mud accumulates are often relatively stagnant and low in oxygen. In these places, the bacterial decay rate is low relative to the rate of organic matter sinking and to the rate that the organic matter becomes buried in muddy sediments. Under such conditions, enough organic matter may accumulate to make up several percent or more of the deposited sediment.

Because oil and gas are under pressure, they will move gradually upward to areas of lower pressure through tiny connections between pore spaces and natural fractures in the rocks. Reservoir rocks typically have a considerable amount of pore space, and to be viable there must be a way of trapping the oil and gas, such as through a geologic structure or a change in rock type that will prevent the resource from escaping. 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.



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.*



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

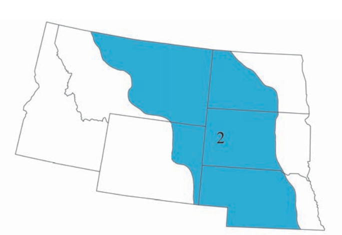
chalk • *a soft, fine-grained, easily pulverized, white-to-grayish variety of limestone, composed of the shells of minute planktonic single-celled algae.*

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.*

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

dolostone • *a rock primarily composed of dolomite, a carbonate mineral.*



fossil fuels may accumulate in what geologists call a "reservoir." Reservoirs are typically found in porous sedimentary layers and thin natural fractures. Most oil and gas has been extracted using the conventional technique of searching for such reservoirs and then drilling into them, which allows the gas or oil to come to the surface through a vertical well. Reservoir rocks in the Great Plains include **dolomites**, **chalks**, and organic-rich shales.

There have been estimates of some 400 billion barrels of untapped oil in the Bakken Formation, and large reserves of both oil and natural gas in the Niobrara Formation, though estimates of the size of oil and gas reserves that can or will be economically extracted are in dispute. The Fort Union Formation in the Powder River Basin is also a significant source of coalbed methane. Thanks to these geological units, this region is a net exporter of energy, providing much of the central US with its oil and gas.

The Bakken Formation formed in the late **Devonian** and early **Mississippian**, in a continental sea that filled what we now call the Williston Basin. The Bakken is known only from coring, as it does not outcrop at the surface. The source rock for the formation's oil is present in its upper and lower dark shale layers, and a reservoir layer of dolomite lies between the shales. Since 2000, oil production rates in the Bakken Formation expanded enormously through the application of horizontal drilling combined with high volume hydraulic fracturing. This method fractures rocks beneath the surface, releasing gas and oil trapped in source rocks that have very low permeability (also known as "tight" layers). Hydraulic fracturing uses high volumes of water introduced at high pressure through horizontal wells along the source rock layer, to create thousands of tiny fractures (*Figure 7.8*). Most horizontal wells are drilled where the source rock is about 100–150 meters (330–490 feet) thick. The fractures are held open by small grains of **sand** carried by gel in the water, increasing its viscosity. A number of chemicals are added to the water to increase the recovery of fossil fuels, including a chemical to reduce friction as the mixture is introduced (thus the term "slickwater"). "Slickwater, high-volume hydraulic fracturing"—often shortened to "hydraulic fracturing" or simply "fracking"— has greatly increased the accessibility of available fossil fuel resources and the production rate of oil and gas. It has also been controversial, in part because of associated environmental impacts. Unlike some famous "fracked" formations in other areas, such as the Barnett Shale in Texas and Marcellus Shale in Pennsylvania, the part of the Bakken Formation most intensively hydraulically fractured has been its **dolostone** reservoir unit rather than the dark shale source rock. This unconventional drilling activity is centered in North Dakota, which has become the nation's second largest oil-producing state after Texas (*Figure 7.9*).

The Niobrara Formation, also known as the Niobrara Chalk or Niobrara Shale, extends from the Gulf of Mexico to the Arctic, and originates from sedimentary deposition in the late Cretaceous Western Interior Seaway. Where the formation outcrops at the surface, it is famous for its **fossil** faunas. The Niobrara is tapped for fossil fuels in the Denver Basin (also known as the Julesburg or D-J Basin), which underlies northeastern Colorado, a small corner of southeast Wyoming, and southwest Nebraska. The formation contains alternating chalks and organic-rich **marls** and shales; the marls and shales are a source of petroleum, and the adjacent chalks have become reservoir rocks. Natural gas and oil from

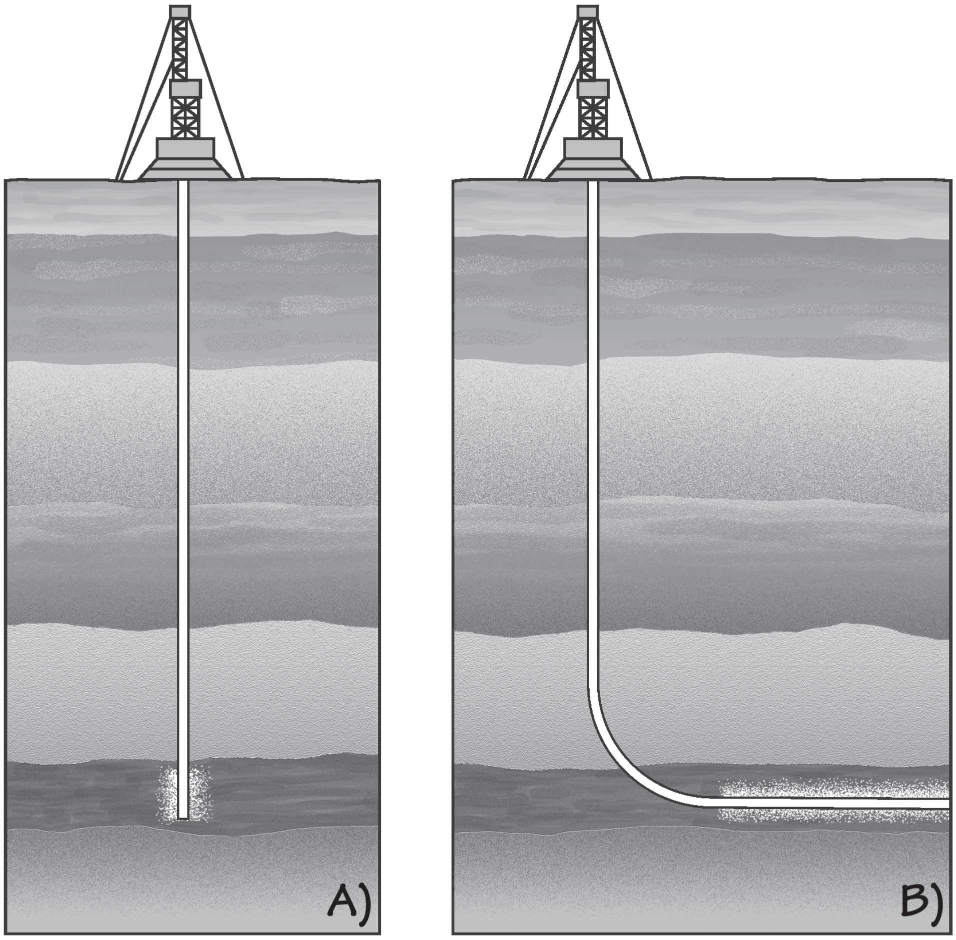
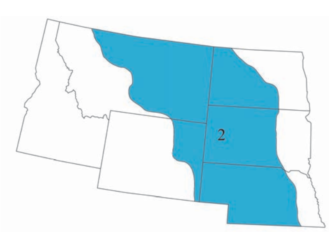


Figure 7.8: Oil wells (not to scale). A) A conventional vertical well. B) An unconventional horizontal well. Hydraulic fracturing may be carried out along horizontal wells running for a mile or more along layers with oil or gas trapped in pore spaces.

Figure 7.9: Oil pumpjacks in McKenzie County, North Dakota. The flame on the right-hand side is a flare that burns off natural gas separated from the oil.

fossil • *preserved evidence of ancient life.*

marl • *a fine-grained sedimentary rock consisting of clay minerals, calcite and/or aragonite, and silt.*



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

coalification • *the process by which coal is formed from plant materials through compression and heating over long periods of time.*

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

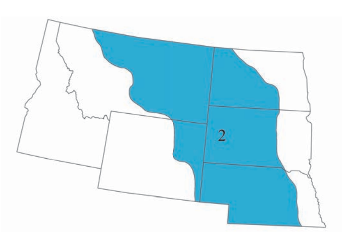
How does oil drilling work?

Once an oil trap or reservoir rock has been detected on land, oil crews excavate a broad flat pit for equipment and supplies around the area where the well will be drilled. Once the initial hole is prepared, an apparatus called a drilling rig is set up. The rig is a complex piece of machinery designed to drill through rock to a predetermined depth. A typical drilling rig usually contains generators to power the system, motors and hoists to lift the rotary drill, and circulation systems to remove rock from the borehole and lubricate the drill bit with mud. It also contains high-pressure blowout prevention equipment to prevent pressurized oil or gas from rising uncontrollably to the surface after being tapped. The support structure used to hold the drilling apparatus is called a derrick. In the early days of oil exploration, drilling rigs were semi-permanent structures and derricks were left onsite after the wells were completed. Today, however, most rigs are mobile and can be moved from well to well. Once the well has been drilled to a depth just above the oil reservoir, a cement casing is poured into the well to structurally reinforce it. Once the casing is set and sealed, oil is then allowed to flow into the well, the rig is removed, and production equipment can be put in place to extract the oil.

conventional drilling have been extracted from the Niobrara since the early 1900s, and in the past decade unconventional drilling below about 1830 meters (6000 feet) has greatly increased oil production in southeastern Wyoming.

See Chapter 3: Fossils to learn about fossils of the Niobrara Formation.

The Powder River Basin hosts significant quantities of coalbed methane. Coal mines have long been vented to the **atmosphere**, in part because of the build-up of methane (CH_4, the primary gas in natural gas) released from fissures around the coal. This methane is a byproduct of the process of **coalification**, by which ancient plant material was transformed into coal, and it accounts for over 5% of US methane production. While originally considered a hazard to be mitigated in subsurface mines, methods have been developed to trap this methane as an additional energy source. In some subsurface coal seams, water saturates fractures in the seam, transforming it into an **aquifer** (which



in some places may be clean enough to be part of the local water supply). If there is sufficient water pressure, methane present in the coal fractures may be trapped in the coal. To extract this methane, water can be removed via wells, thereby reducing pressure and allowing the gas to escape toward lower pressures along the well bore (*Figure 7.10*). Methane is then separated from the water. After the water is removed, it may take some years for the aquifer to be recharged, that is, refilled with water that infiltrates below the surface to the aquifer. Production rates climbed steeply beginning in the early 1990s, though in recent years it has decreased both in absolute and relative quantity as shale gas methane production has increased. Wyoming is one of the three leading US states for coalbed methane production (approximately equal to that of Colorado and New Mexico), each of which account for about 25% or more of the national total.

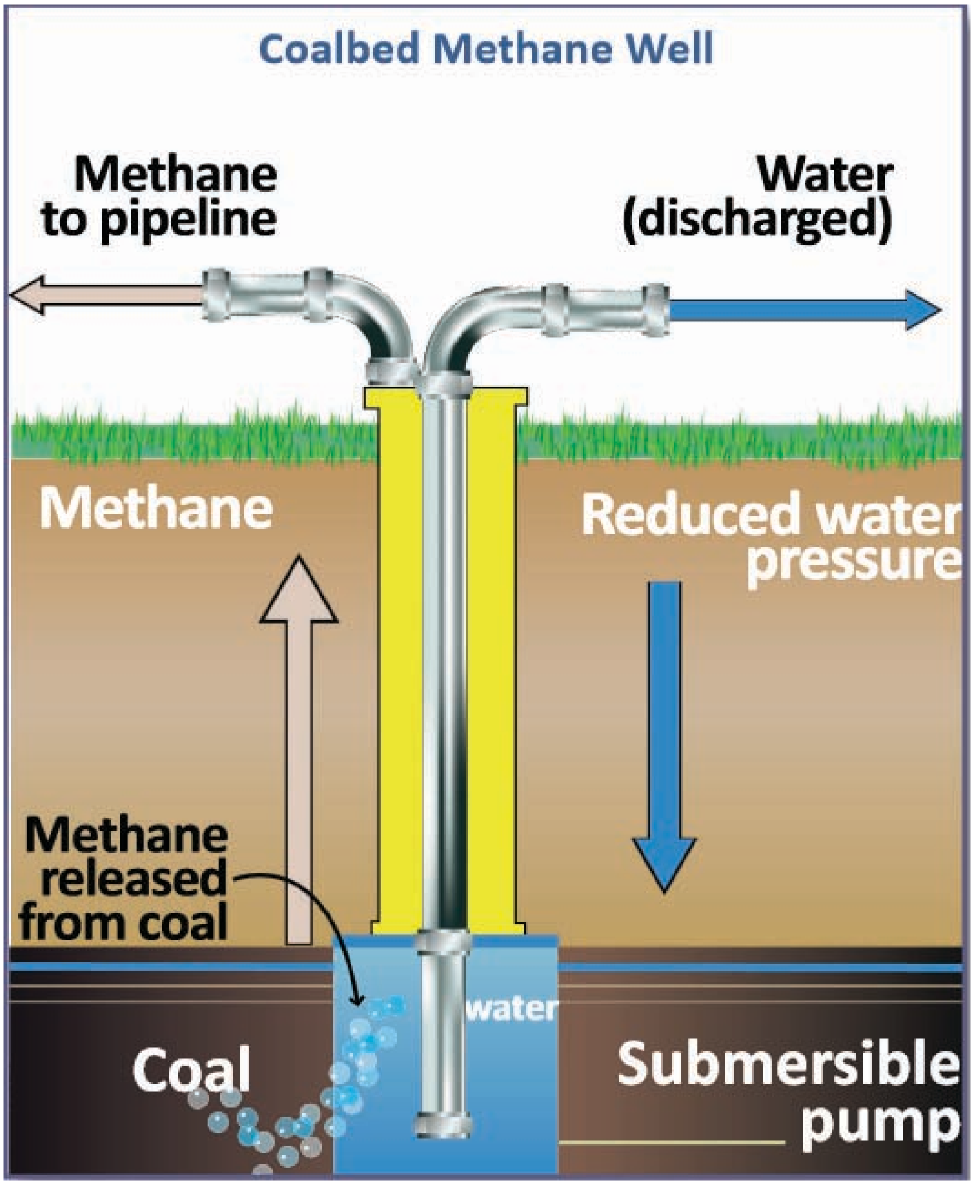
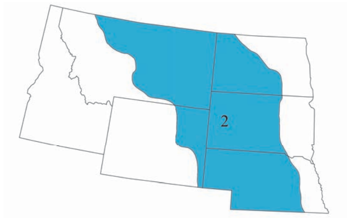


Figure 7.10: Coalbed methane production involves using water or other fluids to reduce pressure on the coal seam by creating a crack through which the methane can escape into a well.



Energy

Region 2

Eocene *• a geologic time period extending from 56 to 33 million years ago.*

Oligocene *• a geologic time interval spanning from about 34 to 23 million years ago.*

Wind Energy

The Great Plains (in this case referring to the full area that runs from Texas to Montana and into Canada) has been called the "Saudi Arabia of Wind Energy," at least in terms of potential (*Figure 7.11*). Wind energy provides about a third of the renewable energy produced in the US, with hydroelectric representing about half; solar, geothermal, and biomass account for the remaining sixth. In contrast to hydroelectric, wind energy is growing rapidly—it grew tenfold on a national scale from 2004 to 2014, and wind farms on the Great Plains have played a significant role in that growth. In the Northwest Central, the five Great Plains states are among the top 16 states for wind energy as a percentage of state electricity generation (South Dakota 25%, North Dakota 18%, Wyoming 9%, Nebraska 7%, and Montana 7%). This is all the more remarkable considering the rate of local petroleum and coal extraction.

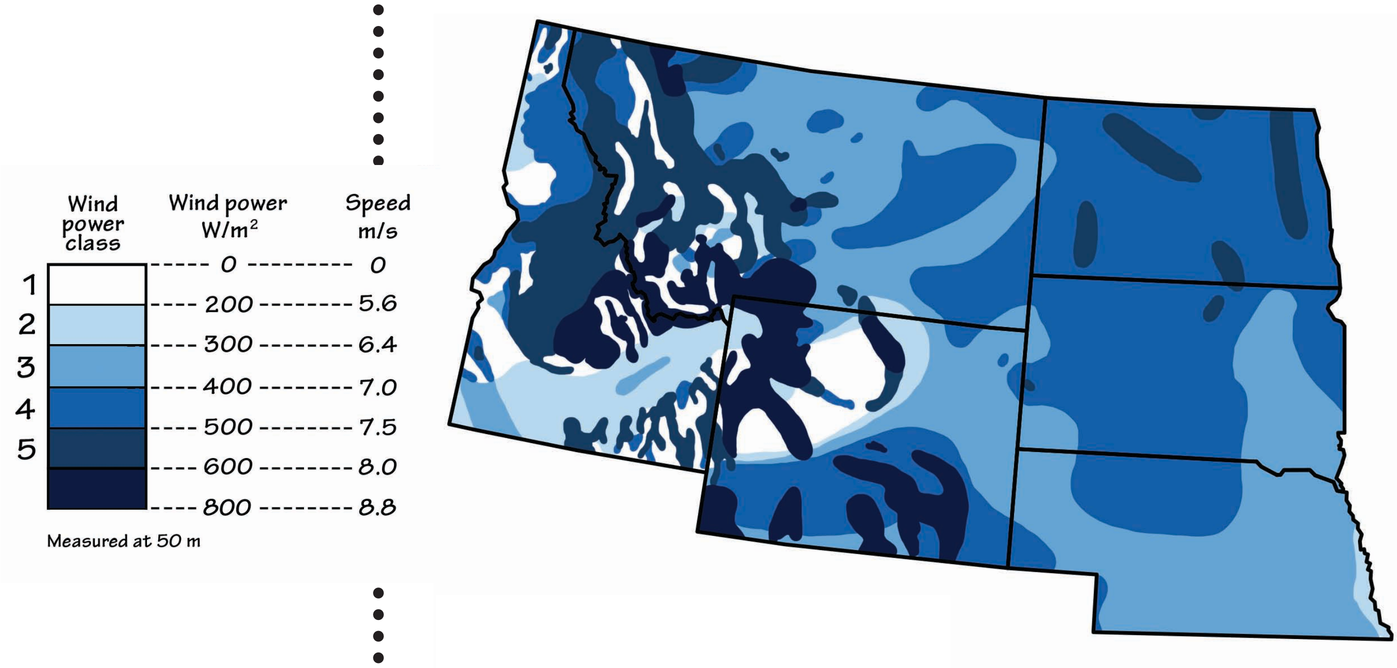
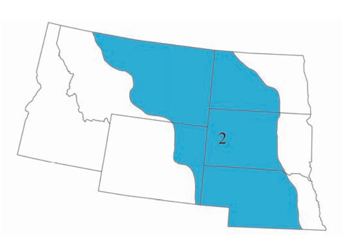


Figure 7.11: Wind energy potential in the Northwest Central US.

Uranium

Uranium used in nuclear power plants is mined from certain sedimentary rocks in the Great Plains. Economic deposits of uranium are found in Paleocene and **Eocene** sandstones in the southern Powder River Basin of Wyoming and in **Oligocene** rocks in northwest Nebraska (Crow Butte). The Paleocene lignitic coals of North Dakota also contain significant uranium content. Despite the prevalence of uranium resources throughout the Great Plains, however, nuclear power is not generated here.



Energy 7

Regions 2–3

Wind Energy and Landscape

Economically useful wind energy depends on steady high winds. Variation in wind speed is in large part influenced by the shape and elevation of the land surface. For example, higher elevations tend to have higher wind speeds, and flat areas can allow winds to pick up speed without interruption; thus high plateaus are especially appropriate for large wind farms. Since plateaus with low grass or no vegetation (or water bodies) have less wind friction than do areas of land with higher crops or forests, they facilitate higher winds. For all these reasons, the Great Plains region has high average wind speeds throughout its extent.

The Rockies and the Basin and Range, however, may have *locally* high wind speeds that can support strategically placed wind farms. For example, constricted valleys parallel to wind flow may funnel air into high velocities. Elevated ridges perpendicular to wind flow can also force fast winds across them. Thus, the wind velocities of these areas can vary geographically in quite complicated ways.

Laramide Orogeny* • *a period of mountain building that began in the Late Cretaceous, and is responsible for the formation of the Rocky Mountains.

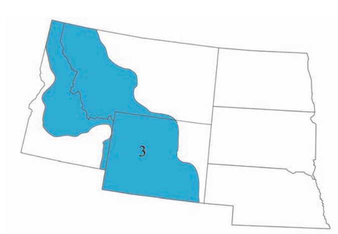
mineral* • *a naturally occurring solid with a specific chemical composition and crystalline structure.

Energy in the Rocky Mountains
Region 3

The high topography of the Rocky Mountains provides context both for hydroelectric power and wind energy. The same rugged peaks and valleys that contribute to localized high winds also make large-scale wind energy development difficult. The Rocky Mountains region is also known for coal, oil, and gas, in this case from large freshwater sedimentary deposits in the Greater Green River Basin.

Oil and Gas

Petroleum resources are extracted in the Greater Green River Basin (*see Figure 7.5*). The Greater Green River Basin is itself made up of several smaller basins and arches between them, formed during the **Laramide Orogeny** from the end of the Cretaceous period into the Eocene. The basin is known for its Eocene-aged surface rocks that contain both **mineral** and fossil fuel resources,



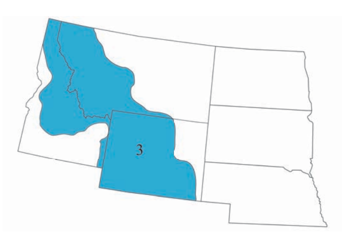
along with its unusually well-preserved terrestrial fossils in the Green River Formation. Fossil fuels, thought to be derived from blue-green algae living in ancient lakes, are found in particularly thick sequences of Eocene oil shale. The Green River Formation hosts the largest known oil shale deposits in the world.

See Chapter 5: Mineral Resources to learn more about the wide variety of minerals found in the Rocky Mountains.

delta • *a typically wedge-shaped deposit formed as sediment is eroded from mountains and transported by streams across lower elevations.*

The Greater Green River Basin also contains other fossil fuel resources of lesser renown. For example, the largest of the arches in the basin, the Rock Springs Uplift (which divides the basin into the Green River Basin on the west and smaller basins in the east) contains coal deposits that were first mined as fuel for the Union Pacific Railroad during the building of the Transcontinental Railroad and subsequent railroad operations. Conventional oil and gas drilling has also occurred in the basin, in Cretaceous-aged **deltaic** rocks from the Western Interior Seaway (*Figure 7.12*). The Wamsutter gas field, occupying a 89-kilometer-long (55-mile-long) portion of Wyoming's Red Desert, has recently experienced an energy boom, with more than 2000 gas wells projected to be operational there by 2020.

Figure 7.12: Natural gas drilling rigs in the Upper Green River Valley.



Hydroelectric Power

Since the Rocky Mountains provide an abundance of water to lower regions in the east and west, hydroelectric power is substantial in this area (*Figure 7.13*). The Clark Fork and Kootenai Rivers (tributaries of the Columbia River that flow through Montana and Idaho) are major rivers that provide the potential for much of the Rocky Mountains' hydropower, which uses the gravitational force of falling or rushing water to rotate turbines that convert the water's force into energy. The three largest hydropower plants in Montana—Noxon Rapids Dam (580.5 MW), Libby Dam (525 MW), and Hungry Horse Dam (428 MW)—are located along these rivers and their tributaries, helping to make Montana one of the largest producers of hydropower in the US (*Figure 7.14*).

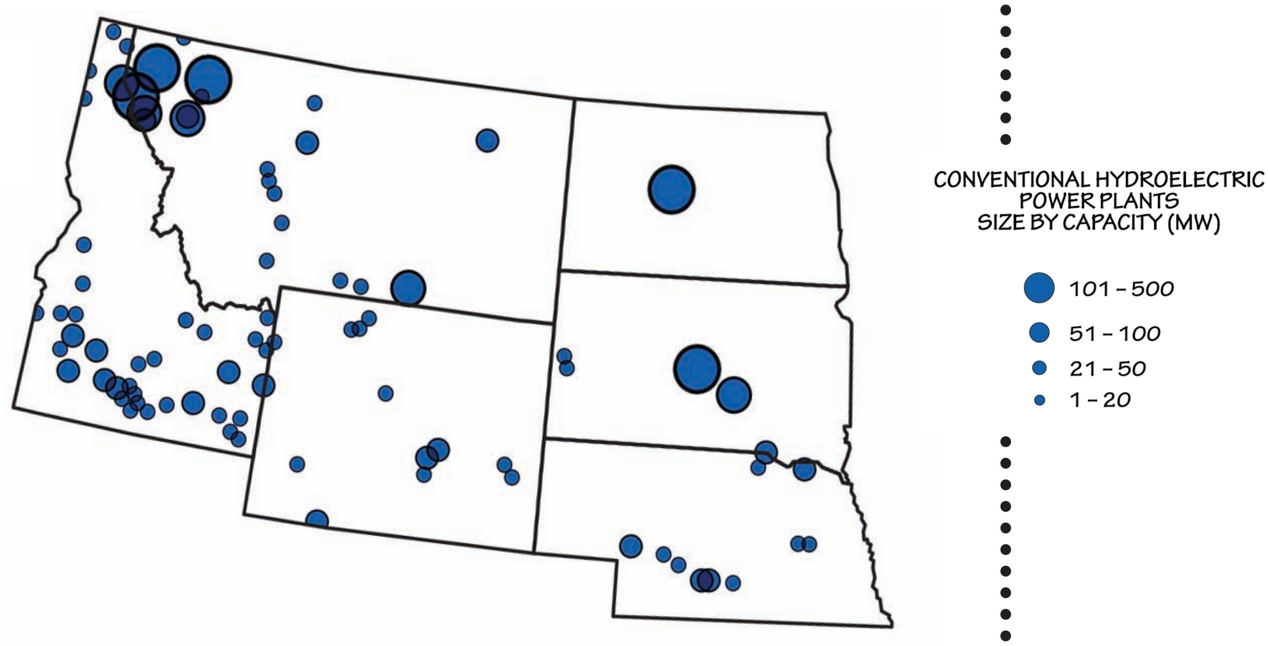
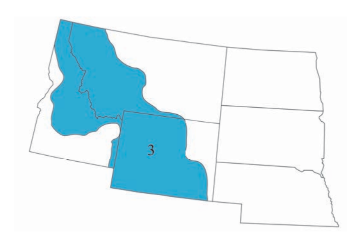


Figure 7.13: Hydroelectric plants in the Northwest Central.

Wind Power

The Rocky Mountains region has some of the highest potential for wind energy in the US (*see Figure 7.11*), though the area's terrain and lack of infrastructure can make tapping into this resource challenging. Windmills along I-80 in southeast Wyoming near Medicine Bow, where a gap exists in the Rockies, were among the first large-scale wind farms in the US. These facilitated high voltage transmission lines along the Interstate. There are a number of locations in southwestern Montana and northwestern Wyoming where valleys are oriented such that winds are funneled relatively consistently through the year; these areas have future potential for expanded wind farms.



Energy

Figure 7.14: Libby Dam, on the Kootenai River in Lincoln County, Montana. This dam is 129 meters (422 feet) tall and 931 meters (3055 feet) long, with a generating capacity of up to 600 megawatts.

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

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

Energy in the Columbia Plateau
Region 4

The active tectonics that resulted in the Columbia Plateau flood **basalts** and the growth of the Rocky Mountains to the east have created a region rich in hydroelectric and wind energy, as well as the potential for geothermal energy. More comprehensive development of geothermal energy may be an area of growth in the future. Fossil fuel development, however, has not been significant in the Columbia Plateau.

Fossil Fuels
The Columbia Plateau has seen very little fossil fuel development because it is covered by thick **volcanic** deposits that make exploration and recovery challenging. The volcanic rocks overlie Cenozoic lake deposits and older marine rocks that may contain oil and gas resources, but they have not been considered economically viable to develop.

Alternative Energy
With the Owyhee Mountain Range to the west and the Caribou Mountains and Forest bordering the east, the Snake River Valley and Bruneau Valley are host to many lakes and waterways. With its mouth at the Columbia River, the Snake River is over 1600 kilometers (1000 miles) long and is the largest tributary

that empties into the Pacific Ocean. With all of this water, it is no surprise that hydropower is a primary source of energy in the region—58% of Idaho's electricity comes from hydropower (*see Figure 7.13*). There are 15 dams along the Snake River; some provide irrigation for farming, but there are many that provide hydropower. There are also over 30 hydroelectric power stations on or near the Snake River in this region, three of the largest of which—Brownlee Dam (585 MW), Hells Canyon Dam (391 MW), and Oxbow Dam (190 MW)—are along the Idaho-Oregon border.

There are other renewable energy resources on the Columbia Plateau, including geothermal, biofuel, and wind energy. Although not yet a significant source of energy for the region, research and development into both geothermal and wind power is aimed at making both sources a lucrative option for the area.

Most of Idaho's wind farms run in a southward arc along the highway route from Boise in the west to Idaho Falls in the east. The Goshen North Wind Farm near Idaho Falls, at an elevation of over 1400 meters (4600 feet), is the state's largest wind farm. It has the capacity to produce about 125 MW. Wind accounts for about 16% of Idaho's electricity generation (*Figure 7.15*).

Figure 7.15: Wind turbines dot the landscape at this wind farm in Power County, Idaho.

Geothermal energy potential is abundant on the Columbia Plateau in Idaho; however, immediately east, on Yellowstone Plateau near the western edge of Wyoming, geothermal heat is not developed for energy because of the area's status as a National Park. Though geothermal accounts for only a small percentage of Idaho's electricity generation relative to hydroelectric and wind power, the state ranks sixth nationally in the use of geothermal energy (*Figure 7.16*).

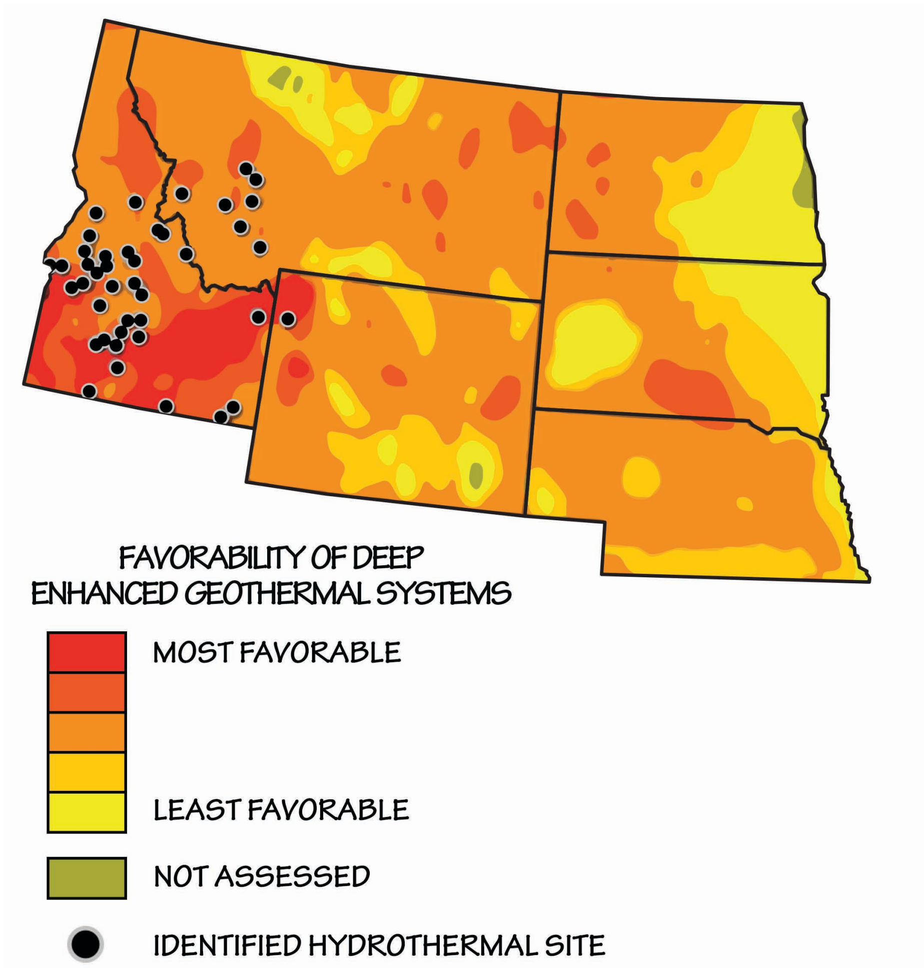
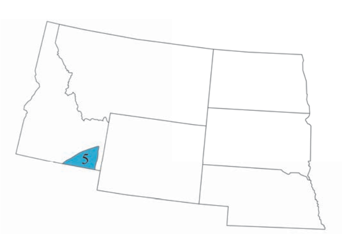


Figure 7.16: Geothermal energy resources iin the Northwest Central.

Energy in the Basin and Range
Region 5

Like the Columbia Plateau region, active tectonism yields an opportunity for the growth of geothermal energy in the Basin and Range. Hydroelectric power development is associated with the region's steep topography, in particular that of the Snake River, which flows from western Wyoming through the Snake River Plain of southern Idaho and discharges water at a rate of over 1500 cubic meters per second (54,000 cubic feet per second). The largest hydroelectric plant in the Basin and Range is Palisades Dam on the Snake River, though it is less than half the size (about 175 MW) of the largest hydro plant in the Columbia Plateau region.



Energy 7

Region 5

Geothermal energy comes from heat within the Earth, which is created on an ongoing basis by **radioactivity**. This energy powers **mantle convection** and **plate tectonics**. The highest-temperature conditions exist in tectonically active areas, including the Basin and Range, Iceland (a mid-Atlantic ridge), Japan (an area of **subduction**), and Hawaii and Yellowstone (areas with **hot spots**). Idaho's Basin and Range is home to the Raft River Geothermal Power Plant. Operated by Geothermal, Inc., the plant is actually a former US Department of Energy (USDOE) geothermal research and demonstration facility (*Figure 7.17*). The facility uses a "binary" energy system developed and tested by the USDOE. Unlike typical geothermal power plants that make direct use of vapor from heated water to spin turbines, this system passes hot geothermal water through a heat exchanger to heat a secondary liquid that vaporizes at a significantly lower temperature than water. This enhances the energy capture capacity of the system, thus increasing energy production.

Figure 7.17: The 13 MW Raft River Geothermal Plant near Malta, Idaho was the first commercial-sized binary cycle geothermal plant in the world. The plant's condensers and heat exchangers are pictured here.

radioactivity • *the emission of radiation by an unstable atom.*

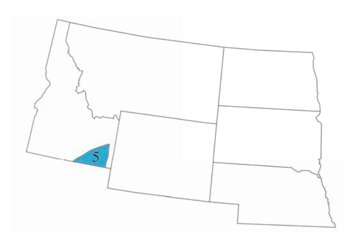
mantle • *the layer of the Earth between the crust and core.*

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

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

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

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



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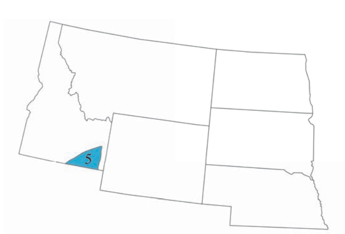
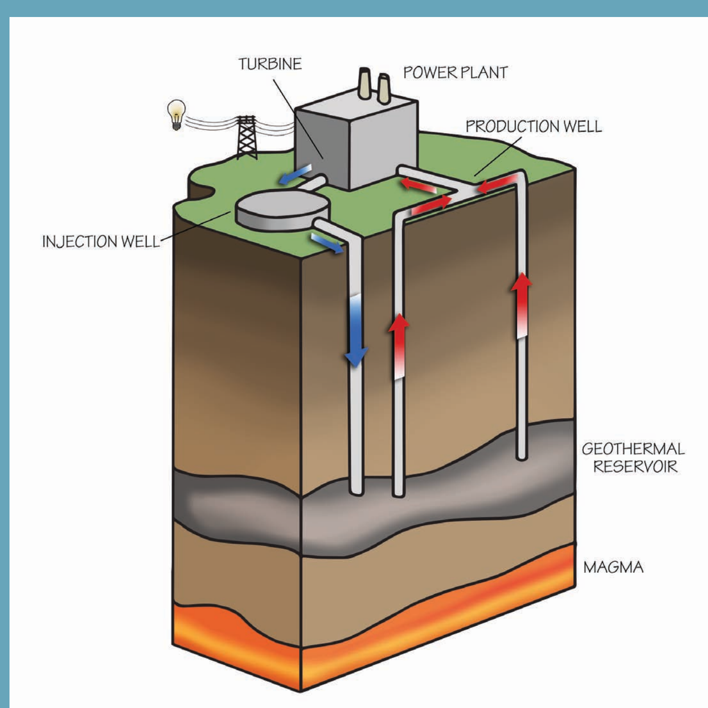


How does geothermal energy work?

Geothermal power stations use steam to power turbines that generate electricity. The steam is created either by tapping a source of heated groundwater or by injecting water deep into the Earth where it is heated to boiling. Pressurized steam is then piped back up to the power plant, where its force turns a turbine and generates power. Water that cycles through the power plant is injected back into the underground reservoir to preserve the resource.

There are three geothermal sources that can be used to create electricity. Geopressurized or dry steam power plants utilize an existing heated groundwater source, generally around 177°C (350°F) in temperature. Petrothermal or flash steam power plants are the most common type of geothermal plant in operation today, and they actively inject water to create steam. Binary cycle power plants are able to use a lower temperature geothermal reservoir by using the warm water to heat a liquid with a lower boiling point, such as butane. The liquid butane becomes steam, which is used to power the turbine.



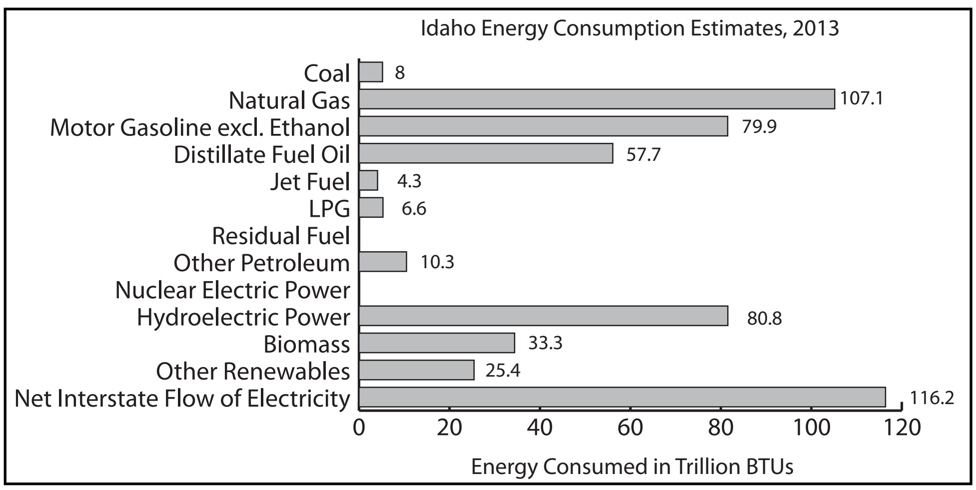
State Facts

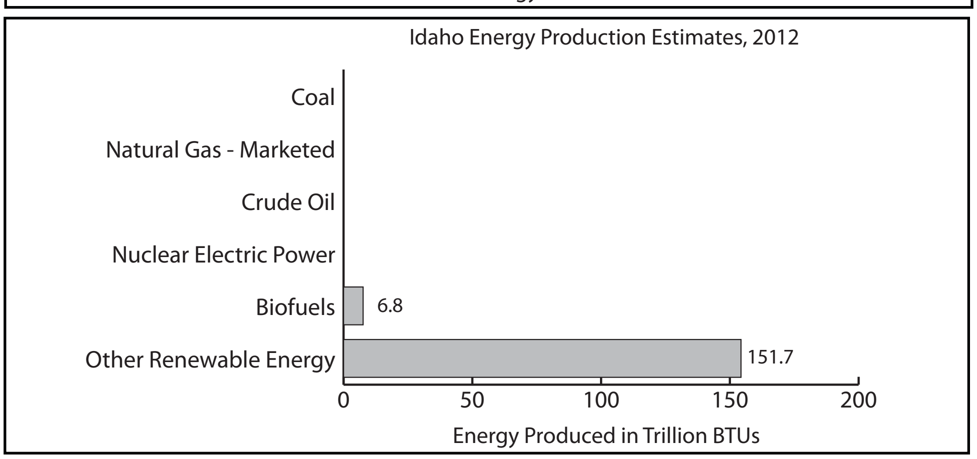
Energy Facts by State

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 Northwest Central (from http://www.eia.gov).

Idaho

- Idaho is rich in renewable energy resources; geothermal energy capable of generating electricity at commercial levels is present in most of the state.
- In 2012, Idaho's in-state net electricity generation equaled 55% of the state's total electric industry retail sales. The remainder came from other states and international imports.
- In 2013, 78% of Idaho's net electricity generation came from renewable energy resources, and Idaho had the lowest average electricity prices in the United States.
- Hydroelectric power supplied 58% of net electricity generation in Idaho in 2013.
- Idaho's wind generation increased by nearly 35% in 2013, providing 16% of net electricity generation.





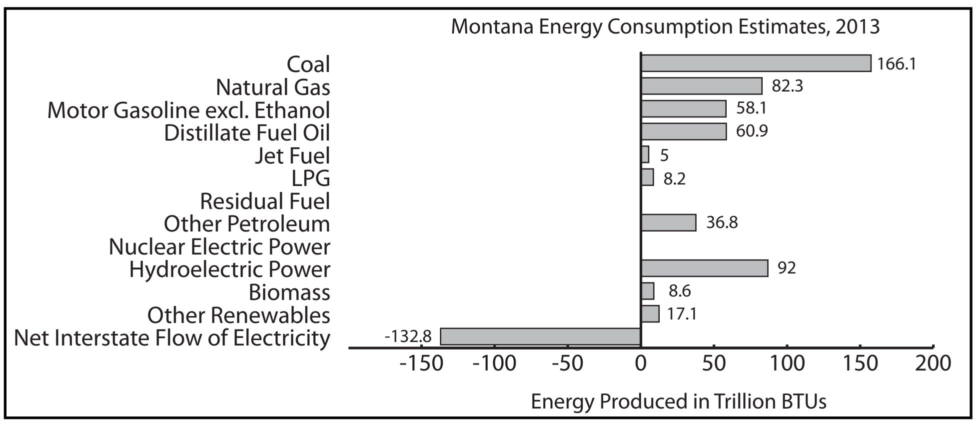
7

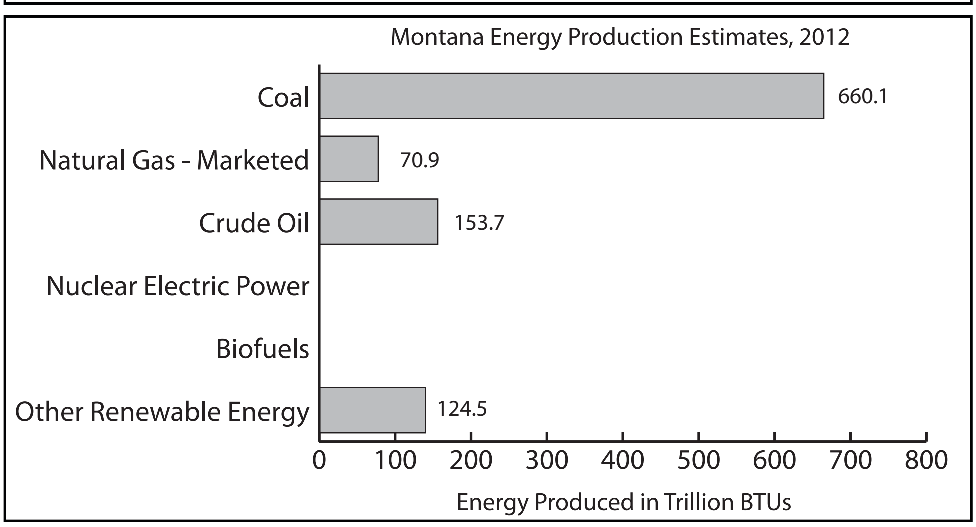
Energy

State Facts

Montana

- The Williston Basin of Montana and North Dakota holds one of the largest accumulations of crude oil in the United States; its Bakken and Three Forks formations are currently estimated to be capable of producing 7.4 billion barrels of oil.
- As of the end of 2012, Montana held over one-fourth of the nation's estimated recoverable coal reserves at producing mines and was the eighth largest coal-producing state. It produced 3.6% of US coal in 2012 and distributed coal to nine other states.
- Montana's four refineries, with almost 30% of US Petroleum Administration for Defense District 4 (Colorado, Idaho, Montana, Utah, and Wyoming) refining capacity in 2012, are able to process heavy Canadian crude oil for regional markets.
- Wind electric power generation in Montana grew by almost 32% in 2013 and supplied 6% of the state's net electricity generation.
- Montana has created a Renewable Energy Resource Standard requiring that public utilities and competitive electricity suppliers obtain 15% of electricity sales from renewable energy resources by 2015.



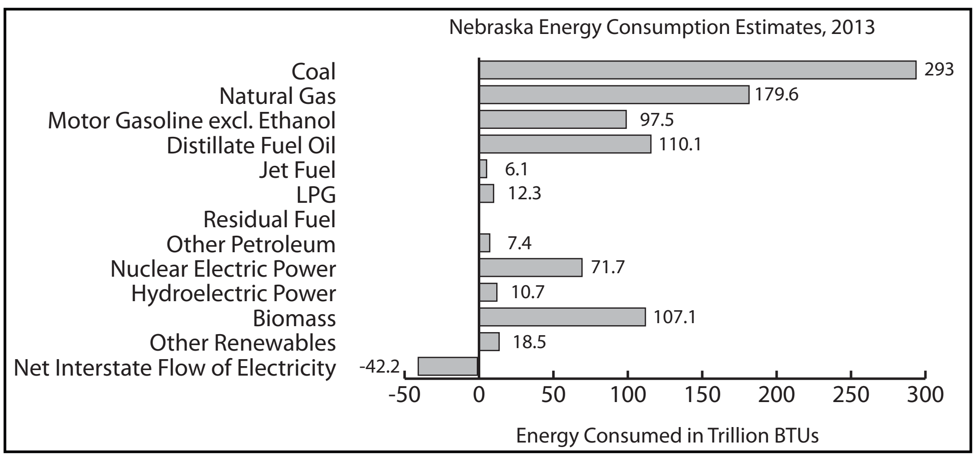


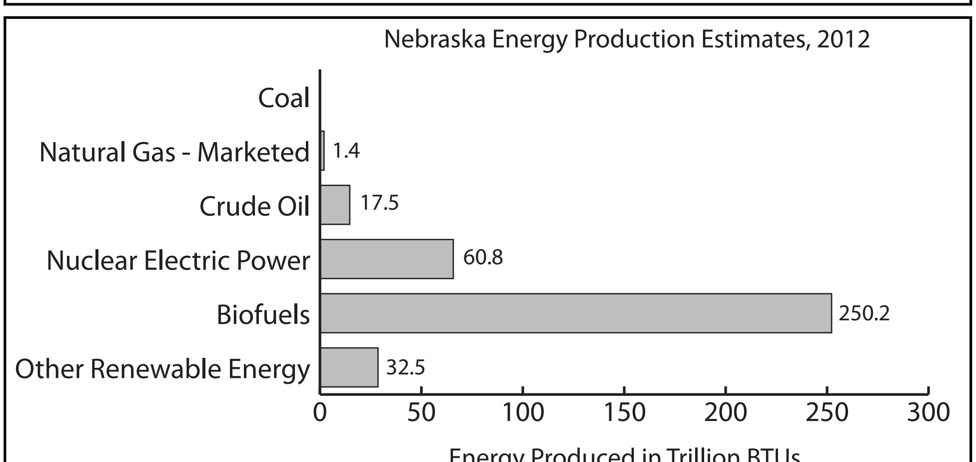
Energy 7

State Facts

Nebraska

- The Niobrara shale formation is an emerging oil play that includes southwest Nebraska, northeast Colorado, and northwest Kansas.
- The National Renewable Energy Laboratory estimates that almost 92% of Nebraska has suitable conditions for wind-powered electricity generation.
- In 2013, Nebraska ranked 22nd among the 50 states in crude oil production. Most of the production came from small oil reserves in the western part of the state.
- Nebraska's net electricity generation from its two nuclear reactors was 38% lower in 2013 than in 2010, as a result of the temporary closure of the Fort Calhoun nuclear power plant between April 2011 and December 2013.
- Nebraska ranked second in the nation, after Iowa, in corn-based ethanol production capacity in 2014.



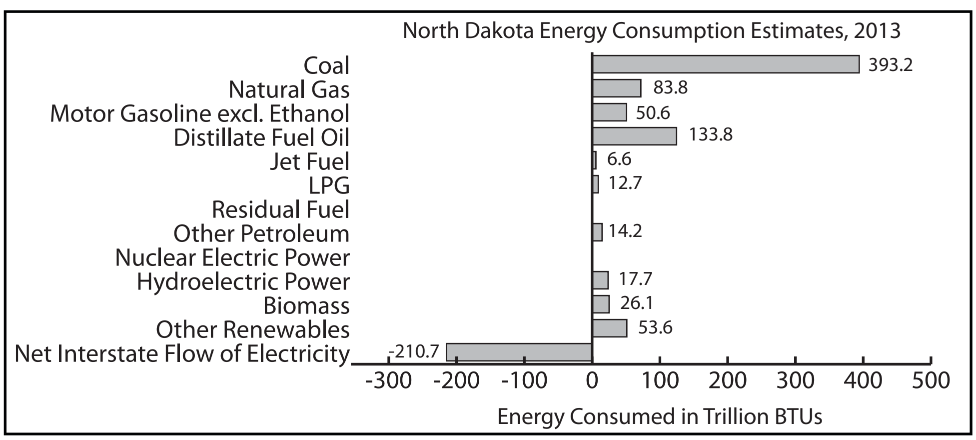


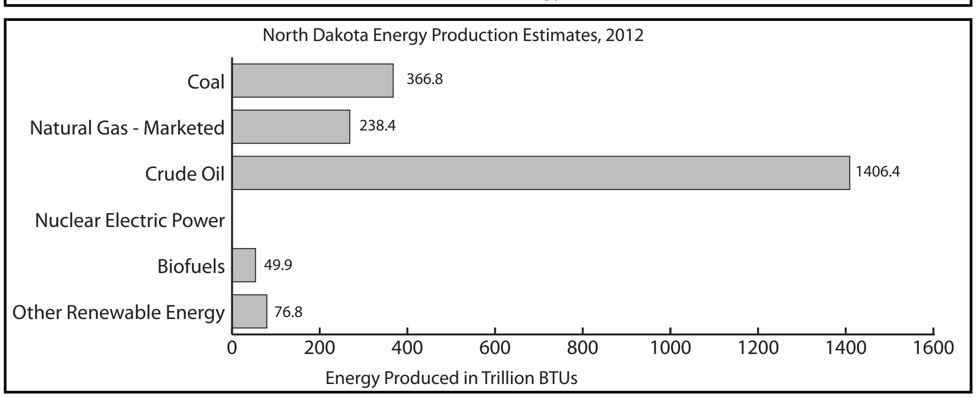
7 Energy

State Facts

North Dakota

- Although North Dakota's total energy consumption is among the lowest in the nation as a result of its small population, the state's consumption per capita ranks among the highest, in part because of the energy-intensive industrial sector and high heating demand in winter.
- North Dakota had 6% of the nation's recoverable coal reserves at producing mines as of 2012; the state's coal production, which all came from surface mines, accounted for 2.7% of US coal production in 2012.
- In 2013, North Dakota was the second largest crude oil-producing state in the nation and accounted for over 11.5% of total US crude oil production; a 177% increase in production from 2010 to 2013 was primarily driven by horizontal drilling and hydraulic fracturing in the Bakken formation.
- In 2013, 79% of North Dakota's net electricity generation came from coal, almost 16% came from wind energy, and about 5% came from conventional hydroelectric power sources.
- North Dakota has abundant wind resources and ranked 6th in the nation in wind energy potential, 11th in utility-scale generation, and 12th in installed capacity in 2013.





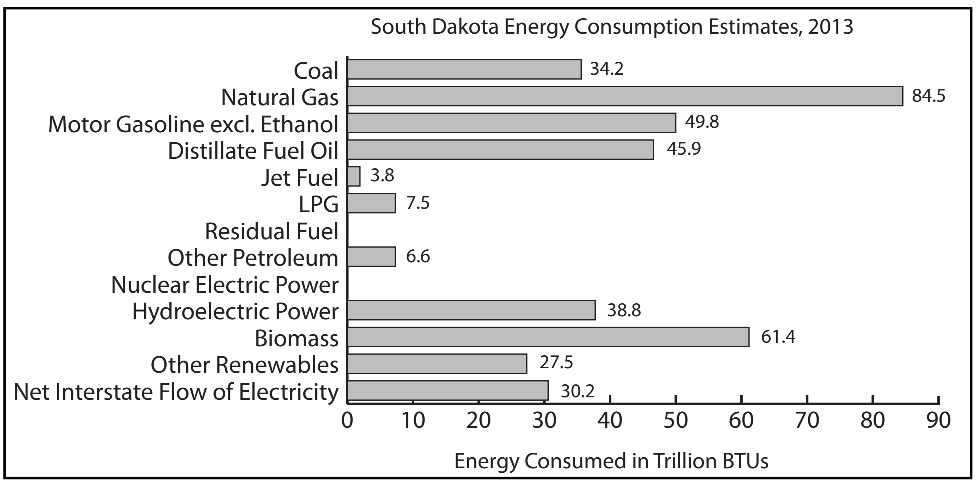
Energy

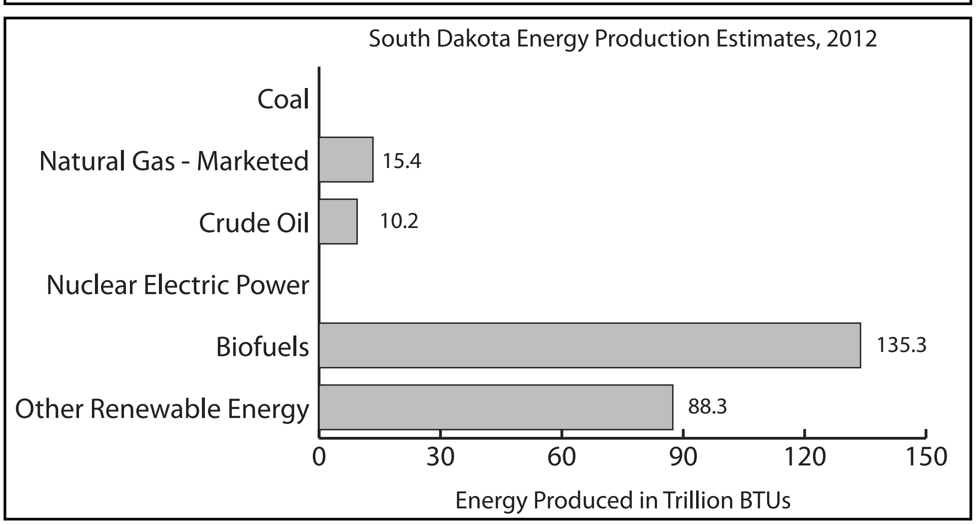
7

State Facts

South Dakota

- The National Renewable Energy Laboratory estimates that 88% of South Dakota's land area is suitable for wind resource development.
- In 2013, South Dakota had more net electricity generated from hydroelectric power than from any other source.
- Wind and hydroelectric power provided 65% of South Dakota's total net electricity generation in 2013.
- South Dakota ranked fifth in the nation in ethanol production capacity in 2014.
- South Dakotans' price for electricity averaged 8.83 cents per kilowatt hour in 2013 across all sectors, compared to the national average of 10.08 cents per kilowatt hour.



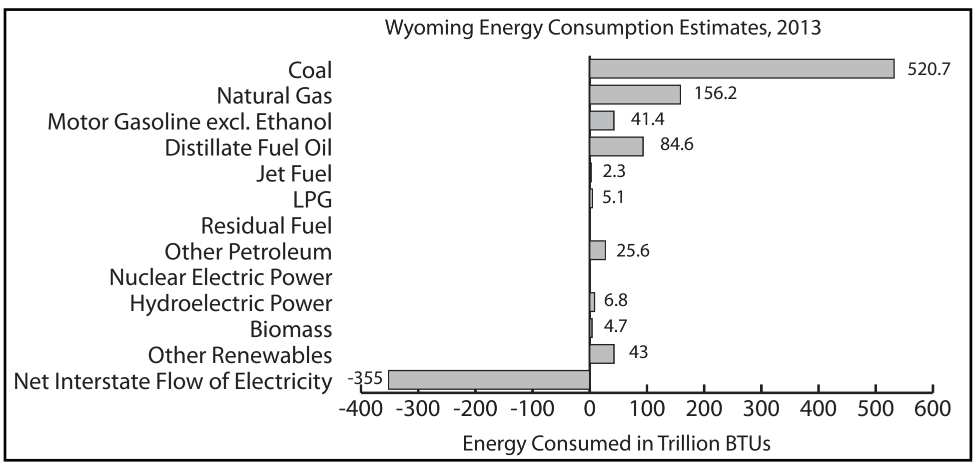


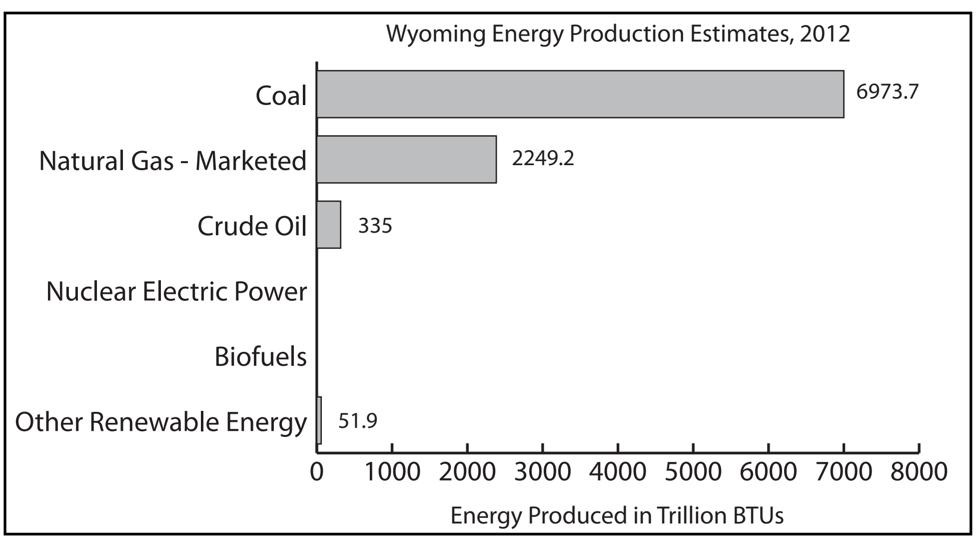
Energy

State Facts

Wyoming

- Wyoming produced 39% of all coal mined in the United States in 2012.
- In 2012, 34 states received coal from Wyoming mines, with 9 states, including Wyoming, obtaining more than 90% of their domestic coal from Wyoming.
- Wyoming accounted for 7.4% of US marketed natural gas production in 2013.
- In 2013, almost 89% of net electricity generation in Wyoming came from coal and about 10% came from renewable energy resources, primarily wind.
- Wyoming had the third lowest average electricity price of any state in 2013.





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 altering our supply, production, and demand for energy. Increases in temperatures will be accompanied by an increase in energy 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 affecting energy production and supply. For example, 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 types of disruptions affect us both locally and nationally, are diverse in nature, and will require equally diverse solutions.

See Chapter 9: Climate for more information about climate change in the Northwest Central.

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 can 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 which 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 people living in the Northwest Central are probably not the same as for those in other areas, such as the Southwest or Northeast.

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

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

***hurricane* •** *a rapidly rotating storm system with heavy winds, a low-pressure center, and a spiral arrangement of thunderstorms.*

***tornado* •** *a vertical funnel-shaped storm with a visible horizontal rotation.*

***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.*

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; roughly 2% of electricity production now goes to data centers, for example—a 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.

See Chapter 10: Earth Hazards to learn more about extreme weather events.

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 the 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 those of 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.

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Chapter 8: Soils of the Northwest Central 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 is the interface between living earth and solid rock, between biology and geology. The engineer, the scientist, and the gardener may all look at the soil beneath 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 well versed in the science of their soil. Soils store and purify water, and they exchange gases with the **atmosphere**. They support agriculture and natural ecosystems and provide a grassy surface for our parks and fodder for our gardens. Everyone, everywhere, every day, depends upon the soil.

What is Soil?

Generally, **soil** refers to the top layer of earth—the loose surface of earth as distinguished from rock—where vegetation grows. The word is derived (through Old French) from the Latin *solum*, which means "floor" or "ground." Soil is one of the most important resources we have—the most basic resource upon which all terrestrial life depends. The Northwest Central has a wide variety of soils, and each type of soil has a story to tell of its origin.

Soils form from the top down, and typically reach a depth of about one meter (3.3 feet) at their more developed stages, although some can reach much deeper. 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 nutritious organic matter that helps soil to nourish future plant growth. The second important component of soil is sediment derived from the **weathering** of rock that is then transported by **wind**, water, or gravity. Both of these components influence the texture (*Figure 8.1*) and consistency of the soil, as well as the **minerals** available for consumption by plants.

All soils might seem alike, but there can be vast differences in soil properties even within small areas! A single acre may contain 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. Soil textures have specific names, as indicated in *Figure 8.1*.

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

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

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

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

color (soil) • *a physical property of soils, influenced by mineral content, the amount of organic material, and the amount of water.*

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.*

CHAPTER AUTHOR

Spencer A. Cody

8 Soils

Review

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.*

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

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

loess • *very fine grained, wind-blown sediment, usually rock flour left behind by the grinding action of flowing glaciers.*

biota • *the organisms living in a given region, including plants, animals, fungi, protists, and bacteria.*

parent material • *the original geologic material from which soil formed.*

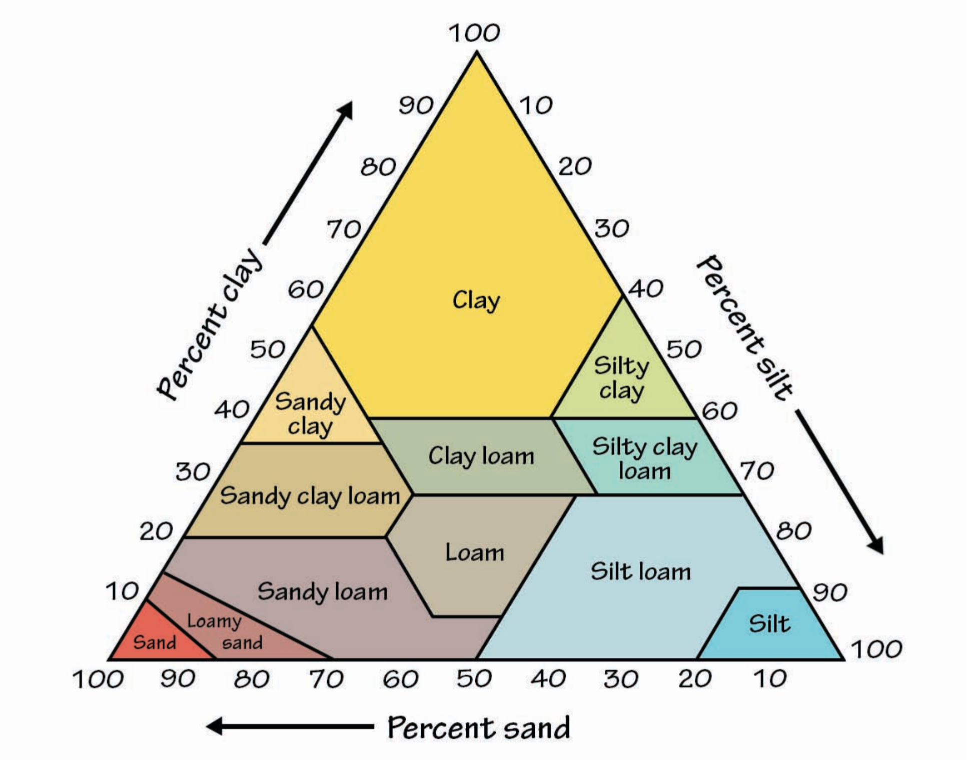


Figure 8.1: Soil texture triangle.

Generally, the best agricultural soils are those with about equal amounts of **clay**, **silt**, and **sand**. A soil of that type is called a **loam**. Soils that are mostly sand do not hold water very well and dry quickly, while soils with too much clay may never dry out. Soil structure refers to the way the soil forms clumps, known as **peds**. 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.

Five main variables affect the characteristics of soil worldwide. In the Northwest Central, all soils are the products of subtle differences among these five factors:

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**, **loess**, and rock fragments.

2. *Climate* strongly determines the temperature regime, amount of moisture, and type of **biota** that interact with the **parent material**. This affects the extent of chemical and physical weathering on the soil-forming material. For example, if a particular climate lacks precipitation,

mechanical weathering from wind or ice fracturing will predominate. If, however, a climate has abundant precipitation, chemical erosion from water will be accelerated, resulting in substantial leaching.

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. As the slope increases, water can carry larger sediment sizes, allowing for large sediment loads during major precipitation events. **Topography** also 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. Areas with steep slopes that are susceptible to frequent **erosion** typically have very young soils, as they do not have long to develop before the ingredients are rearranged and the clock is reset. Flatter, more arid areas may have more time to develop, but they have significantly less plant life and will produce a very different soil than will a wetter environment. Slope also frequently determines the types of vegetation covering a soil—for example, different slopes on the same hill might receive varying amounts of sunlight during the growing season—which in turn can cause the characteristics of the soils to diverge if differing forms of vegetation dominate opposite slopes.

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. In fact, more than 90% of the nutrients used by a forest in a given year are derived from the decomposition of old organic matter fallen to the forest floor. Animal burrows also create spaces in the soil horizons that allow for deeper penetration of air and water, which, in turn, aid plant development by helping to dissolve mineral nutrients into a form that plants can absorb and process. 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. Older soils have deeper and thicker **subsoils** than do younger soils, but only if other soil forming factors remain constant. In central South Dakota, for example, it takes approximately 500 years to generate a new 2.5 centimeters (1 inch) of **topsoil** beneath the prairie grass—but it only takes a few years for erosion and weathering to destroy the same amount of unprotected topsoil.

Several types of **chemical reactions** are important for soil development; of these, acid-base reactions are some of the most important and complex. When carbon dioxide (CO_2) dissolves in water it forms weak carbonic acid. CO_2 found

Review

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

erosion • *the transport of weathered materials.*

humus • *a soil horizon containing organic matter.*

subsoil • *the layer of soil beneath the topsoil, composed of sand, silt and/or clay.*

topsoil • *the surface or upper layer of soil, as distinct from the subsoil, and usually containing organic matter.*

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

Review

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

silica • *a chemical compound also known as silicon dioxide (SiO_2).*

aluminum • *a metallic chemical element (Al), and the most abundant metal in the Earth's crust.*

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

titanium • *a metallic chemical element (Ti) that is important because of its lightweight nature, strength and resistance to corrosion.*

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

in soil water can come from the atmosphere, where it dissolves in rainwater. Even more CO_2 usually comes from the soil itself, where it is produced by respiring organisms. The amount of CO_2 in soil gases can easily reach levels ten times higher than the amount found in the atmosphere (over 4000 ppm in soil vs. 400 ppm in the atmosphere), making soil water potentially more acidic than rainwater. As this acidic water slowly reacts with fresh minerals, it buffers the soil's pH and keeps it in a range (6–8) preferred by many organisms. Acid-driven weathering breaks down the soil's primary **igneous** minerals, typically transforming them to **silica**-rich clays. As the soil's primary minerals are depleted, it loses the ability to buffer acidity, and the pH of highly weathered soil can drop to around 4. These weathered soils tend to be rich in **aluminum**, **iron**, and **titanium**.

In highly weathered settings, soil loses most of its nutrients, and the store of nutrients that remains is mostly found in organic matter. In weathered soils, only the top 25 centimeters (10 inches) or so may be very biologically active, and rooting depths are very shallow. If this thin layer is lost to erosion, the underlying mineral soil may be infertile and incapable of rapid recovery.

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. Soil develops in horizons, or layers, whose formation is dependent on the available ingredients, environmental conditions, and the time it takes to mature. Since the organic and chemical processes that form soils first impact the top of the soil column and then work their way downward, horizontal layers of soil with different characteristics are formed, resulting in divergent colors, textures, and compositions.

A vertical cross-section of all the horizons or layers of soil present in a given area is referred to as a soil profile. Some horizons are completely absent in certain profiles while others are common to most. Each horizon corresponds to a stage in the weathering of rock and decay of plant matter, and each is found at a specific position beneath the surface (*Figure 8.2*). The *O horizon* at the top of the profile contains partially decayed plant material and transitions down to the *A horizon*, which contains mineral matter with a mix of humus and is commonly referred to as topsoil. Below the A horizon lies the *B horizon* or subsoil, which contains mineral material that has leached from above. The *C horizon* at the base of the soil profile contains partially altered parent material.

Soils can also be categorized by their location (northern vs. southern soils), the type of vegetation growing on them (forest soils vs. desert 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** *(Figure 8.3)*, and it was developed by the United States Department of Agriculture (USDA) with the help of soil scientists from across the country. It provides a convenient, uniform, and detailed classification of soils throughout the US (*Figure 8.4*), allowing for an easier understanding of how and why different regions have developed unique soils.

Soils 8

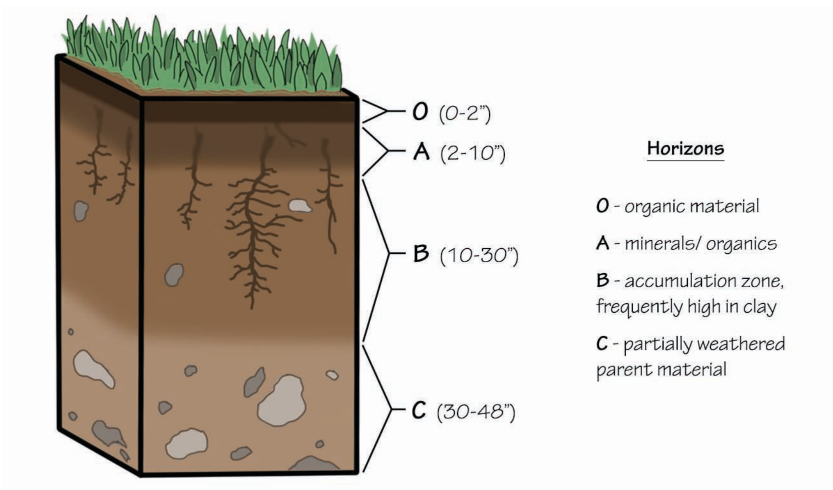


Figure 8.2: A typical soil profile shows the transition from the parent material (horizon C) to the highly developed or changed horizons (O through B). Not every soil profile will have all the horizons present.

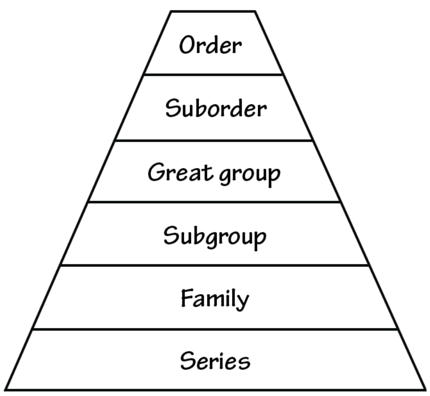


Figure 8.3: Soil taxonomy.

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**, parent material, 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. 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 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.

Review

soil taxonomy • *the system used to classify soils based on their properties.*

soil orders • *the twelve major units of soil taxonomy, which are defined by diagnostic horizons, composition, soil structures, and other characteristics.*

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).*

8 Soils

Review

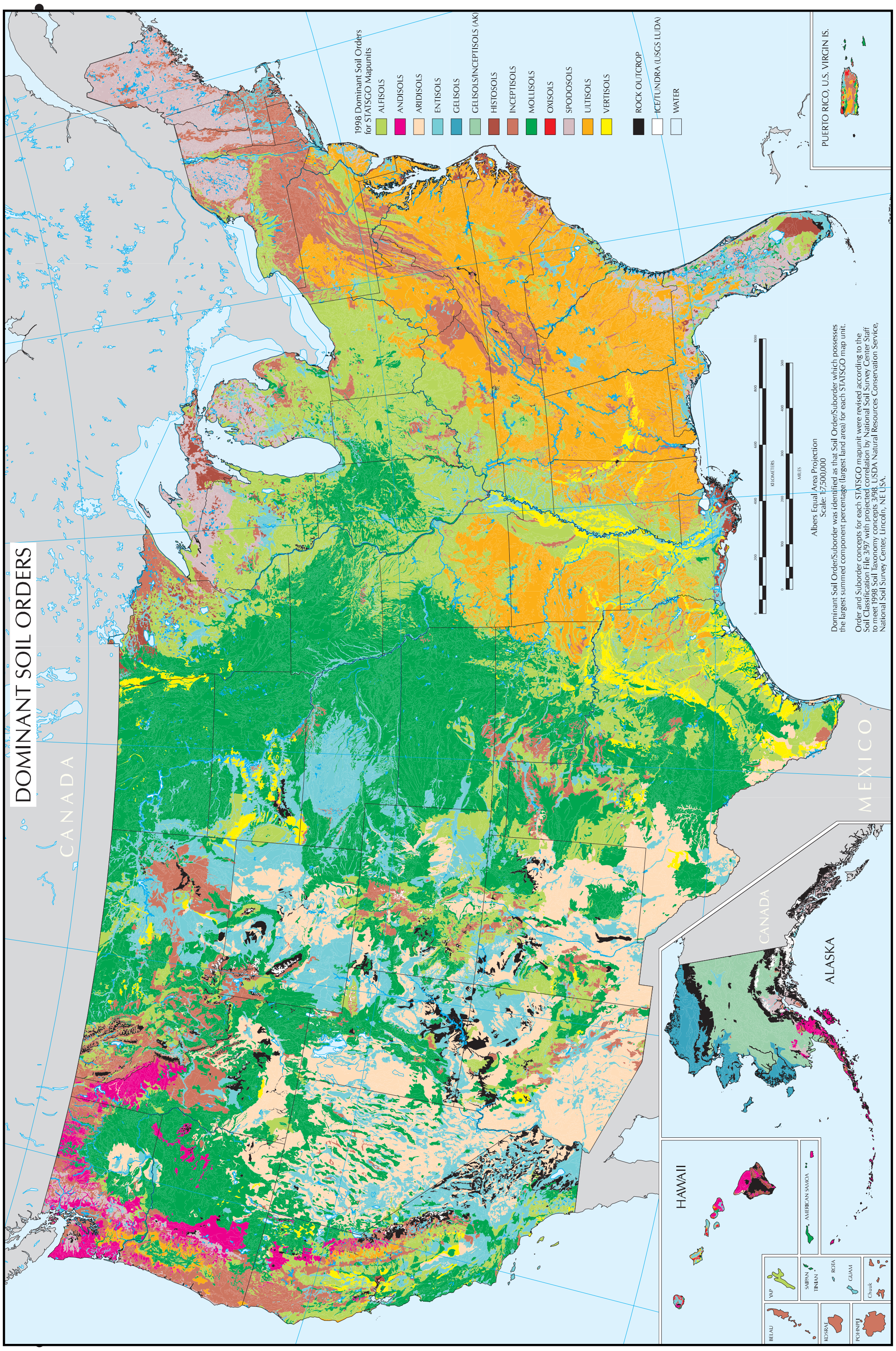


Figure 8.4: Dominant soil orders of the United States. (See TFG website for a full-color version.)

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 flood-plains, 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

***volcanic ash** • fine, unconsolidated pyroclastic grains under 2 millimeters (0.08 inches) in diameter.*

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

***calcium carbonate** • a chemical compound with the formula $CaCO_3$, commonly found in rocks in the mineral forms calcite and aragonite, as well as the shells and skeletons of marine organisms.*

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

***periglacial zone** • a region directly next to an ice sheet, which, although never covered by ice, has its own distinctive features.*

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

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

Dominant Soils of the Northwest Central

The Northwest Central US contains a diverse variety of soils, and 7 of the 12 soil orders are present there in abundance.

Alfisols are partially leached soils with a high degree of fertility that tend to develop in cooler, more forested environments. They commonly form a band separating more arid areas from humid areas. In the Northwest Central, they are largely associated with the Black Hills of South Dakota and the northern Rockies of Montana (*Figure 8.5*).

Andisols are acidic soils associated with **volcanic ash** and debris deposits. They can be both weakly and heavily weathered soils that contain sediments derived from **volcanic** material. They are especially prevalent in northern Idaho, where they support productive forests (*Figure 8.6*).

Aridisols are very dry soils that form in arid environments. Water content is very low or even nonexistent for most of the year, leading to limited leaching. These soils contain abundant **calcium carbonate**, making them quite alkaline. Commonly found in the rain shadow areas of Wyoming and Idaho (*Figure 8.7*), Aridisols are unsuitable for plants that are not adapted to store water or to survive extreme drought.

Entisols are soils of recent origin with poorly developed horizons, typically formed near **floodplains**. These soils are found throughout the Northwest Central, and are common near major rivers as well as in **periglacia**l areas where **glacial** sediment has accumulated (*Figure 8.8*).

Inceptisols are soils with poorly developed horizons that are associated with steep slopes and resistant parent material. These soils are most commonly found on the mountainous slopes of the Rockies (*Figure 8.9*).

Mollisols are the dominant soils of grasslands. The thick, black A horizon makes these soils extremely productive and valuable to agriculture. They are one of the most abundant soil types in the Northwest Central, and have made Nebraska and the Dakotas leaders in crop cultivation and grazing (*Figure 8.10*).

Vertisols are very dark soils, rich in swelling clays. Their distinguishing feature is that they form deeply cracked surfaces during dry periods, but swell again in the wet season, sealing all the cracks. As a result, they are very difficult soils to build roads or other structures on. These soils are commonly associated with exposed marine **shales** in the Dakotas and Montana (*Figure 8.11*).

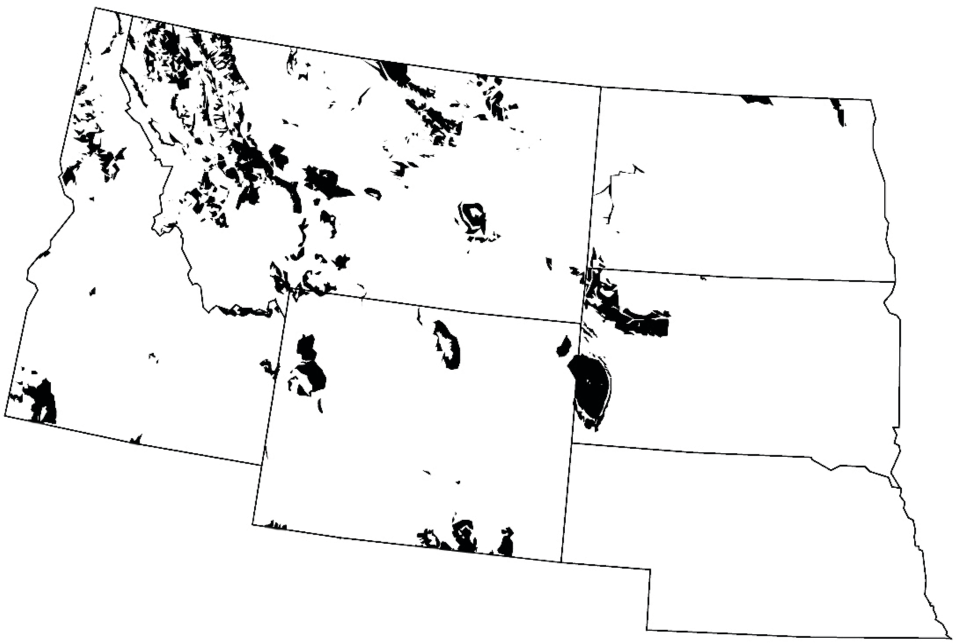


Figure 8.5: Alfisols of the Northwest Central.

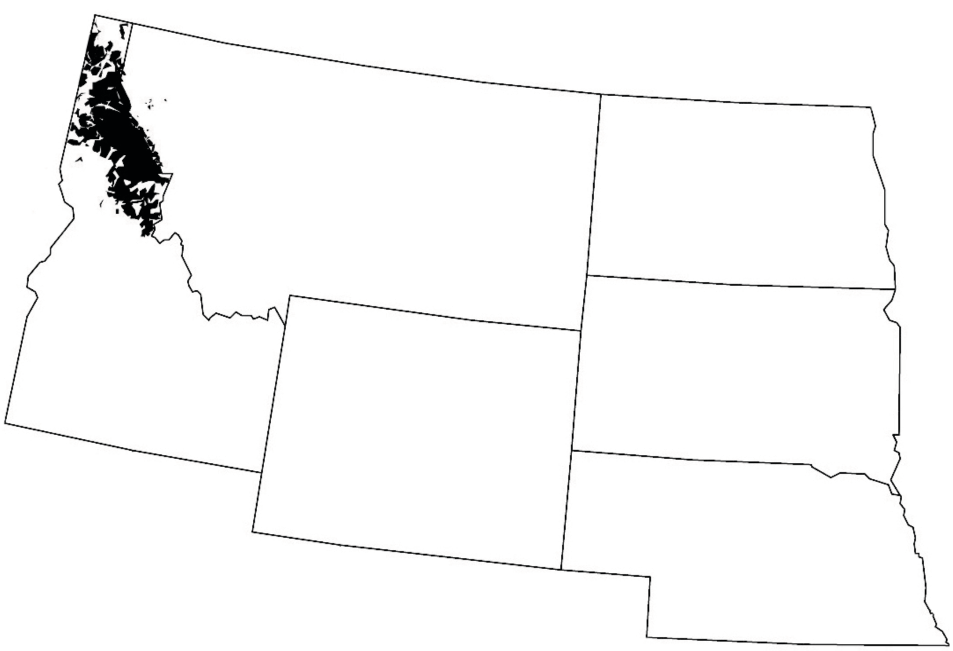


Figure 8.6: Andisols of the Northwest Central.

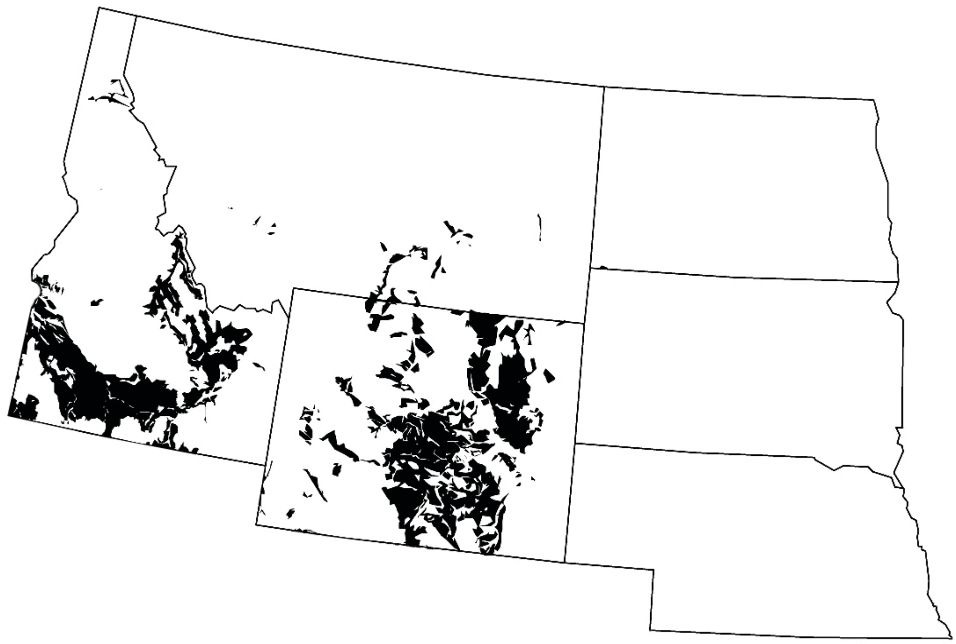


Figure 8.7: Aridisols of the Northwest Central.

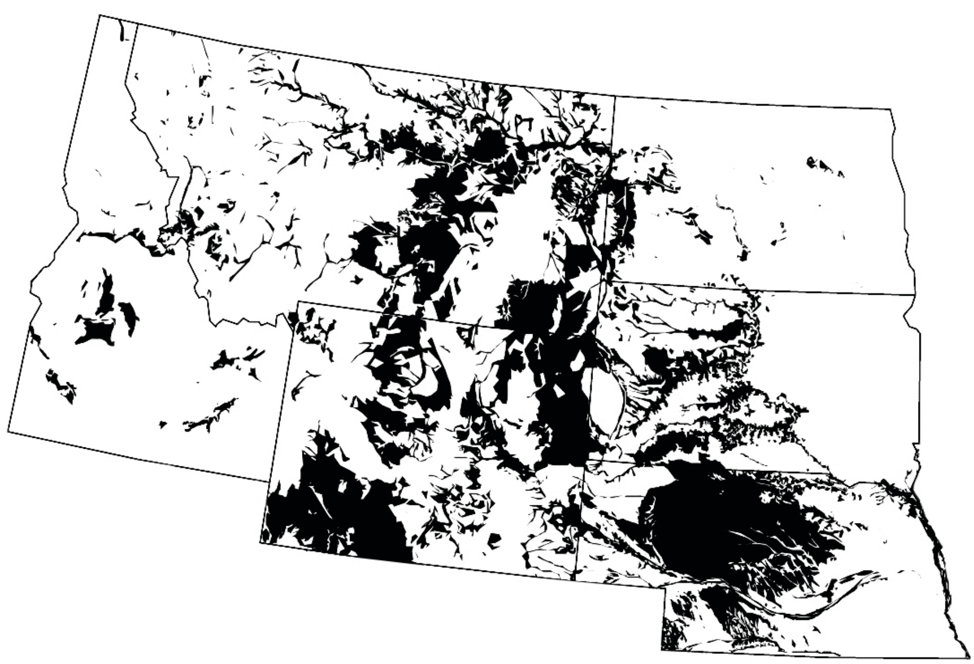


Figure 8.8: Entisols of the Northwest Central.

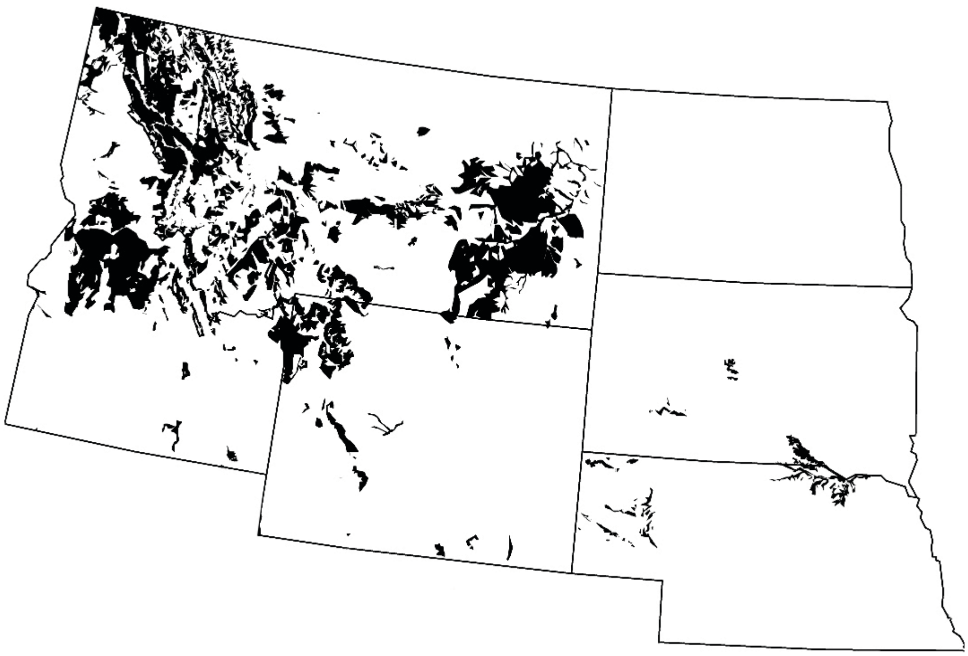


Figure 8.9: Inceptisols of the Northwest Central.

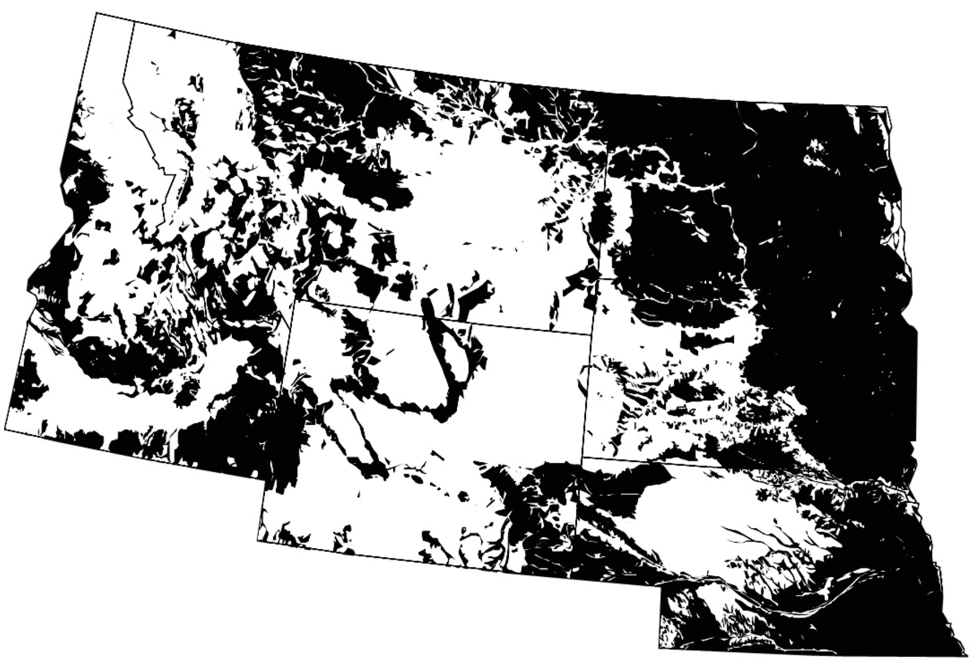


Figure 8.10: Mollisols of the Northwest Central.

Review

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

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

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

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

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

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

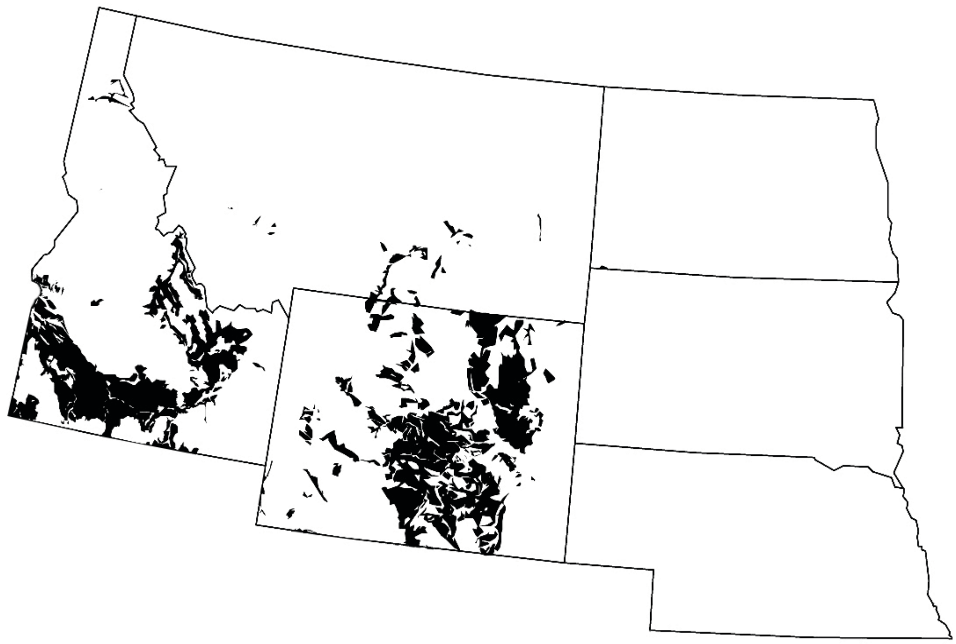


Figure 8.11: Vertisols of the Northwest Central.

Geology of the Northwest Central: Parent Material

The Northwest Central is home to a variety of parent materials—the minerals and organic matter from which its soils are derived (*Figure 8.12*). Mineral material determines a soil's overall fertility, and the vegetation it supports.

Weathered sedimentary rock is perhaps the most ubiquitous parent material in the Northwest Central. **Sandstone**, siltstone, **limestone**, and shale are among the most common bedrocks across the Northwest Central States; over time, erosional processes have contributed to the formation of soils from all of these sedimentary substrates. Much of this rock was laid down during the **Cretaceous**, when the Western Interior Seaway flooded the landscape.

A significant portion of the Northwest Central was also subjected to glaciation during the **Quaternary**, leading to the accumulation of loess deposits (*Figure 8.13*) carried by wind and deposited by river systems. These glacial sediments are responsible for the development of some of the extremely productive agricultural soils found there today.

The soils in the western regions of the Northwest Central are derived largely from igneous and metamorphic rocks. Many of these were generated during the tectonic events that led to the **uplift** of the Rocky Mountains, while others are related to volcanism at the Yellowstone **hot spot**.

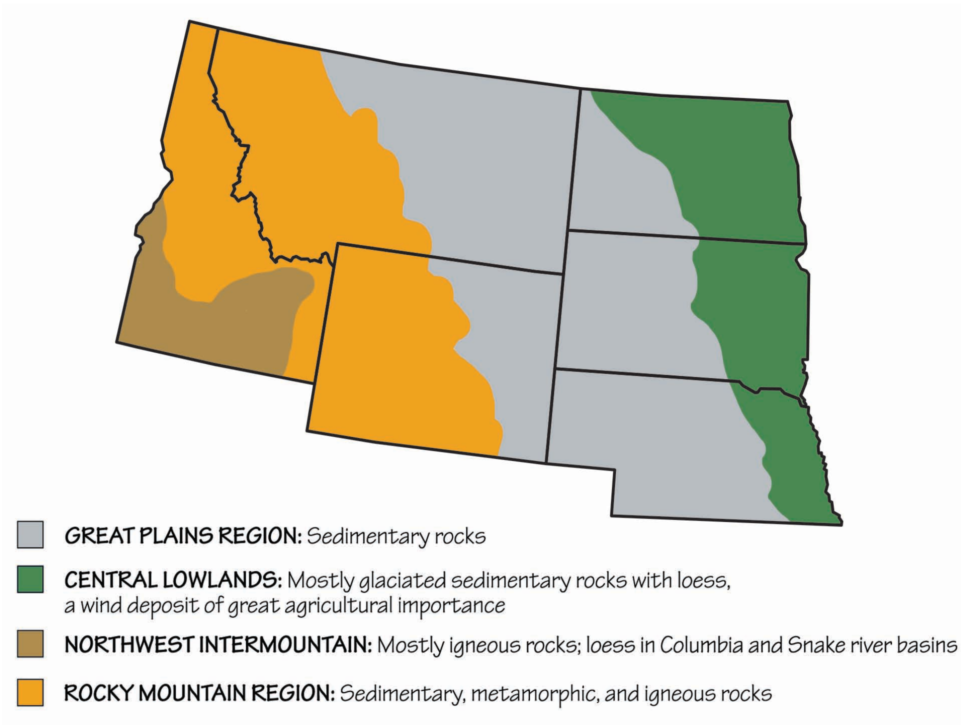


Figure 8.12: Physiographic and regolith map of the South Central.
(See TFG website for full-color version.)

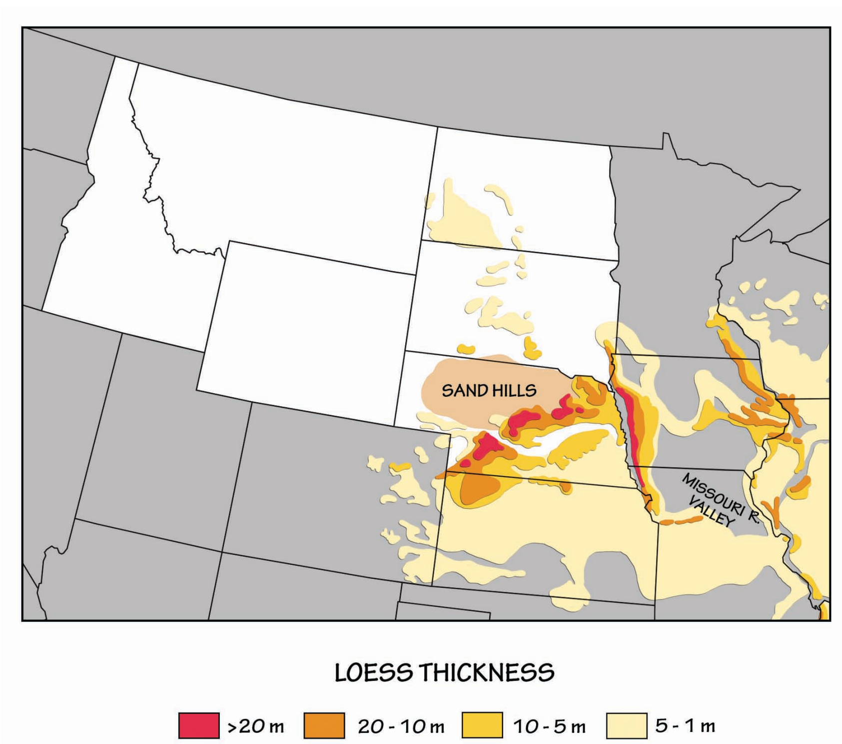
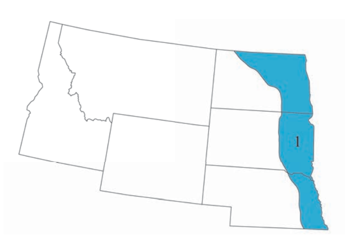


Figure 8.13: Loess deposits in the Northwest Central and surrounding states.
(See TFG website for full-color version.)

Region 1

relief • *the change in elevation over a distance.*

hectare • *a metric unit of area defined as 10,000 square meters.*



Soils of the Central Lowland
Region 1

The Central Lowland is a broad and mostly flat expanse of the North American interior, stretching approximately 2400 kilometers (1500 miles) across its east-west diameter. Recent glaciation has repeatedly ground down any preexisting topographical **relief**, burying the region's pre-glacial geology in a layer of unsorted sediment and windblown loess that was carried and processed by the advance and retreat of continental glaciers. The combination of low levels of topographical relief, recent glacial deposits of till, and the dominance of a tall grassland ecosystem has produced remarkably rich and fertile soils with high agricultural value.

Mollisols are the dominant soil type in the Central Lowland region, formed where organic matter accumulates beneath prairie grasses and in poorly drained forests. In many cases, these soils are underlain by thick deposits of glacial loess, which has contributed to their rich nutrient content (*see Figure 8.13*). Mollisols are highly productive dark soils (*Figure 8.14*), and most of the native grassland that produces them has been converted to agricultural land. Tallgrass prairie once covered more than 69 million **hectares** (170 million acres) of North America, but today nearly 96% of it has been converted for agriculture. The eastern Dakotas and eastern Nebraska contain some of the most productive land in the world. Thanks to fertile Mollisols, these states are national leaders in the production of corn, soybeans, wheat, flaxseed, rye, sorghum, oats, hay, alfalfa, and barley. All three states are generally ranked at or near the top ten in annual yield of these crops, and also support a robust livestock and dairy industry along with the bulk of the nation's honey production.

Figure 8.14: A farmer ploughs a field of rich, dark Mollisols in North Dakota's Red River Basin.

The Mollisols of the Central Lowland reflect a climatic gradation from wetter to drier conditions. The dominant Mollisols found in the region, especially in the Red River Valley and near the Missouri and Platte rivers, are wetter and occur close to the **water table.** Southeastern South Dakota and northeastern Nebraska contain drier Mollisols that form under semi-arid climates.

Entisols, young soils lacking in horizons, are found where erosion and deposition occur faster than the rate of soil formation. In the Central Lowland, they typically appear in floodplains where **alluvial** sediments are deposited. They are prevalent along the Platte and Missouri rivers in Nebraska.

Wet Vertisols, which remain saturated for large parts of the year but occasionally dry out enough to form cracks, can be found all throughout North Dakota's Red River Valley.

Soils of the Great Plains
Region 2

The Great Plains, a broad plateau that is home to intermediate and short grasslands, stretches for 3200 kilometers (2000 miles) from the Canadian interior south to the Mexican border. Its 800-kilometer (500-mile) wide expanse is sandwiched between the Central Lowland and the **Canadian Shield** to the east and the Rocky Mountains to the west.

Conditions in the Great Plains become increasingly drier as one travels from east to west. Highly fertile Mollisols with a thick, black top horizon are found in the region's eastern extent. These soils allow for the greatest productivity and are often associated with intensive agricultural operations. As one moves westward, decreasing moisture and vegetation impacts soil development, making soils thinner and less productive, which naturally produces shorter grasses (*Figure 8.15*). The central Great Plains are dominated by dry Mollisols belonging to the suborder Ustolls, which form in semi-arid conditions. These soils can become even more dusty and dry during drought conditions (*Figure 8.16*), limiting crop yields and leading to damaging dust storms such as those that occurred during the Dust Bowl of the 1930s. In the western Dakotas, western Nebraska, eastern Montana, and eastern Wyoming, the decreased precipitation and lower soil fertility provides for a localized agricultural economy based heavily in rangeland livestock—these states are leaders in the production of beef cattle and sheep. Crops here often require irrigation from local **aquifers** or various surface water impoundments.

In many western areas of the Great Plains, the soils are heavily influenced by existing sedimentary rock material lain down during the uplift of the Rockies and the deposition of **Mesozoic** sediments. The erosion of exposed Cretaceous marine shales produces Vertisols, soils that experience drastic fluctuations in volume when exposed to water (*Figure 8.17*). Locals refer to such soil as "gumbo" and consider it to be unworkable and impassable when wet. It is also

water table • *the upper surface of groundwater.*

alluvial • *a thick layer of river-deposited sediment.*

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

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

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

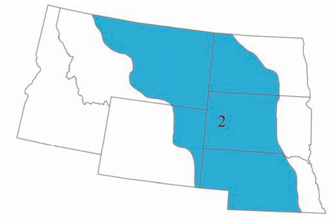
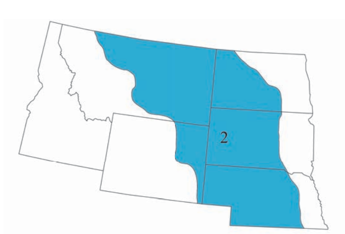


Figure 8.15: Seemingly endless stretches of rolling short and intermediate grasses dominate the drier soils of the Great Plains.

Figure 8.16: Dust rises from dry Ultisols in the Great Plains' Prairie Pothole Region.

Figure 8.17: Cracked Vertisols in central Montana.



a major engineering concern for structures involving roads and buildings due to its predisposition to shifting and developing **creep** or slow mass movement of earth. This same shifting ability discourages the formation of any distinct horizons. Clayey Vertisols are highly alkaline and water restrictive, inhibiting crop yields and forcing most agricultural usage into rangeland grazing.

Alfisols are scattered throughout Montana as well as concentrated in the Black Hills of South Dakota. These soils generally form in forested areas as a result of weathering processes that leach minerals from the surface layer into the subsoil, where nutrients are retained. The Black Hills' unique geology makes them a forested oasis amidst a sea of grassland—and perfectly suited to the development of Alfisols.

See Chapter 2: Rocks to learn more about Black Hills geology.

Aridisols are present throughout Wyoming on the western edge of the Great Plains, approaching the Rocky Mountains. These soils, which have no viable agricultural use, occur where the ground remains dry throughout most of the year due to limited precipitation. Consequently, Aridisols show very little evidence of leaching, and they contain abundant accumulations of clay. The Powder River Basin in eastern Wyoming, which receives 23–51 centi-meters (9–20 inches) of precipitation each year, is one example of an arid expanse dominated by Aridisols.

Entisols, young and unstable soils lacking in horizons, are found where erosion and deposition occur faster than the rate of soil formation. Both the soils that overlay loess structures in eastern Nebraska and the rapid erosional surfaces of the Badlands of South Dakota, North Dakota, Montana, and Wyoming exhibit similar Entisol characteristics (*Figure 8.18*). In the Sandhills of north-central Nebraska and south-central South Dakota, the underlying Ogallala Formation's sandy **conglomerate** has contributed to the sediment load needed to form the **aeolian** or windblown formations found in the area. Fully 52,000 square kilometers (20,000 square miles) of land is covered in sand dunes and sand sheets, which were largely created from windblown material eroded by glaciers during the late **Pleistocene**. Recent surveys of the dunes, which are currently covered with a thin veneer of grassland vegetation, have suggested that they were active within the last several thousand years, and may become active again in the event of a severe drought.

See Chapter 4: Topography for more information about the Sandhills.

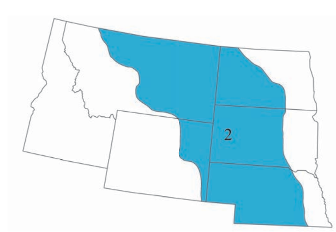
Inceptisols can be found scattered throughout grasslands and lightly forested areas in Montana, South Dakota, and Nebraska.

creep *• the slow movement or deformation of a material under the influence of pressure or stress.*

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

aeolian *• pertaining to, caused by, or carried by the wind.*

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



Regions 2–3

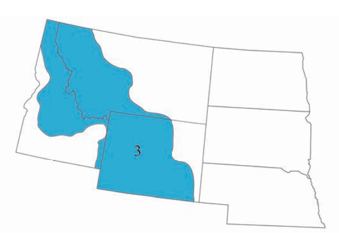
__Laramide Orogeny__ • a period of mountain building that began in the Late Cretaceous, and is responsible for the formation of the Rocky Mountains.

Figure 8.18: The Badlands of South Dakota form new soil quickly due to the phenomenal average erosion rate of approximately 2.5 centimeters (1 inch) per year.

Soils of the Rocky Mountains
Region 3

The Rocky Mountains, a series of at least 100 different mountain ranges that stretch some 4800 kilometers (3000 miles) from northern Alberta southward to New Mexico, make up the great western backbone of the North American continent. The history of the uplift that formed the Rockies is complex, but the bulk of mountain building appears to have occurred during the **Laramide Orogeny**, which experienced its peak activity between 70 to 50 million years ago. Many of this region's soils, especially those in the Northern and Middle Rocky Mountains (Idaho, Montana, and northeastern Wyoming), are poorly developed and thin because they have not had sufficient time to develop.

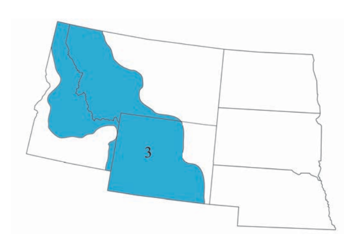
Since Entisols are commonly associated with steep slopes and poorly developed soils, it is easy to imagine why this soil type would be abundant in the Rocky Mountain region. The Bighorn Mountains and Wind River Range of Wyoming and the Big Belt Mountains of central Montana host abundant Entisols. These soils frequently have little agricultural value due to their poorly developed nature and rocky settings, but some high valley systems with sufficient water or irrigation resources can be productive (*Figure 8.19*). However, Entisols are not always directly associated with mountain slopes. The Killpecker Sand Dunes of the Red Desert in southwestern Wyoming provide a stunning example of poorly



developed soils periodically disturbed by active and reactivated sand dunes (*Figure 8.20*). These dunes, which formed from collected glacial sediments, are part of the largest active dune field in the United States.

Figure 8.19: The Entisols of high mountain alpine environments support a remarkable variety of forbs and other plant species.

Figure 8.20: The Killpecker Sand Dunes, Wyoming.



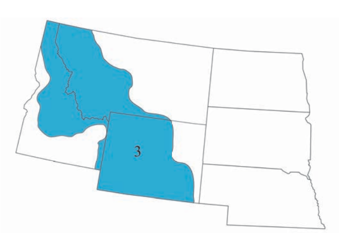
intermontane *• between or among mountains.*

While Inceptisols represent a level of soil development one step above that of Entisols, they are still very poorly developed. Inceptisols are found on reasonably steep slopes and involve parent rock material that is quite resistant to weathering, so they are frequently associated with mountain formations (*Figure 8.21*). Both the Clearwater and Salmon River mountains of Idaho and the Bitterroot Range, which straddles the Montana and Idaho border, host a high concentration of these soils. Many of the Inceptisols in this region are associated with forestry, rather than crop cultivation. The thin, rocky nature of the soils prevents significant water retention, placing lower limits on timber production.

Figure 8.21: Castle Peak, in Idaho's White Cloud Mountains, erodes to form weathered Inceptisols.

Aridisols are commonly found in the **intermontane** Wyoming Basin, due to the influence of a rain shadow effect from the tall mountains to the west. The Red Desert, a high-altitude desert and sagebrush steppe, hosts an abundance of these poorly developed and unstable soils. While many Aridisols are beyond the practicality of common agricultural and economic practices, not all have been left undeveloped. With major irrigation projects such as the Shoshone Project, which irrigates nearly 40,000 hectares (100,000 acres) of crop and grazing land with dammed flood waters from the Shoshone River, large portions of the rain-shadowed Bighorn Basin have proven to be quite productive, yielding soybeans, alfalfa, barley, oats, corn, sugar beets, and pastureland used to support local livestock production.

Andisols are soils formed from volcanic ash and a varied assortment of volcanic ejecta (*Figure 8.22*). Globally, they are the least common order, making up less



Regions 3–4

Figure 8.22: An example of an Andisol soil. These soils are formed from volcanic materials.

Figure 8.23: An Alfisol soil from the forests of Montana.

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

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

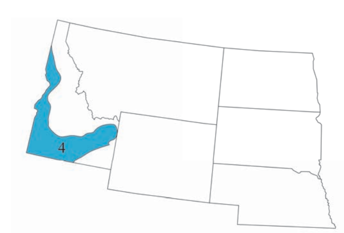
than 1% of all soil coverage. Similarly, in the US, they represent a mere 1.7% of total soil coverage. However, in the Rocky Mountain region, they are commonly found in the Clearwater, Coeur D'Alene, and Cabinet Mountains of Northern Idaho. These soils support some of the most productive **conifer** forests in the United States due to their unique chemical and physical properties. Andisols frequently contain high concentrations of volcanic glass and various weathered iron- and silica-rich material. Andisols have a high capacity for water retention and often fix large amounts of phosphorus, making it unavailable to plants.

Scattered Alfisols support forests throughout the Rockies of western Montana (*Figure 8.23*), and the high mountains of Montana and Wyoming also contain rich Mollisols that support rangeland and forest vegetation.

Soils of the Columbia Plateau
Region 4

The Columbia Plateau region forms an intermontane plateau bordered by the Northern Rocky Mountains to the east and the Cascade Range to the west. The plateau covers approximately 260,000 square kilometers (100,000 square miles) in Idaho, Oregon, and Washington and is one of the world's largest accumulations of volcanic rock.

The Snake River Plain that stretches in a bow across southern Idaho was formed by volcanic eruptions starting 11 to 12 million years ago. The eastern Snake River Plain follows the path the North American **plate** has taken over the



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

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

Yellowstone hot spot, which is now currently underneath Yellowstone National Park. This area is blocked by mountains on all sides, and therefore moisture is limited, leading to an accumulation of calcium carbonate and various **salts** and clays that form Aridisol soils (*Figure 8.24*). The Aridisols of the Snake River Plain have proven to be quite productive when heavily irrigated, and they compose much of Idaho's agricultural land. This is possible because of the relatively flat nature of the high plain, making crop cultivation practical when water is available. Irrigation yields crops such as potatoes, corn, wheat, sugar beets, mint, alfalfa, and onions. When not irrigated, these Aridisols usually support a sagebrush steppe.

See Chapter 2: Rocks for more information about Yellowstone National Park.

Figure 8.24: Aridisols of Idaho's Snake River Plain, near Craters of the Moon National Monument.

Mollisols, with their dark surface horizon, are common on the periphery of the Snake River Plain and along the western Idaho border in central Idaho. Due to the semiarid conditions of the region, irrigation is still necessary to take advantage of the rich, well-developed soil. Unirrigated Mollisols in the area tend to support a sagebrush steppe environment as well. It is important to note, however, that northwestern Idaho has some of the richest dryland wheat and pulse production in the world. This level of productivity is possible because these particular Mollisols are formed on loess overlying the **basalt**.

In southwestern Idaho, the juniper-pinyon woodlands found on rocky or **gravelly** uplands host a concentration of Alfisols. These Alfisols have a subsurface horizon with accumulated clays. Alfisols can be productive soils, and agriculture here is practiced largely in the form of grazing where sufficient sagebrush steppe is available.

Entisols associated with floodwater and **fluvial** deposits are found scattered along the extent of the Snake River.

gravel • *unconsolidated, semi-rounded rock fragments larger than 2 millimeters (0.08 inches) and smaller than 75 millimeters (3 inches).*

fluvial • *see outwash plain: large sandy flats created by sediment-laden water deposited when a glacier melts.*

Soils of the Basin and Range
Region 5

The Basin and Range covers a vast area of the western United States from northwestern Mexico to southern Idaho. Even though the region is generally arid, the portion of the Basin and Range that extends into southeastern Idaho is cooler and higher in elevation than the Snake River Plain to the north, receiving more moisture and supporting more heavily forested terrain.

Mollisols are the most common soil here, and they support a high-elevation sagebrush steppe, shrubland, and forest. Slopes facing the north support forests consisting of Douglas fir, subalpine conifers, aspen, and lodgepole pine. Slopes facing to the south support sagebrush and various grasses. In broad open areas, grassland is prevalent, and is often used for grazing. In areas with less topographical relief, Idaho's Mollisols support dry land or irrigated farming, which is dominated by potatoes.

Inceptisols and Entisols can also be found in this region. Higher elevations support forested slopes with a mixture of conifer species. These soils are commonly associated with the newly formed soils of mountainous terrain and do not lend themselves well to agriculture due to their poor development.

fossil • *preserved evidence of ancient life.*

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

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.

Idaho
The state soil of Idaho is the Threebear series. A type of Andisol, it is formed from silt and volcanic ash, resulting in a silty loam. These soils are found on hill slopes with a 5% to 35% grade and are associated with timber production.

Montana
Scobey soils are Mollisols that are found in north-central Montana and cover more than 280,000 hectares (700,000 acres) of till plains and **moraines**. These soils consist of brown clay loam and are ideal for growing wheat, which dominates the region's agriculture.

Nebraska
In south-central Nebraska, Holdrege soils cover nearly 810,000 hectares (two million acres) of land and support cropland and rangeland. These Mollisols formed from calcareous and silty loess material, and commonly support crops of soybeans, corn, and wheat.

North Dakota
The state soil of North Dakota is the Williams series, light gray to brown loamy Mollisols. These soils are widely found throughout the state on more than 810,000 hectares (two million acres) of land. Hilly areas of this soil are used for grazing, while level areas are used to produce flax, sunflowers, barley, oats, and wheat.

South Dakota
Houdek soil, a deep, loamy Mollisol, is the state soil of South Dakota. Found throughout the East River area of South Dakota, this grassland soil is heavily developed for agricultural purposes.

Wyoming
Forkwood soils are brown, clay loam Aridisols that are derived from the slopewash alluvium of shales and sandstone. These soils are primarily used for wildlife or grazing livestock.

Resources

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Lindbo, D. L., 2012, *Know Soil, Know Life*, Soil Science Society of America, Madison, WI, 206 pp.

Logan, W. B., 1995, *Dirt: the Ecstatic Skin of the Earth*, Riverhead Books, New York, 202 pp.

Soil Survey Staff, 2014, *Keys to Soil Taxonomy, 12th edition*, US Department of Agriculture, Natural Resources Conservation Service, Washington, DC, 362 pp., 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, NE, 498 pp., http://www. nrcs.usda.gov/wps/PA_NRCSConsumption/download?cid=stelprdb1247203&ext=pdf.

General Websites on Soils

K–12 Soil Science Teacher Resources, Soil Science Society of America, http://www.soils4teachers.org/.

Soil Survey Reports (by state and county/parish), The Cooperative Soil Survey, http://soils.missouri.edu/survey/selectstate.asp.

Soil Sustains Life, Soil Science Society of America, https://www.soils.org.

Soils Tutorial, The Cooperative Soil Survey, http://soils.missouri.edu/tutorial/index.asp.

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, technical publications, soil data, and much more.)

Soils of Specific Parts of the Northwest Central

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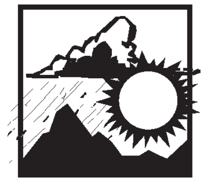

Chapter 9: Climate of the Northwest Central US

Climate is a description of the average temperature, range of temperatures, 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—San Francisco, for example—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 it can of course also define time periods millions of years in length.

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 Northwest Central have a diverse wardrobe, especially in low-lying areas that experience seasonal extremes of hot and cold. The entire area experiences great seasonal variation, although hot summer temperatures are moderated at higher elevations.

Past Climates

Climate, like other parts of the Earth system, is not static but changes over time, on both human and **geologic 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 Earth as a whole have varied through time, altering what kinds of climates are possible. Throughout its long history, parts of the Northwest Central US have been covered in ice, filled with subtropical swamps and forests, and submerged in warm, shallow seas.

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 of that of the Northwest Central. Unfortunately, we do not have as clear an understanding of climate

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

system *• a set of connected things or parts forming a complex whole.*

weather *• the measure of short-term conditions of the atmosphere such as temperature, wind speed, and humidity.*

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

tree *• any woody perennial plant with a central trunk.*

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

CHAPTER AUTHORS

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for the earliest part of Earth history 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 (CO_2), and nitrogen to the atmosphere. As the Earth cooled enough for liquid water to form, the vapor formed clouds from which the rain poured forth in such a deluge as the planet will never experience again. 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 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 about 3.7 billion years ago, the surface of the Earth was cooling to form a solid **crust** of rock (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,

helium *• a gaseous chemical element (He), which is the second most abundant and second lightest element in the universe.*

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

meteorite *• a stony or metallic mass of matter that has fallen to the Earth's surface from outer space.*

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

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

while more buoyant rock floats higher on the **magma** and is pushed around on the slow conveyor belts of mantle-formed rock (*Figure 9.1*). Denser rock forms oceanic **plates** that are lower and covered in water, and 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 rearrangement 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.

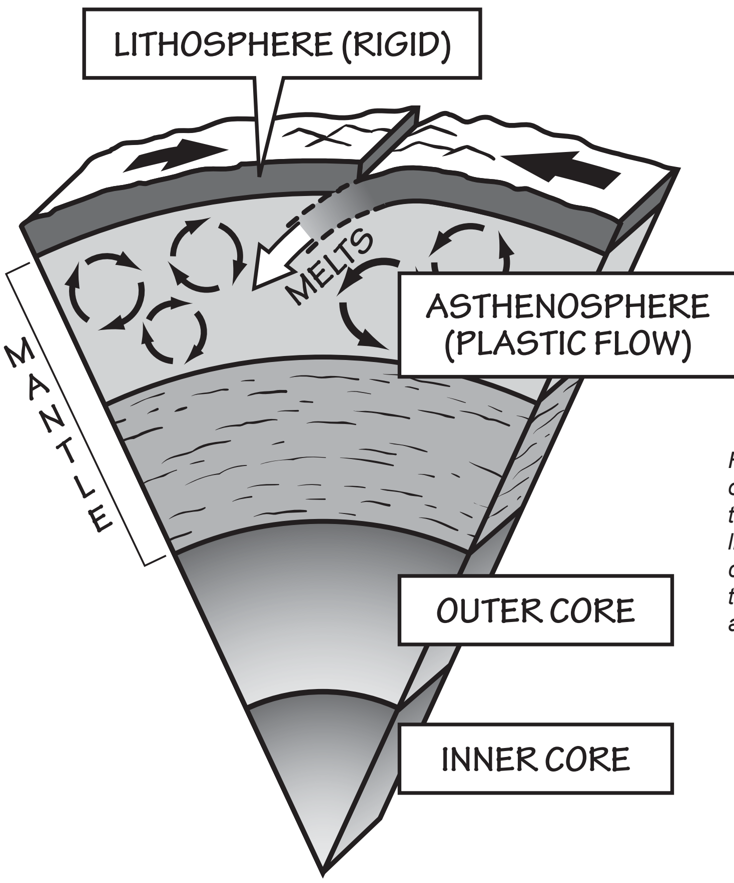


Figure 9.1: The layers of the Earth include the rigid crust of the lithosphere, which is constantly moving over the plastically flowing asthenosphere.

Nearly one billion years ago, the Earth began fluctuating between warm and cool periods lasting roughly 150 million years each. During cool periods, there is usually persistent ice at the poles, while during warm periods there is little or no glaciation anywhere on Earth. Today, we are still in a cool period—although the world has been cooler than it is at present, it has been far hotter for much of its history (*Figure 9.2*). Through the shifting global climate and the movement of the continents, what is now the Northwest Central has at times been submerged beneath a shallow sea, a plain filled with swamps, rivers, and grasslands, and even buried under thick ice.

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

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

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

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

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.

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

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).

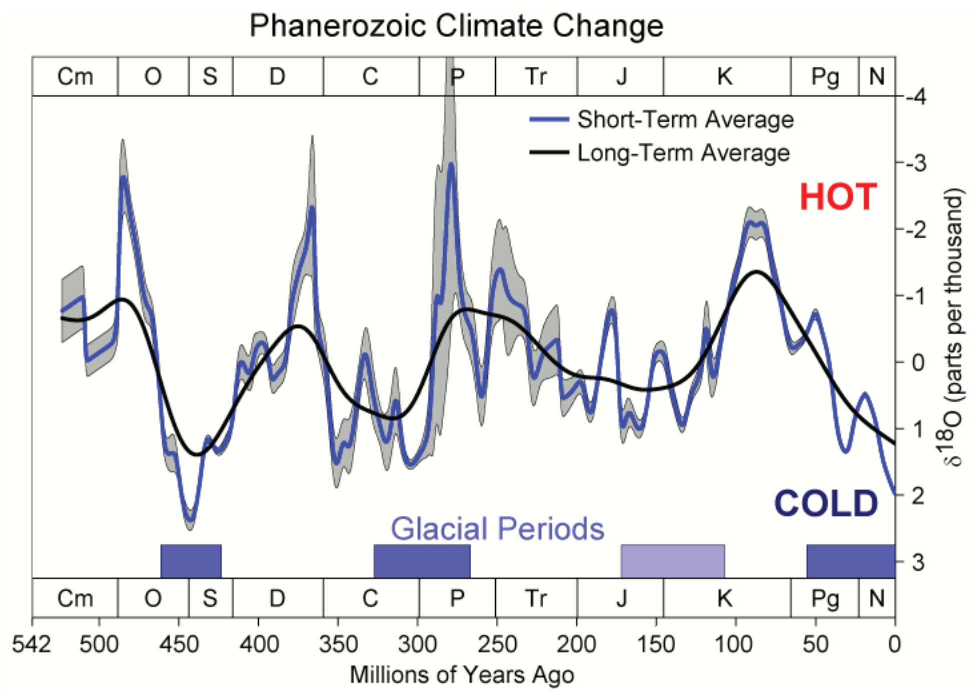


Figure 9.2: Changing global climate throughout the last 542 million years. These data were compiled using the ratios of stable oxygen isotopes found in ice cores and the carbonate skeletons of fossil organisms. (See TFG website for full-color version.)

Snowball Earth

There is evidence suggesting that the entire surface of the planet has been covered in ice several times, a hypothesis called Snowball Earth (*Figure 9.3*). 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.

See Chapter 6: Glaciers to learn more about past glaciations.

An ice-covered planet would remain that way because almost all of the sun's energy would be reflected back into space; however, this did not happen on Earth because of **plate 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. While these gases are usually removed from the atmosphere by organisms and the weathering of rocks, this was not possible through miles of ice! After millions of years, the concentrations of methane and CO_2 increased to the point that greenhouse warming began to melt the **ice sheets**. Once the

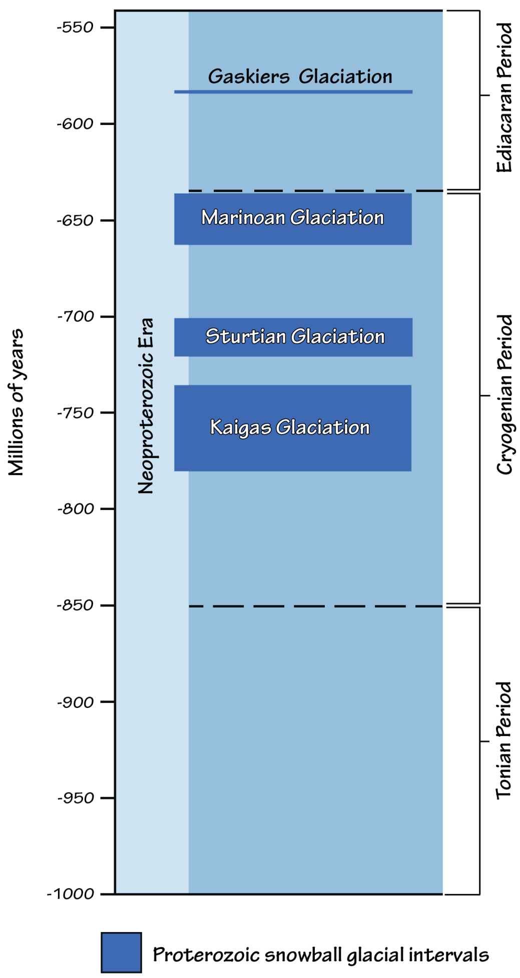


Figure 9.3: Snowball Earth periods during the Proterozoic.

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 derived 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, which was capable of combining with freshly thawed carbon sources to make more carbon dioxide, further enhancing the warming.

For the next 1.5 billion years, the Northwest Central US, free of ice, drifted around the surface of the Earth. **Stromatolites** found in Glacier National Park in Montana, as well as in Idaho and Wyoming, indicate periods of warm, shallow seas between 1.7 and 1 billion years ago.

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 subjected to mountain building and other plate tectonic processes. 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 located near the equator, and there were two more Snowball Earth cycles

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

stromatolite *• regularly banded accumulations of sediment created by the trapping and cementation of sediment grains in bacterial mats.*

Rodinia *• a supercontinent that contained most or all of Earth's landmass, between 1.1 billion and 750 million years ago, during the Precambrian.*

craton *• the old, underlying portion of a continent that is geologically stable relative to surrounding areas.*

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.*

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.*

9 Climate

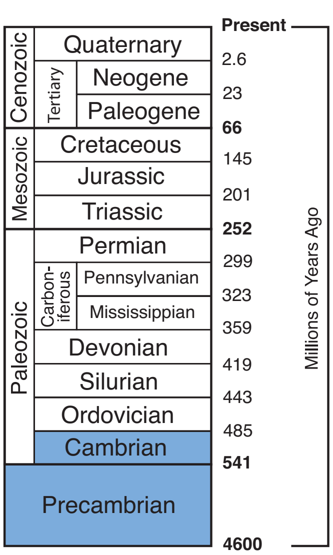
Past

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

passive margin *• a tectonically quiet continental edge where crustal collision or rifting is not occurring.*

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

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.*



during this time. Idaho contains deposits from the first of these, called the Sturtian (about 710 million years ago), and the fact that Idaho was at such a low latitude yet still experienced glaciation is strong evidence that the Earth really did freeze over completely. As Rodinia began to break up, another Snowball Earth event occurred during the Marinoan glaciation (about 640 million years ago).

By the late **Precambrian**, 600 to 550 million years ago, the Earth had warmed again, and the North American continent, including most of the modern Northwest Central US, was again near the equator.

Life and Climate

In this Guide we divide the Northwest Central States into five regions, but it is possible to more generally recognize two broad areas of strikingly different geology: the Cordilleran (Idaho, western Montana, and western Wyoming; Regions 3–5) and the Great Plains (North and South Dakota, the rest of Wyoming and Montana, and Nebraska; Regions 1 and 2). The main difference between the two areas is that the Cordilleran area has been subjected to mountain building, while the Plains area has remained tectonically quiet. Throughout most of the **Paleozoic**, the Northwest Central was part of a large **passive margin** that formed when Rodinia broke up, and major changes in deposition there were related to changes in climate and sea level.

With the start of the Paleozoic era, climates across the world were warm, and North America was located in the low and warmer latitudes of the Southern Hemisphere. As the **Cambrian** progressed, North America moved northward; by about 480 million years ago, what would become the Northwest Central was located just above the equator (*Figure 9.4*). Cambrian fossils reveal that most of the area was covered by warm, shallow seas during this time.

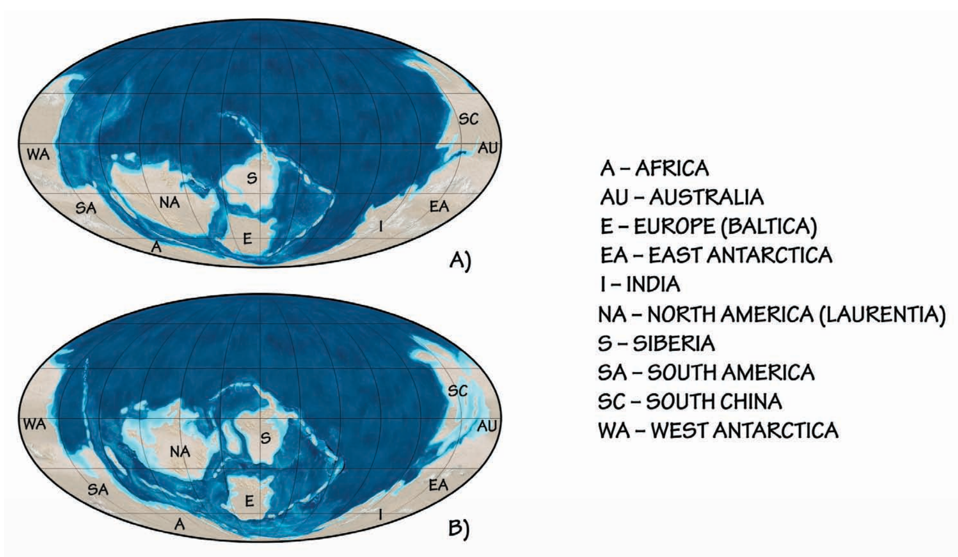


Figure 9.4: The location of the continents during the A) early and B) late Cambrian. Note the position of North America.

The Earth went through another ice age from 460 to 430 million years ago, and although sea level dropped during this event, North America's position near the equator kept its climate relatively warm. The change in sea level meant that the environment of the Plains area fluctuated from shallow marine, to brackish, to freshwater, and back. Farther west, in what is now the northern Rocky Mountains, the environment mostly alternated between shallow and deeper marine. **Ordovician** rocks in Idaho contain abundant fossils of **graptolites**, which are thought to have floated in the open ocean, and thus indicate deeper waters than those implied by bottom-dwelling **brachiopods**, corals, **cephalopods**, and other fossils common in other Paleozoic rocks. One of the characteristics of these warm, shallow sea deposits is that they often alternated between **limestone**, **sandstone**, and mudstone; **reefs** were not common at this time.

See Chapter 3: Fossils to learn more about Paleozoic fossils, including Cambrian trilobites and Ordovician graptolites.

A major interruption in this overall picture occurred during the **Devonian** period, when the huge Bakken oil formation that underlies parts of Montana and North Dakota formed. This oil-rich rock is part of a larger complex of such deposits that covered not just this area but large areas farther east as well. The richness of the organic matter indicates a sea that was highly productive, with such abundant planktonic life that the organic matter from the dead organisms took up all the oxygen in the water, allowing the rest to remain undecayed and preserved in the sediments.

See Chapter 7: Energy to learn about oil-rich deposits throughout the Northwest Central.

During the late Paleozoic, the sea gradually began to withdraw. The Plains area became terrestrial, but the sea still flooded parts of the northern Cordilleran area—this time farther west, in southeastern Idaho—and became exceptionally productive during the **Permian**. This is evidenced by the large deposits of phosphorite—a rock mined for fertilizer in Idaho, Wyoming, and Montana.

See Chapter 5: Mineral Resources for more about phosphate minerals mined in Idaho.

Around 220 million years ago the Northwest Central moved north from the equator. By this time, the sea had withdrawn completely from the area. Sediments suggest that the **Triassic** climate in the Northwest Central was warm. Initially arid, it gradually shifted to a humid climate with abundant, seasonal rainfall. The climate resembled that of modern India, where monsoons soak the land in the summer and completely dry out in the winter. At the very end of the Triassic, climate once again became arid. After reaching its greatest size during the Triassic period, **Pangaea** began to break apart into continents that would drift toward their modern-day positions (*Figure 9.5*).

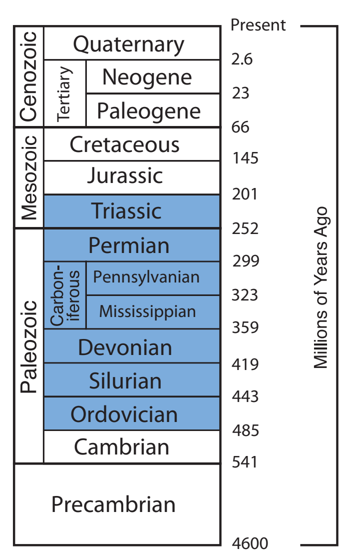
Past

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

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.*

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

Pangaea • *supercontinent, meaning "all Earth," which formed over 250 million years ago and lasted for almost 100 million years.*



Climate

Past

microcontinent *• a piece of continental crust, usually rifted away from a larger continent.*

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

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

active plate margin *• the boundary between two plates of the Earth's crust that are colliding, pulling apart, or moving past each other.*

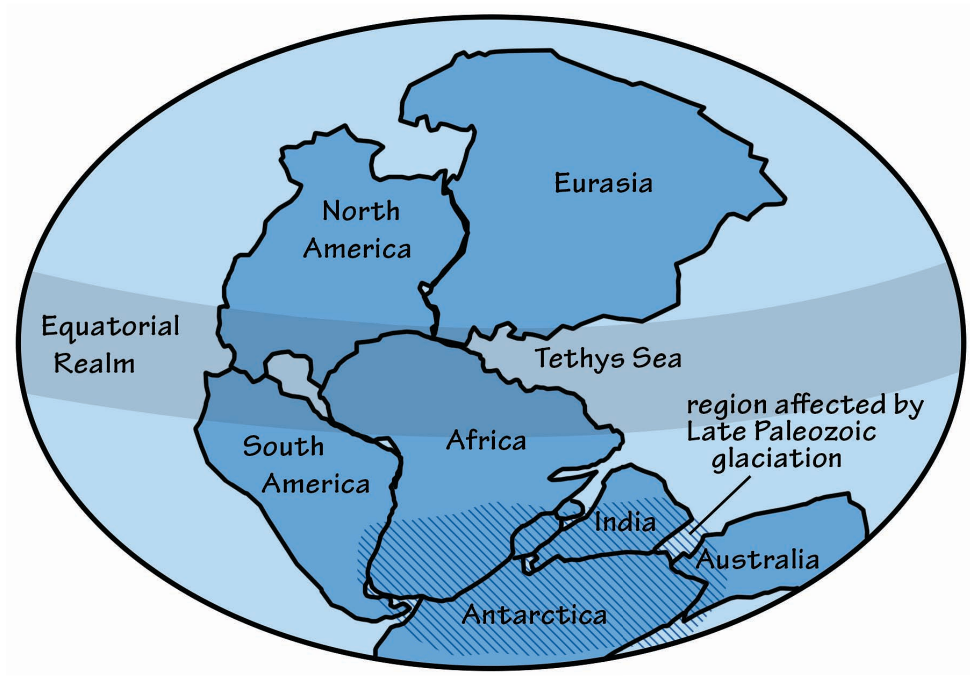
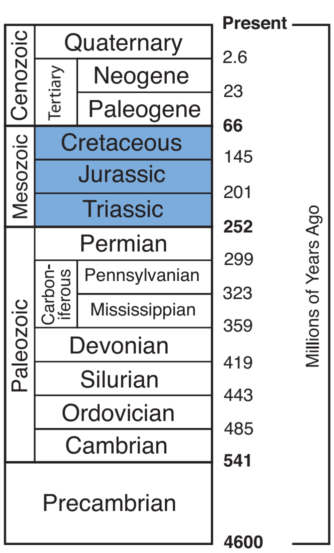


Figure 9.5: The breakup of Pangaea began around 220 million years ago.

Some Triassic rocks now found in the Northwest Central were not, however, part of the continent at that time. Triassic rocks in western Idaho include tropical reefs, and the fossils found in them (such as corals and brachiopods) are not similar to fossils found in the rest of North America. Many parts of the Western US, especially Alaska, originated as **microcontinents** (also called **terranes**) that drifted in during the process of **subduction** at the continent's **active plate margin** and **accreted** to North America as they collided with it. The Triassic reef deposits in Idaho rode in on one such microcontinent.

See Chapter 1: Geologic History to learn about the ways in which subduction and accretion shaped the Northwest Central.

The **Jurassic** and **Cretaceous** climates remained warm, but gradually became wetter, this time without the strong seasonality of the Triassic. The region was ruled by **dinosaurs**, and some of the most famous dinosaur localities in North America, including Como Bluff in Wyoming and the Judith River Formation in Montana, are found in the Northwest Central States. By this time, mountain-building (the **Laramide Orogeny**) was underway. The Black Hills were **uplifted** and sediment was deposited from both west and east. Ancient **metamorphic rocks** of the continental core were uplifted and eventually exposed in the Black Hills and even farther west.



The Earth warmed near the beginning of the Cretaceous, and sea level rose. Throughout the Cretaceous, sea level was an average of 100 meters (330 feet) higher than it is today, largely as a result of water displacement by continental rifting and rapid sea-floor spreading. Shallow seaways spread over many of the continents, and by the start of the late Cretaceous, North America was divided in two by an **inland sea** known as the Western Interior Seaway (*Figure 9.6*). Areas in the Northwest Central preserve both the eastern and western shorelines of this sea. Cretaceous fossils from modern-day North Dakota show that the seaway supported **sharks**, rays, **mosasaurs** (large marine reptiles), and giant turtles, while crocodiles and dinosaurs were abundant on land. This seaway was also productive, although most of its organic-rich rocks lie just south of the Northwest Central States.

At the close of the Cretaceous, 65 million years ago, global climates (though still much warmer than those of today) were cooler than at the era's start. At the very end of the Cretaceous, the Gulf Coast experienced an enormous disruption when an asteroid or comet collided with Earth in what is now the northern Yucatán

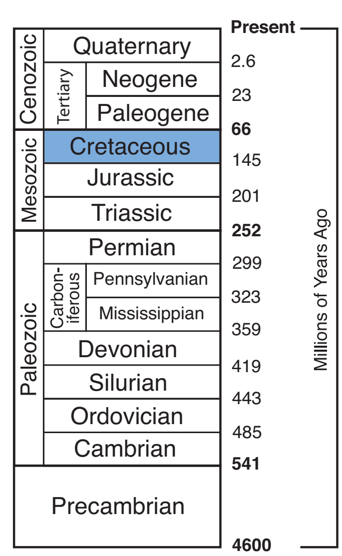
Figure 9.6: The Western Interior Seaway.

accretion *• the process by which a body of rock increases in size due to the addition of further sedimentary particles or of large chunks of land.*

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

Laramide Orogeny *• a period of mountain building that began in the Late Cretaceous, and is responsible for the formation of the Rocky Mountains.*

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



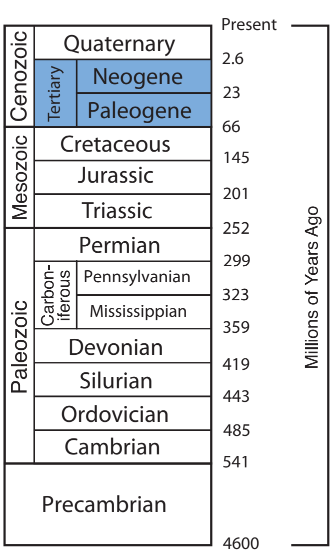
Eocene *• a geologic time period extending from 56 to 33 million years ago.*

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

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

Miocene *• a geological time unit extending from 23 to 5 million years ago.*

carbonate rocks *• rocks formed by accumulation of calcium carbonate, often made of the skeletons of aquatic organisms.*



Peninsula in Mexico. Following that event, the climate may have cooled briefly (as suggested, for example, by an abundance of ferns), but it soon rebounded to a warmer state, and continued to warm into the **Eocene**. Around 60 million years ago, much of the Northwest Central US had a milder climate than it does today, and it was even subtropical in some areas. Dinosaurs gave way to mammals, and forests with ferns, palms, and dawn redwoods provided food for browsers. Studies of ancient **soils** show that parts of Montana, Nebraska, and Wyoming went through several periods of warm, wet climate between 35 and 4 million years ago, although overall the climate became drier. The climate was wet enough in the Eocene to support large lakes in Wyoming, although these lakes occasionally dried out. The lakes supported an abundant diversity of fish and other organisms that today are exquisitely preserved as the famous Green River Formation fossils.

See Chapter 3: Fossils to learn more about extraordinary accumulations of perfectly preserved fossils known as lagerstätten.

By the early **Cenozoic**, the continents had approached their modern configuration, and India began to collide with Asia to form the Himalayas. The formation of the Himalayas had a significant impact on global climate, with the newly exposed rock serving as a sink to take up atmospheric CO_2. With the reduction of this greenhouse gas, global temperatures cooled. Antarctica moved south, and by 30 million years ago, temperatures were low enough that glaciers began to grow on its mountains. Grasses evolved during the **Miocene** as climate became drier. Miocene rocks in Nebraska support some of the most amazing sites for fossil mammals known anywhere.

Silicate and *carbonate rocks* both weather chemically in reactions that involve CO_2 and water, typically creating *clays*, bicarbonate, and calcium ions. *Silica* weathering occurs relatively slowly, taking place on a large scale in the weathering and erosion of mountain ranges, and may have an impact on atmospheric carbon dioxide levels on time scales of tens or hundreds of millions of years. On the other hand, carbonate rocks weather (in this case, dissolve) quickly relative to silicates. In both cases, the products of weathering often end up in seawater, where they may be used in the *calcium carbonate* skeletons of marine organisms or taken up during photosynthesis. Skeletal material and organic matter often sink to the sea floor and become buried, effectively removing carbon from the global carbon cycle (and thereby the atmosphere) for many millions of years.

Eventually, a sheet of sea ice formed over the Arctic, and ice sheets spread over northern Asia, Europe, and North America, signaling the start of the most recent ice age. Since just 800,000 years ago, a type 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 sheet's maximum extent, it reached into Montana, the Dakotas, and Nebraska (*Figure 9.7*). The portions of the Northwest Central that were not covered by ice experienced a variety of cold climates and abundant lakes. These lakes were also related to two very large flooding events, among the largest floods on Earth. The first was the Bonneville megaflood: melting glaciers fed the waters of ancient Lake Bonneville (the remains of which are today the Great Salt Lake), which broke through a dam of loose sediment and rapidly drained northward through southern Idaho, along what is now the Snake River, all the way to northern Idaho. The second was a series of floods that occurred when the ice sheet alternately blocked and retreated from what is now the Clark Fork River in northwestern Montana and northern Idaho. When the river was blocked, an enormous lake built behind the ice dam, and when the ice dam failed,

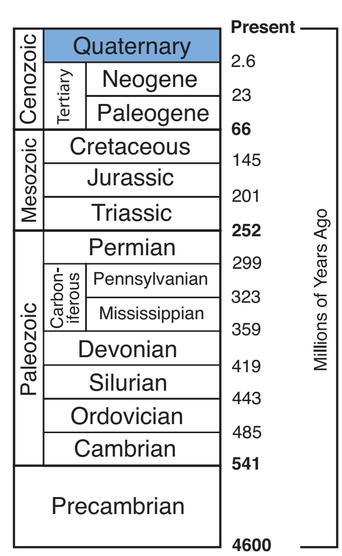
Figure 9.7: Extent of glaciation over North America during the last glacial maximum.

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

silica *• a chemical compound also known as silicon dioxide (SiO_2).*

calcium carbonate *• a chemical compound with the formula $CaCO_3$, commonly found in rocks in the mineral forms calcite and aragonite, as well as the shells and skeletons of marine organisms.*

ice cap *• an ice field that lies over the tops of mountains.*



***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.*

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

***Köppen system** • a commonly used system of climate categorization developed by Russian climatologist Wladimir Köppen, based on the kinds of vegetation that areas sustain.*

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

the water was released catastrophically. Although the floods mostly affected central Washington, large ripples from the intense flow are preserved both near Missoula, Montana, and just downstream from where the ice dammed the river in northern Idaho. Between 13,000 and 8500 years ago, fossil evidence shows that spruce and aspen forests grew in areas of North Dakota that are now warmer, drier, and covered with prairie. Idaho became more humid and warmer than it was during the **last glacial maximum**.

Present Climate of the Northwest Central

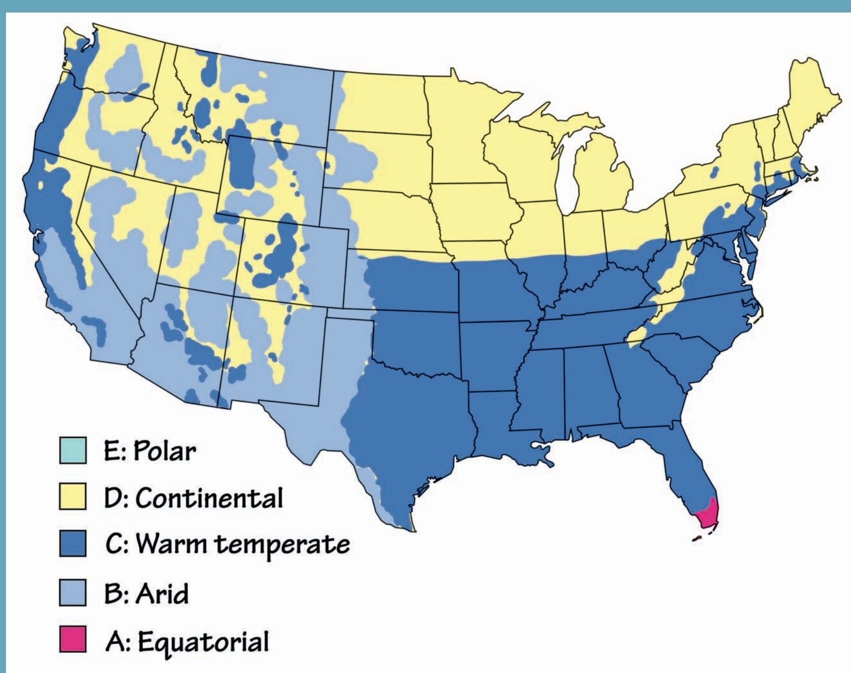
Due to their diverse **topographical** features, the Northwest Central States encompass a broad range of climates, including subarid steppe in the Great Plains, warm temperate highlands in the Cordilleran, and humid continental plains in the eastern Central Lowland. Even individual states can have tremendous diversity—depending on which of the many **Köppen system** maps you refer to, the state of Idaho alone contains as many as eight different climate types. The main drivers of climate in the Northwest Central US are exposure to Arctic air from Canada in the winter, the lack of large bodies of water nearby (except for Idaho, whose climate is influenced by the Pacific Ocean), and the presence of the Rocky Mountain chain in the west. These mountains block moist Pacific Ocean air from the interior of the continent and create a cold, high altitude zone.

Temperatures in the Northwest Central are characterized by seasonal extremes. South Dakota's temperature, for example, varies between an average low of -14°C (6°F) in January and an average high of 86°F (30°C) in July. Record lows and highs are astonishing: -57°C (-70°F) in Montana in 1954 and 49°C (121°F) in North Dakota in 1936. Average temperatures in the Northwest Central tend to decrease northward, which is in part influenced by latitude: lower latitudes receive more **heat** from the sun over the course of a year. The overall warmest temperatures are found in Nebraska, and the coolest are found in North Dakota and parts of Wyoming (*Figure 9.8*). The Northwest Central States' overall average high temperature of 14°C (57°F) and average low of 0.7°C (33°F) are indicative of a generally cool climate. By comparison, the average high and low temperatures for the entire United States are 17ºC (63ºF) and 5ºC (41ºF), respectively.

Average Annual Temperatures			
	Overall (ºC[ºF])	Low (ºC [ºF])	High (ºC [ºF])
Idaho	6.9 (44.4)	0.8 (33.4)	14.9 (58.8)
Montana	5.9 (42.7)	-0.8 (30.6)	13.3 (55.9)
Nebraska	9.3 (48.8)	2.7 (36.9)	17.0 (62.6)
North Dakota	4.7 (40.4)	-1.2 (29.8)	11.7 (53.1)
South Dakota	7.3 (45.2)	1.3 (34.3)	14.6 (58.3)
Wyoming	5.6 (42.0)	-2.1 (28.2)	13.4 (56.1)

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.)

The Northwest Central US is dry compared with many other parts of the United States, so dry that all the states within it except Nebraska rank within the top 10 driest states based on annual precipitation. Precipitation generally tends to decrease to the west across the Rocky Mountains, with an average annual precipitation of 65–90 centimeters (25–35 inches) in the Central Lowland region of the eastern Dakotas and Nebraska, about 25–50 centimeters (10–20 inches) in the Great Plains, and less than 25 centimeters (10 inches) in parts of Wyoming and Idaho (*Figure 9.9*). By comparison, the average amount of precipitation for the United States is 85.6 centimeters (33.7 inches). The decrease in precipitation is due in large part to rain shadow effects from

9 Climate

Present

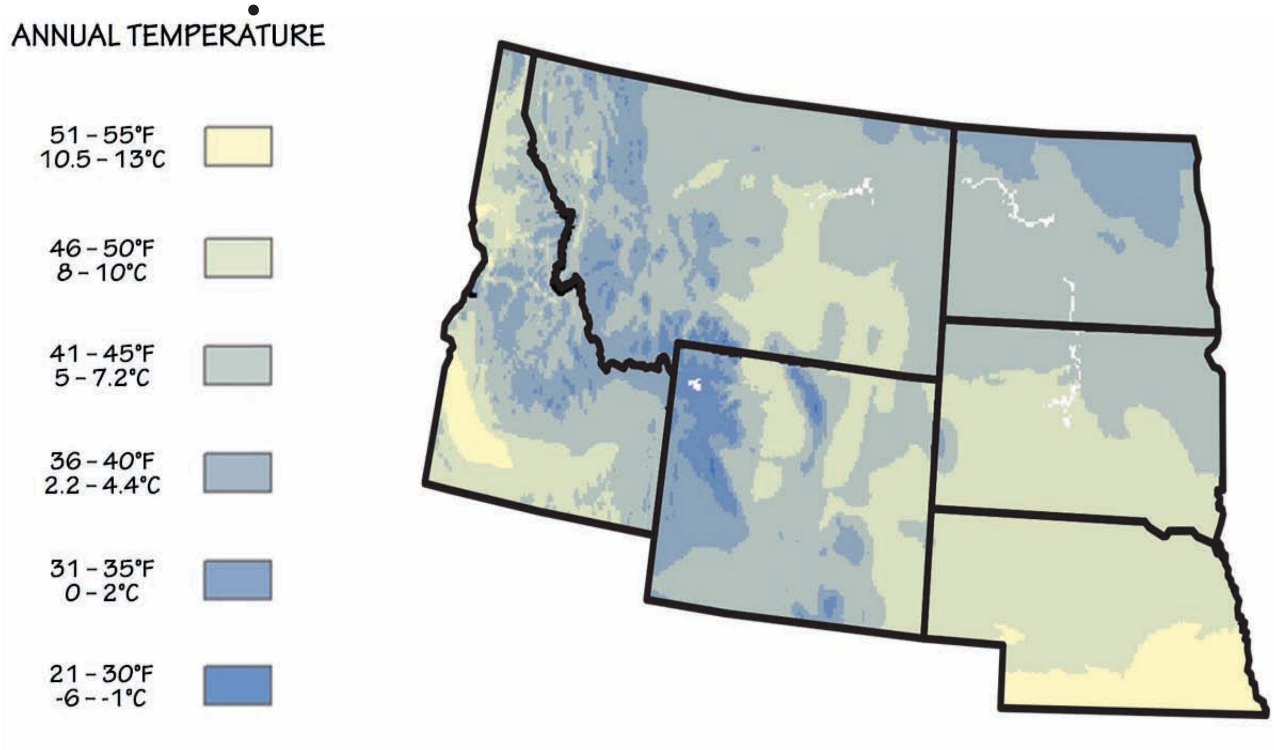


Figure 9.8: Mean annual temperature for the Northwest Central States. (See TFG website for full-color version.)

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

badlands • *a type of eroded topography that forms in semi-arid areas experiencing occasional periods of heavy rainfall.*

mountain ranges located west of as well as within the Northwest Central. Rain shadows occur when moist air moves eastward with the prevailing **winds**, and is pushed upward and cools when it encounters a mountain chain. Water vapor condenses from this cool air and falls as rain or snow on the western side of the mountain. The air that continues to move east over the mountains is now much drier, and as it moves down the eastern side of the mountain range it warms, promoting evaporation (*Figure 9.10*) .The mountainous Continental Divide, which runs through western Montana, creates a rain shadow effect that contributes to the aridity of the plains and **badlands** in the eastern part of the state. Nebraska's semi-arid west and fairly uniform average temperatures are moderated by dry, warm rain shadow winds blowing eastward from the Rocky Mountains.

Exceptions to the westward drying trend are found in the mountainous parts of northwestern Wyoming and Montana, and in northern Idaho, where average annual precipitation is typically 101 to 127 centimeters (40 to 50 inches), demonstrating the impact of moisture carried inland from the Pacific Ocean. Idaho's climate is strongly moderated by the Pacific Ocean, even though the state lies nearly 560 kilometers (350 miles) from the coast. In the winter,

Present

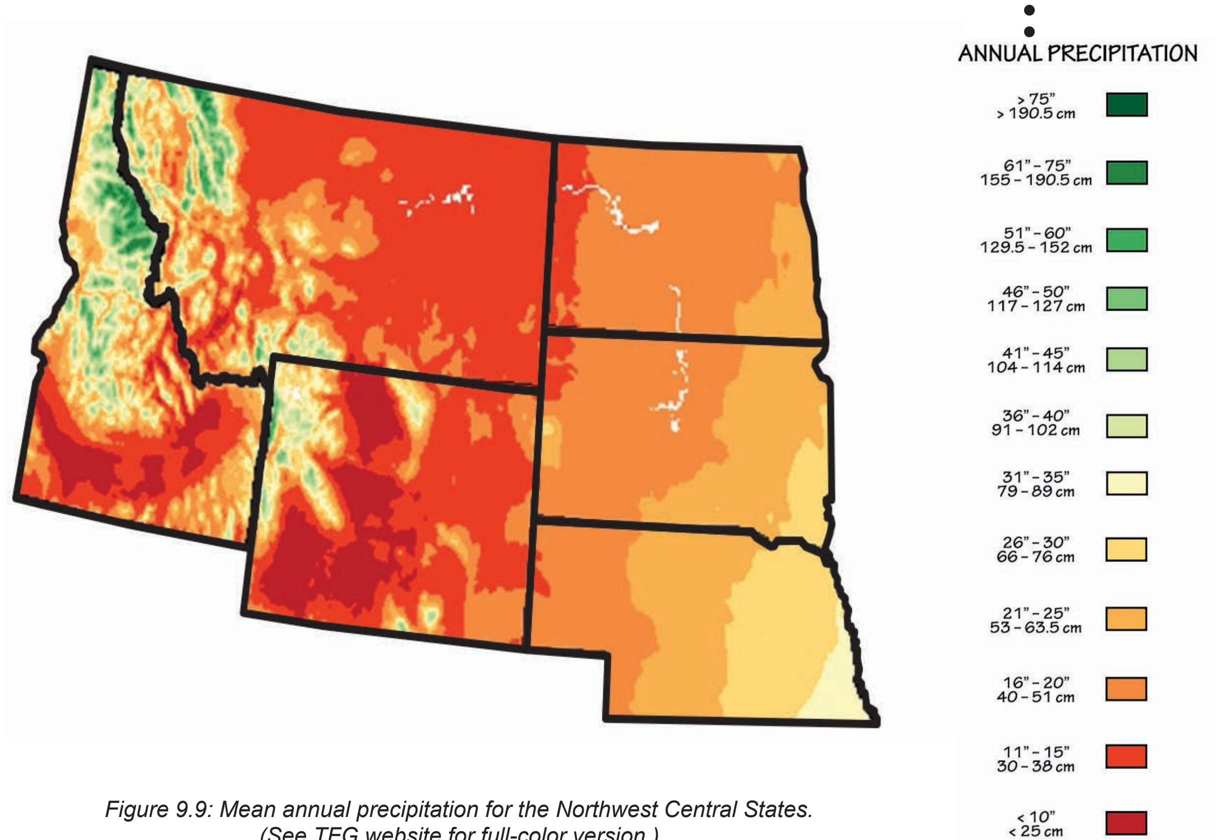


Figure 9.9: Mean annual precipitation for the Northwest Central States. (See TFG website for full-color version.)

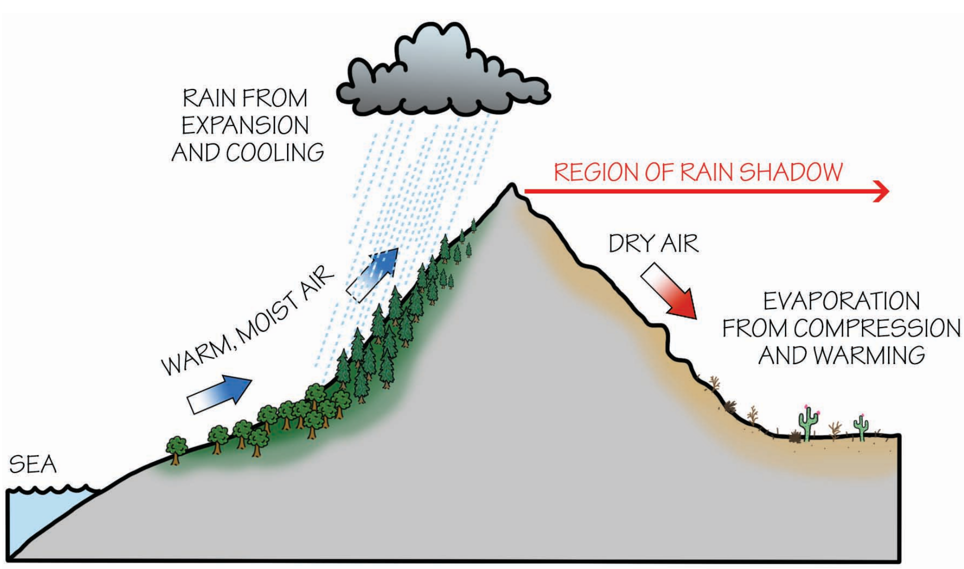


Figure 9.10: The key characteristics of a rain shadow.

Present

jet stream • *a fast-flowing, narrow air current found in the atmosphere.*

erosion • *the transport of weathered materials.*

Figure 9.11: A snow fence near the Grand Tetons in Wyoming. Fences like these are used to force windblown snow to accumulate in a desired place, keeping it off roadways or collecting it for later use as a water supply.

humidity from the ocean creates heavy cloud cover and precipitation that helps to moderate temperature.

Harsh winter storms are a fact of life in the Northwest Central US, carried in by the polar **jet stream**, which typically falls near or over the area, especially in the winter. Blizzards with high winds, large amounts of snowfall, and low visibility are common and are brought on by cold air masses known as the Alberta Low from the north and the Colorado Low from the south. Since the Rocky Mountain region is dry, some residents use fences to capture snow for later use as a water source (*Figure 9.11*). Spring storms are also common, and heavy downpours can lead to flash flooding. Rain coupled with rapid snowmelt in the spring is another common source of flooding in the Rocky Mountain region's river basins.

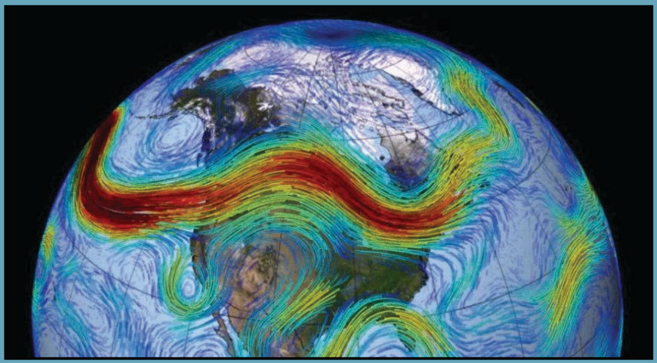
The Northwest Central US is sparsely populated, with less than seven million people. Weather hazards are a concern for communities and for agriculture. When the area experiences severe drought, as Wyoming did from 1999 to 2004, residents experience costly losses in food and water supply, grazing land for livestock, soil **erosion**, wildfire damage, and air quality. The Red River in North Dakota is highly susceptible to flooding, and since it runs through Fargo and Grand Forks, the populations and infrastructure of those cities are put at risk during floods. In the winter, cold waves brought on by Arctic air masses entering the area

See Chapter 10: Earth Hazards for more information about weather hazards that affect the Northwest Central US.

What is a jet stream?

Jet streams—there are more than one—are narrow bands of fast moving air high above a planet's surface. (Jupiter and Saturn have jet streams too.) The Earth's rotation drives these rivers of air and causes them to blow from west to east. On Earth, they are typically found between 6 and 13 kilometers (4 and 8 miles) above the surface and can move at speeds tens to hundreds of kilometers (miles) per hour. Jet streams separate warm and cold air masses, and thus their movements can greatly influence the weather. Polar jet streams are typically found between 50° and 60° North or South latitude, and subtropical jet streams are typically found around 30° North or South latitude. As the boundaries between hot and cold air are sharpest in the winter months, jet streams are stronger in the winter. In the Northwest Central States, the polar jet stream strongly influences the area's weather.

The *polar vortex* is a pattern of winds around the North Pole, including the polar jet stream. In the winters of 2013–2014 and 2014–2015, the polar vortex shifted southward, bringing unusual weather patterns to much of North America. Weaker polar vortices can occur when weather near the pole is warmer than usual, and a weak polar vortex allows for a wandering jet stream. Some climate scientists believe the unusual winters of recent years are explained by natural variations, while others suggest that they could be driven due to decreases in sea ice and faster increases in arctic temperatures when compared to areas at lower latitudes.



The polar jet stream over North America (shown in red). Warmer colors indicate regions of faster airflow.

(See TFG website for full-color version.)

polar vortex • *a regularly occurring area of low pressure that circulates in the highest levels of the upper atmosphere.*

tornado *• a vertical funnel-shaped storm with a visible horizontal rotation.*

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.*

can damage livestock and crops. Nebraska, located in a corridor known as Tornado Alley, commonly experiences violent thunderstorms and **tornados** in spring and summer.

Future Climate of the Northwest Central

By using techniques that help to reconstruct past climates, and by 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 should end, allowing glaciers to advance toward the equator again (although likely not for about 100,000 years). However, because the Earth is already getting warmer, the effects of **anthropogenic** 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.

Causes of Change

While astronomical and tectonic forces will continue to cause climatic shifts, they act so slowly that they will be overshadowed in the near term by human-induced effects. In 1956, NOAA established the Mauna Loa Observatory (MLO) in Hawaiʻi to measure a variety of atmospheric parameters, including carbon dioxide (CO_2) concentration. The CO_2 record extends from 1958 to present, and it shows the influence of both natural and anthropogenic processes (*Figure 9.12*). The zigzag pattern is the result of seasonal photosynthesis in the northern hemisphere. In spring and summer, the growth and increased photosynthetic activity of plants draws CO_2 out of the atmosphere. Conversely, it accumulates in the atmosphere during fall and winter when plants are dormant. The overall upward trend is caused by human activity. Industrialization, **fossil fuel** combustion, and deforestation all contribute CO_2 to the atmosphere, adding it at a rate much faster than natural processes can remove it. Analyses of ancient atmosphere samples preserved in glacial ice cores show CO_2 levels to be 180 parts per million (ppm) at the height of the last ice age and 280 ppm at its end. The amount of CO_2 in the atmosphere has been increasing at a rapid rate since the start of the industrial revolution, and it has accelerated since the end of World War II. In May 2013, measurements at MLO reached 400 ppm CO_2 for the first time.

While some atmospheric carbon dioxide is necessary to keep Earth warm enough to be a habitable planet, the unprecedentedly rapid input of CO_2 to the atmosphere by human beings is cause for concern. Everything we know about atmospheric physics and chemistry tells us that increased CO_2 leads to a warmer planet. Multiple paleoclimate data sets verify this conclusion, and modern measurements confirm that we are living in an increasingly warmer world. 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.

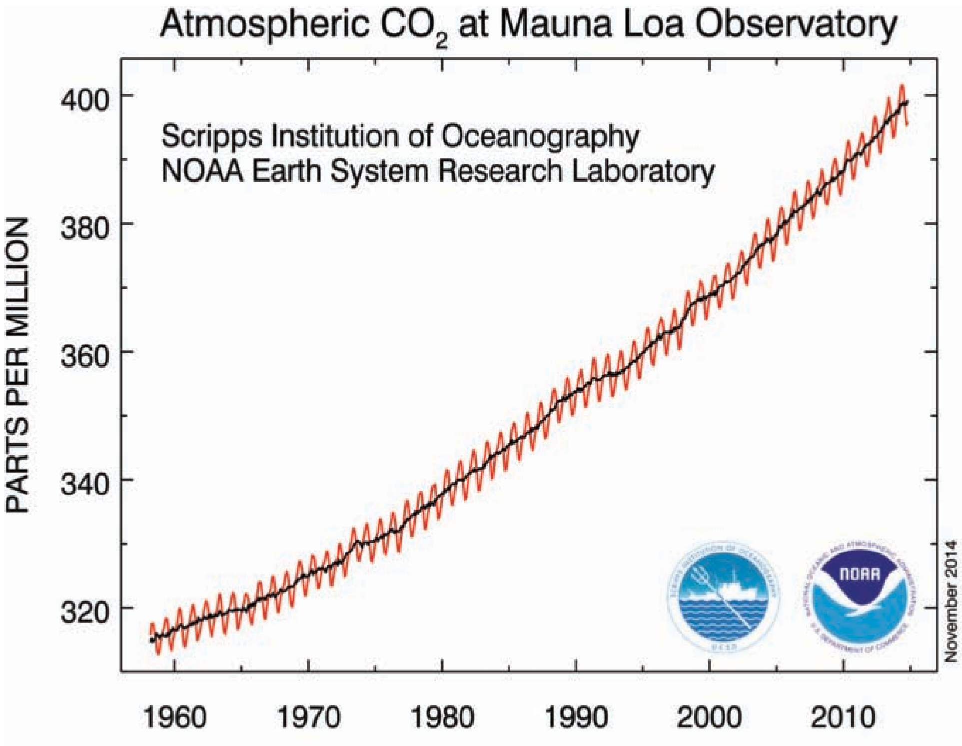


Figure 9.12: Measured concentration of atmospheric carbon dioxide (1958 to present) at MLO.

Future

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.*

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

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

As **permafrost** in high latitudes melts, carbon in the soil becomes 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 actually the most effective greenhouse gas. Higher temperatures increase evaporation and allow the air to retain more water. 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, such as carbon dioxide and methane, linger in the atmosphere for years.

The Northwest Central US contributes to **climate change**, although its total greenhouse gas emissions are lower than those of other areas of the United States. The population of any industrialized and particularly wealthy country produces pollution; the majority of these emissions come from the use of **petroleum**. The 6.5 million residents of the Northwest Central use electricity, transportation, and products that come from carbon-rich fossil fuels. Burning fossil fuels releases carbon into the atmosphere, which warms the Earth. Of the Northwest Central States, Wyoming emits the most greenhouse gases, releasing 64 million metric tons of carbon dioxide per year. By contrast, the highest greenhouse gas-emitting state in the nation is Texas, which releases *__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.*

nearly 656 million metric tons of CO_2 per year. Idaho is one of the lowest carbon emitters in the nation, producing only 16 million metric tons of CO_2 annually. However, the Northwest Central's low emissions profile is related to its low population. For example, Wyoming has fewer than 600,000 residents; in 2011 it emitted 113 metric tons of CO_2 per capita, the highest in the nation, while Texas, with a population of 26 million, emitted only 23 metric tons per capita.

Although the Northwest Central still has a relatively low carbon footprint, its greenhouse gas emissions have been growing. As recently as 1990, Montana was estimated to be a net carbon sink, with carbon sequestered in its forests and soils. By 2005, it had become a net carbon emitter, and carbon emissions in other Northwest Central States have increased as well. Over the period from 2000 to 2011, Nebraska experienced a 25% increase in the amount of CO_2 it emitted—the greatest absolute increase in the country—due to an increasing amount of fossil fuel-related energy production.

See Chapter 7: Energy to learn about energy production in each of the Northwest Central states.

On the other hand, many Northwest Central States are also making changes to reduce human impact on the climate. Boise, Idaho, Big Sky, Montana, and Jackson, Wyoming are just a few locations that have adopted the 2030 Challenge, an effort by cities to reduce fossil fuel use in buildings so that both new and renovated buildings would qualify as carbon neutral by the year 2030. Additionally, many states are stepping up their use and production of **renewable energy**. Montana ranks ninth in the nation for renewable energy production, most of which it generates from hydroelectricity.

Trends and Predictions

Studies show that climate in the Northwest Central is changing right now, and that change has accelerated in the latter part of the 20th century (*Figure 9.13*). These changes include the following:

- During the 20th century, the average annual temperature of the Northwest Central US as a whole increased by 0.9°C (1.6°F). North Dakota's average temperature increased 1.9°C (3.4°F) during the last 130 years, the fastest increase in the US.
- Soils in Nebraska have become warm enough to plant corn one to three weeks earlier in the 2000s compared to in the 1990s.
- Springtime snowmelts in Wyoming in 1990 were flowing four days earlier than in 1950.
- The Ogalalla Aquifer, which provides fresh water to most of Nebraska, has been depleted by more than 40% in some areas, thanks to years of decreased rainfall.

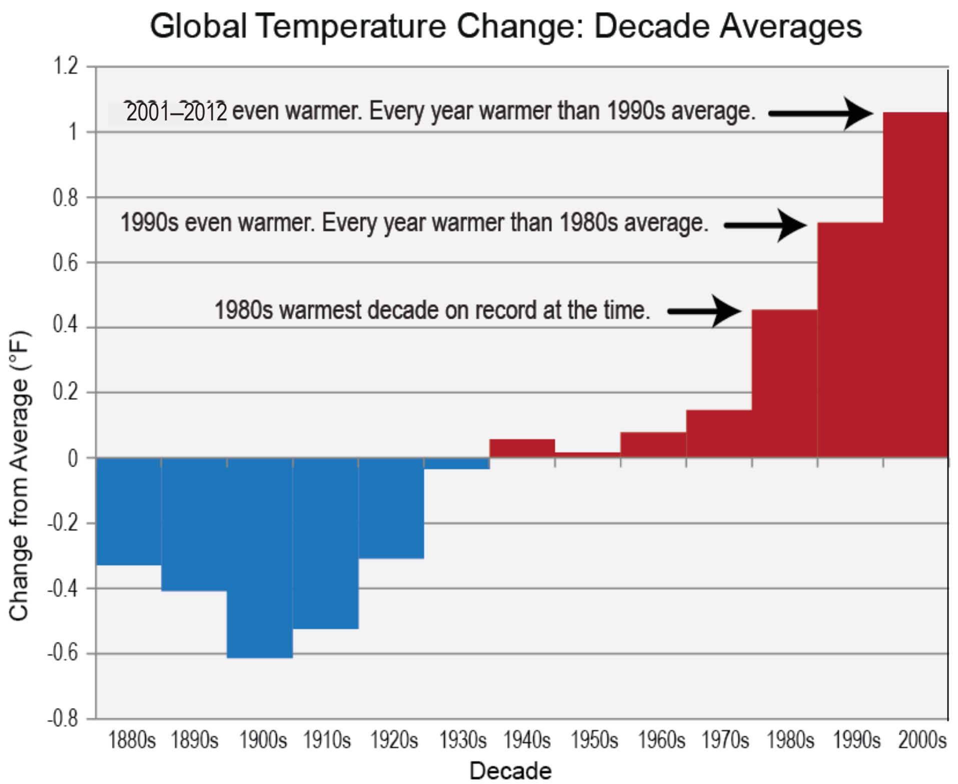


Figure 9.13: Global temperature change since the 1880s. The Earth's average surface temperature has progressively risen over the last five decades.

- The bull trout, an endangered freshwater fish native to northwestern North America, is estimated to have lost 11% of its stream habitat in Idaho's Boise River Basin due to an increase in water temperature.
- In the last century, annual precipitation has increased by up to 20% in South Dakota.
- In 1850, Montana's Glacier National Park contained an estimated 150 glaciers. Today, only 25 glaciers remain. Models predict that all of them will have disappeared by 2030.

Climate models predict that the Northwest Central's climate will continue to warm, and that the average annual temperature in most of the area will rise by 3°C to over 6°C (6°F to over 10°F) by the end of the 21st century. These increased temperatures lead to a whole host of other effects, including drier soils from greater evaporation, and the increased likelihood of drought and fires. In Montana, for example, the annual amount of wildfire-prone land area is predicted to increase by nearly 400% by the end of the century.

Climate

Future

Water supply is a critical issue in the Northwest Central US, and communities will need to adapt to changes in precipitation, snowmelt, and runoff as the climate changes. Models predict that much of the area's climate will become wetter, with more precipitation falling in winter and spring. In Idaho, it's likely that increasingly more precipitation will fall as rain rather than snow, and snow in the mountains will melt earlier in the spring. This could strain the water supply in the warm season. Additionally, because higher temperatures mean greater evaporation and warmer air can hold more water, precipitation will occur in greater amounts at a time (*Figure 9.14*). During the cooler spring this will lead to flooding, while in hot summers, droughts will become more frequent. These drier summers and wetter winters and springs could have significant adverse impacts—drier summer days and higher temperatures will amplify evaporation, increasing the risk of desertification and affecting natural ecosystems as well as increasing pressure on the water supply for agriculture and cities.

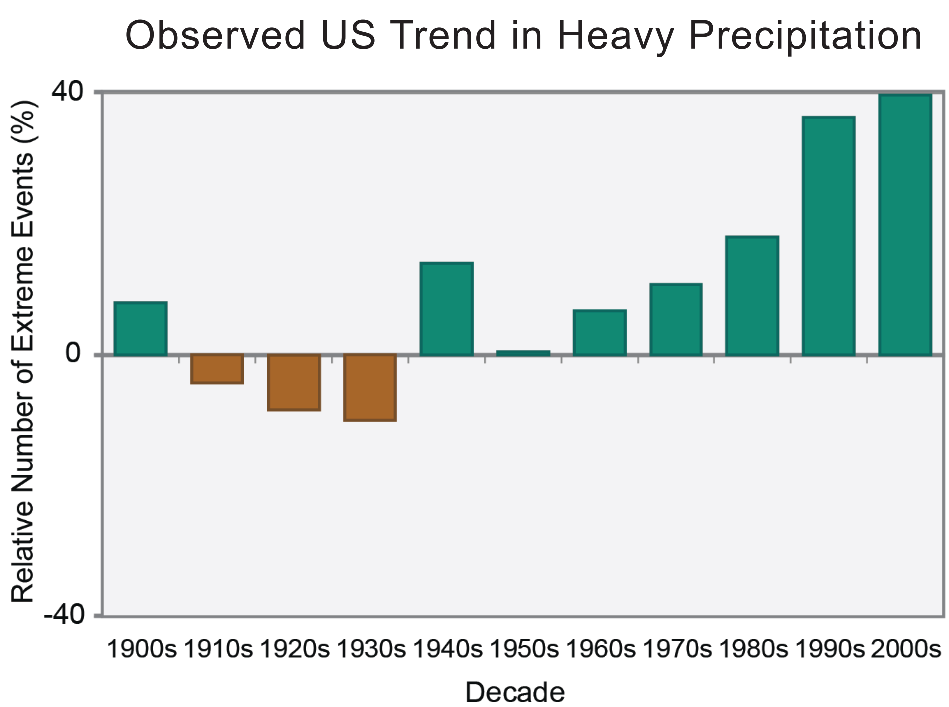


Figure 9.14: Changes in heavy precipitation events from the 1900s to the 2000s. Each event is defined as a two-day precipitation total that is exceeded, on average, only once every five years. The occurrence of such events has become increasingly common.

Agriculture is a huge industry in the Northwest Central US, especially in the Great Plains and Central Lowland. To the advantage of soybean and corn growers in Nebraska, warmer temperatures and increased precipitation have helped bring on longer growing seasons. Warmer temperatures, however, also make it easier for insect pests to overwinter and produce more generations. The European corn borer, a devastating pest found in the central and eastern US, produces more generations in warmer parts of the country (*Figure 9.15*).

hurricane *• a rapidly rotating storm system with heavy winds, a low-pressure center, and a spiral arrangement of thunderstorms.*

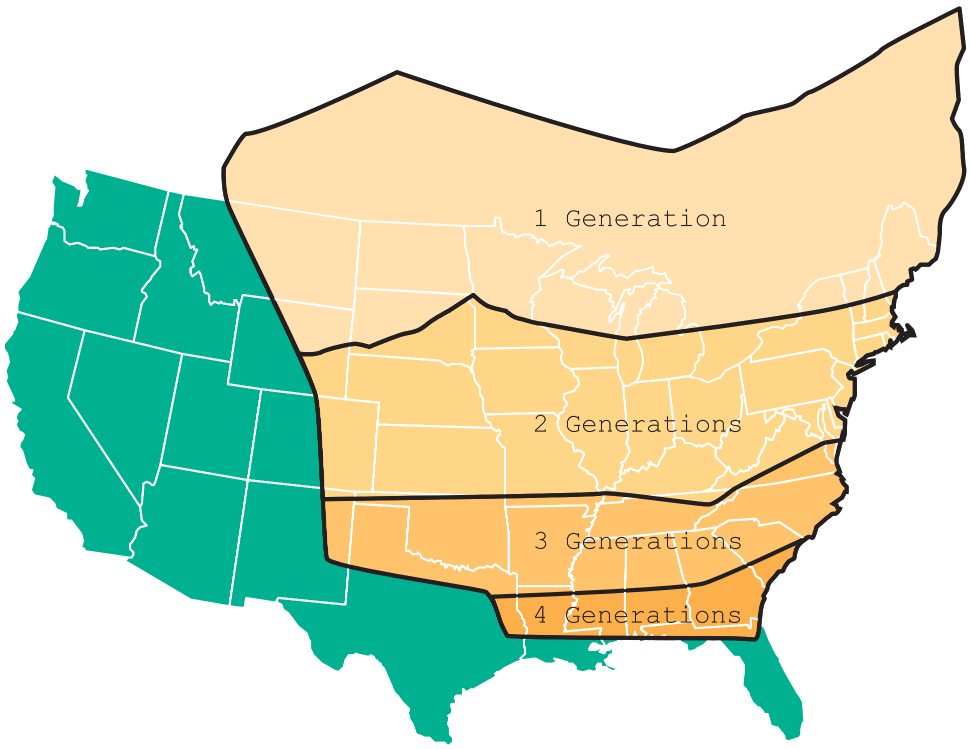


Figure 9.15: The European Corn Borer, an agricultural insect pest, currently produces one to four generations a year depending on its location in the US. As the climate warms farther north, they are expected to produce more generations in the Great Plains and Central Lowland, causing greater crop damage.

As the Great Plains and Central Lowland warm, one can expect three or four generations of these pests annually in regions that previously had only one or two. Another major pest affected by the warming climate is the mountain pine beetle, which has been devastating pine forests throughout the Pacific Northwest and Canada, and is now spreading west into Montana, Wyoming, and the Dakotas. In the last few years, the beetle's numbers have spiraled out of control thanks to warmer temperatures, which extend the breeding season and generate fewer cold-related dieoffs for the insect population. So far, 36 million hectares (88 million acres) of pine forest have been affected, with a 70–90% tree mortality rate (*Figure 9.16*). The death of these trees will have a significant impact on the forests' ability to sequester carbon; researchers have estimated that the dieoffs in Canada alone will have caused the release of 270 million metric tons of CO_2 into the atmosphere by 2020.

The causes of specific weather events such as **hurricanes** and severe thunderstorms are incredibly complex, although climate change has enhanced some correlated factors, such as increased wind speed and an unstable atmosphere. Higher atmospheric moisture content has also been correlated with an increased incidence of tornados and winter storms. However, although climate change is predicted to enhance the intensity of severe weather, there is currently no way to calculate what effect climate change will have on the

Figure 9.16: A swath of dead trees in the Black Hills of South Dakota, destroyed by the mountain pine beetle.

frequency of specific storm events—for example, we might see more powerful tornados, but we do not know if we will see *more* of them.

All over the Northwest Central US, residents and communities have begun to adapt to climate change, and to plan for future changes that are expected to come.

Resources

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Climate has Changed Throughout Earth's History, National Park Service, http://nature.nps.gov/geology/nationalfossilday/climate_change_earth_history.cfm.

Climate Literacy & Energy Awareness Network (CLEAN), http://www.cleanet.org. (A rich collection of resources for educators).

Envisioning Climate Change Using a Global Climate Model, by B. Youngman, M. Chandler, L. Sohl, M. Hafen, T. Ledley, S. Ackerman, and S. Kluge, SERC Earth Exploration Toolkit, http://serc.carleton.edu/eet/envisioningclimatechange/index.html.

Global Climate Change: Vital Signs of the Planet, National Aeronautics and Space Administration, http://pmm.nasa.gov/education/websites/global-climate-change-vital-signs-planet. (Information about global climate change, including spectacular satellite images.)

Global Greenhouse Gas Reference Network, Global Monitoring Division, National Oceanographic and Atmospheric Administration Earth System Research Laboratory, http://www.esrl.noaa.gov/gmd/ccgg/data-products.html. (Data and visualizations.)

Global Weather, Jetstream—Online School for Weather, National Weather Service, http://www.srh.noaa.gov/jetstream/global/global_intro.htm.

Intergovernmental Panel on Climate Change, Fifth Assessment Report (AR5), http://www.ipcc.ch/.

JetStream—Online School for Weather, National Weather Service, National Oceanographic and Atmospheric Administration, http://www.srh.noaa.gov/jetstream/index.htm.

National Climate Assessment, http://nca2014.globalchange.gov. (Reports summarizing impacts of climate change.)

National Weather Service, National Oceanographic and Atmospheric Administration, http://www.weather.gov.

NOAA's El Nino Portal, National Oceanographic and Atmospheric Administration, http://www.elnino.noaa.gov/.

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North America During the Last 150,000 Years, compiled by J. Adams, http://www.esd.ornl.gov/projects/qen/nercNORTHAMERICA.html.

Paleomap Project, http://scotese.com/. (Maps and information about Earth's tectonic and climate history.)

Regional Climate Trends and Scenarios for the U.S. National Climate Assessment, National Oceanographic and Atmospheric Administration, http://www.nesdis.noaa.gov/technical_reports/142_Climate_Scenarios.html.

US Map of Köppen-Geiger Climate Classification, http://koeppen-geiger.vu-wien.ac.at/pics/KG_USA.gif.

Weather Base, http://www.weatherbase.com. (Weather and climate data by country, state, and city.)

Weatherunderground Maps, http://www.wunderground.com/maps. (A variety of types of weather maps, including surface, temperature, moisture, wind, cloud cover, precipitation.)

State- or Region-specific Climate Resources

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Climate of Idaho, Western Regional Climate Center, http://www.wrcc.dri.edu/narratives/IDAHO.htm.

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Our Changing Climate: Great Plains, National Climate Assessment, http://nca2014.globalchange.gov/report/regions/great-plains.

Our Changing Climate: Northwest, National Climate Assessment, http://nca2014.globalchange.gov/report/regions/northwest. (Includes Idaho.)

The Paleontology Portal, http://paleoportal.org/. (North American fossil record and geologic and climate histories, by state.)

Regional Climate Trends and Scenarios for the U.S. National Climate Assessment. Part 4. Climate of the U.S. Great Plains, by K. E. Kunkel, L. E. Stevens, S. E. Stevens, L. Sun, E. Janssen, D. Wuebbles, M. C. Kruk, D. P. Thomas, M. Shulski, N. Umphlett, K. Hubbard, K. Robbins, L. Romolo, A. Akyuz, T. Pathak, T. Bergantino, and J. G. Dobson, 2013, NOAA Technical Report NESDIS 142-4, 82 pp., http://scenarios.globalchange.gov/regions/great-plains.

Weatherbase, http://www.weatherbase.com/weather/state.php3?c=US&s=&countryname=United-States. (Monthly averages and forecasts for cities for each state.)

Chapter 10: Earth Hazards of the Northwest Central US

Natural hazards or earth hazards are events or processes that have significant impacts on human beings and the environment. Extreme **weather** conditions or geologic activity can cause substantial short-term or long-term changes to our environment. These changes can influence many aspects of the world around us, including crops, homes, infrastructure, and the **atmosphere**. The 4.6-billion-year-old Earth has experienced many naturally generated hazards, while other events are byproducts of human activities, created during mineral and **energy** extraction or in construction practices that modify the landscape.

The Northwest Central is subject to a variety of earth hazards. Weather hazards such as tornados, thunderstorms, and winter storms are particularly common in the Central Lowland and Great Plains, thanks to the unobstructed movement of air masses over areas of low **topographic relief**. The Rocky Mountains are susceptible to extreme winter weather such as heavy snow, blizzards, and high winds. Flooding can occur in areas of low elevation, including low-lying **glacially** sculpted terrain. Geological hazards, including avalanches, **earthquakes**, **landslides**, and rockfalls, are also common throughout the Northwest Central, especially in areas with rugged, mountainous terrain. The Columbia Plateau is susceptible to volcanic material produced by the Cascade Volcanoes to the west, and igneous activity associated with the Yellowstone **hot spot** has made its mark upon the surrounding land.

Earthquakes

Earthquakes occur when a critical amount of stress is applied to the Earth's **crust** and the crust responds by moving. According to the elastic rebound theory, rocks can bend elastically up to a point, until they finally break. The rocks then snap apart, releasing energy in the form of **seismic waves** (*Figure 10.1*). The plane defined by the rupture is known as a **fault**, and the surrounding rock layers become offset along it.

Many earthquakes, including most of those that occur in the Northwest Central US, arise along pre-existing faults. In cases such as these, stress may accumulate from lateral **compressive** pressure, as the rocks are temporarily locked in position by friction and other constraints, until sufficient strain energy has built up to cause sudden slippage along the fault (i.e., an earthquake).

There are two common ways to measure the size of earthquakes: **magnitude** and intensity. Magnitude (M) is the measure of the energy released by the earthquake, whereas the intensity is what people actually experience. The first scale used to measure magnitude was the **Richter scale** (abbreviated

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.*

energy • *the power derived from the use of physical or chemical resources.*

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

relief • *the change in elevation over a distance.*

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

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10 Earth Hazards

Earthquakes

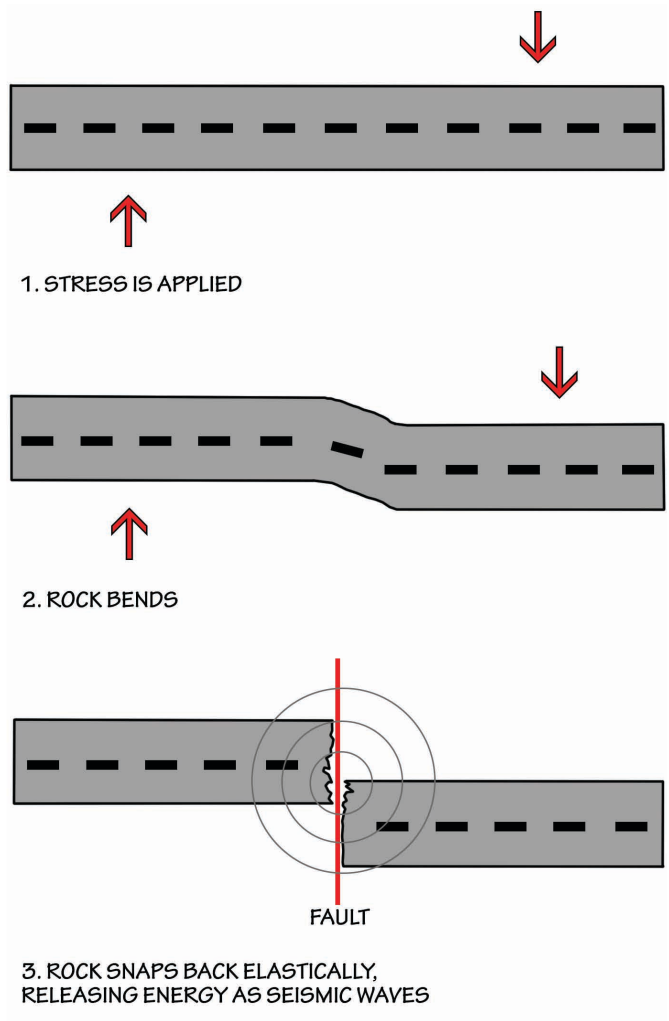


Figure 10.1: Elastic rebound.

M_L), which measures the amplitude of a seismic wave at a defined distance from the source of the earthquake. The Richter scale was designed to classify earthquakes at a local scale, but it does not do a very good job of describing the energy released by very large earthquakes. Geologists therefore developed another measurement, the Moment Magnitude scale (abbreviated M_w), which was introduced in 1979. The Moment Magnitude estimates the total energy released by an earthquake along an entire fault surface.

Both the Richter and Moment Magnitude scales are logarithmic, meaning that an M9.0 earthquake has 10 times the amplitude, and releases 32 times the energy, of an M8.0 earthquake. Accordingly, an M9.0 earth quake would have 100 times the amplitude and 1024 times the energy of an M7.0 earthquake.

Both scales may appear to reach maximum values of 10 (since the largest recorded earthquakes are slightly greater than 9), but technically there is no upper limit. The United States Geological Survey (USGS) describes earthquakes as *minor* (M3.0–3.9), *light* (M4.0–4.9), *moderate* (M5.0–5.9), *strong* (M6.0–6.9), *major* (M7.0–7.9) and *great* (M8.0 or higher). The largest recorded earthquake in US history was the 1964 Alaskan earthquake, which had an M_w of 9.2. By comparison, the largest recorded earthquake in the Northwest Central occurred in 1959 at Hebgen Lake, Montana (M7.3), near Yellowstone National Park.

The 1964 Alaskan earthquake and the 1906 San Francisco earthquake had roughly the same Richter magnitudes, but based on the size of the affected areas and geological movement, the Alaskan earthquake clearly released more energy than the San Francisco earthquake did. Geologists recalculated the magnitudes of these major quakes using the Moment Magnitude scale: the 1964 Alaskan earthquake, which originally had an M_L of 8.3, was found to have had an M_w of 9.2, whereas the 1906 San Francisco earthquake had M_L of 8.3 and an M_w of 7.9.

intensity • *a subjective measurement that classifies the amount of shaking and damage done by an earthquake in a particular area.*

Notable Earthquakes of the Northwest Central States

Date	**Location**	**M_w**
08-18-1959	Hebgen Lake, Montana	M7.3
10-28-1983	Borah Peak, Idaho	M6.9
06-28-1925	Clarkston Valley, Montana	M6.6
10-19-1935	Helena, Montana	M6.3
11-23-1947	Madison County, Montana	M6.3
03-28-1975	Malad City, Idaho	M6.2
07-12-1944	Sheep Mountain, Idaho	M6.1
06-30-1975	Yellowstone National Park, Wyoming	M6.1
05-16-1909	Dickinson, North Dakota	M5.5
03-28-1964	Merriman, Nebraska	M5.1

The magnitude of an earthquake, however, does not tell us how much damage it causes. The amount of shaking and damage is known as the earthquake's **intensity**, and it can be measured by the Modified Mercalli Intensity (MMI) scale. This scale uses the Roman numerals I–XII to describe the effects of the earthquake in a particular location. For example, near the epicenter of a small earthquake, or at a location far from a large earthquake, the intensity may be described with an MMI of II: "*Felt only by a few persons at rest, especially on the upper floors of buildings. Delicately suspended objects may swing.*" Unlike the Moment Magnitude scale, the MMI scale is a subjective gauge, and the USGS has attempted to improve the accuracy of MMI shake maps by soliciting data from the public. *Figure 10.2* shows the intensities felt in surrounding areas after the 1983 Earthquake at Borah Peak, Idaho, which is the largest earthquake known to have occurred in the state.

The Rocky Mountain and Columbia Plateau regions of the Northwest Central, including western Montana, northwestern Wyoming, and most of Idaho, compose one of the most seismically active areas in the United States (*Figure*

Earthquakes

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

seismic belt • *a narrow geographic zone along which most earthquakes occur.*

seismic zone • *a regional zone that encompasses areas prone to seismic hazards, such as earthquakes or landslides.*

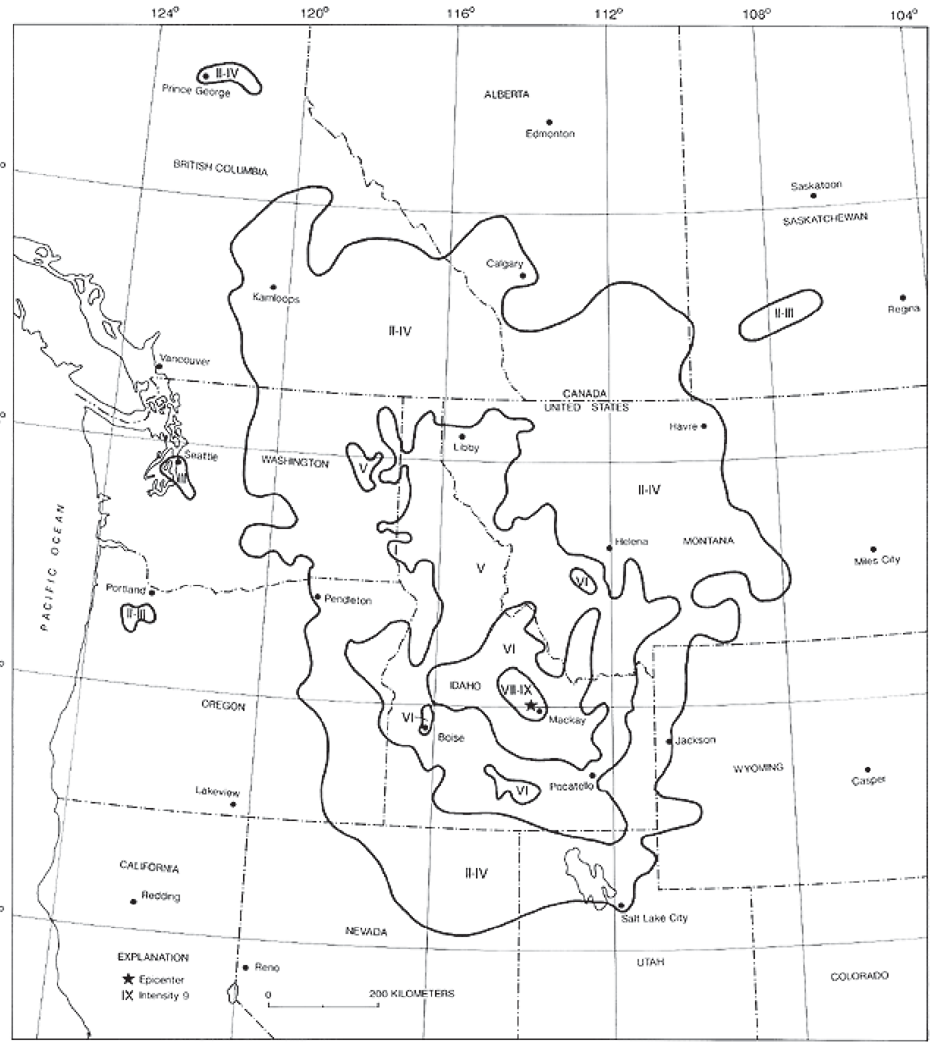


Figure 10.2: Intensity map of the 1983 Borah Peak earthquake.

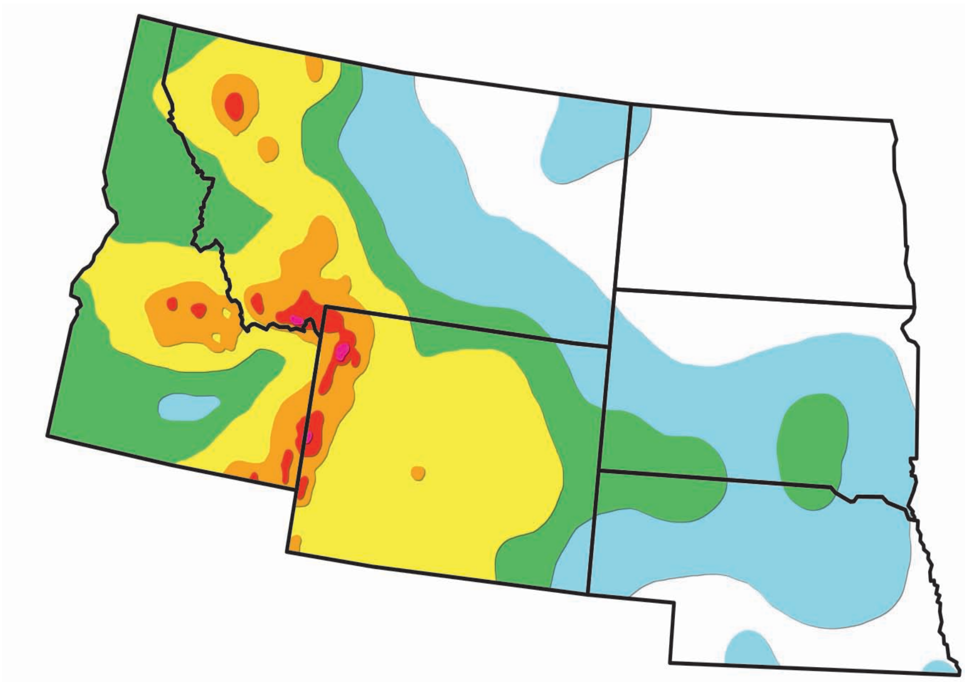
10.3), with as many as 3000 earthquakes occurring each year (although most are too small to feel). Most of these earthquakes are caused by a combination of two phenomena: the **magmatic** activity of the Yellowstone hot spot, and the (possibly related) tectonic activity of the Basin and Range region. The resulting crustal movements cause most earthquakes to be localized in particular areas, either around the Yellowstone area or along linear **seismic belts** or **zones** (*Figure 10.4*).

See Chapter 4: Topography to learn more about the Yellowstone hot spot and the Basin and Range.

The *Intermountain Seismic Belt* is a major zone of earthquake activity that extends from the Flathead Lake region in the northwest corner of Montana, southward through Yellowstone Park, along the Idaho-Wyoming border, through Utah, and into southern Nevada. A branch of the Intermountain Seismic Belt, called the *Centennial Tectonic Belt* or *Central Idaho Seismic Zone*, extends west from the

Earth Hazards 10

Earthquakes



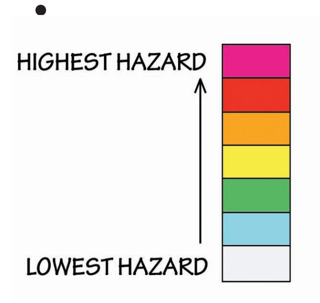


Figure 10.3: Seismic hazard map of the Northwest Central US, based on data in 2014. (See TFG website for full-color version.)

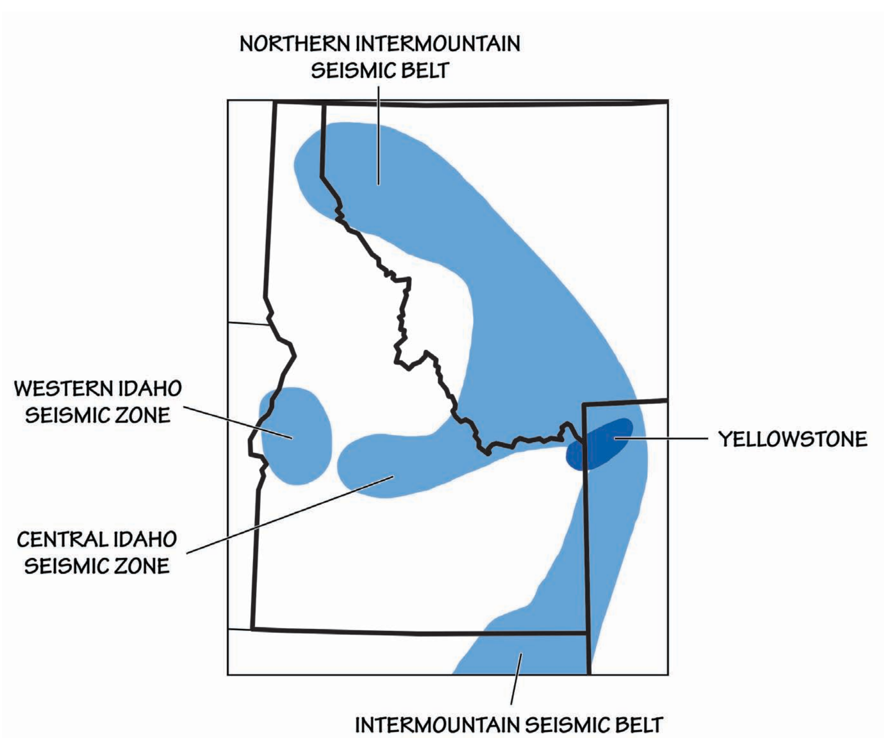


Figure 10.4: Major seismic belts and zones of the Northwest Central US.

Earthquakes

fault scarp • *an escarpment directly beside a fault line, where the ground on one side of the fault has moved vertically with respect to the other side, creating step-like topography.*

northwest corner of Yellowstone National Park through southwestern Montana and into central Idaho. This zone includes at least eight major active faults, and was the site of the two most severe earthquakes in the Rocky Mountains: the Hebgen Lake and Borah Peak earthquakes (*Figure 10.5*). The M7.3 Hebgen Lake earthquake, which occurred near the Montana-Wyoming Border in 1959, caused a major landslide that resulted in 28 fatalities as well as damming a river and destroying roads and buildings (*Figure 10.6*). The M6.9 Borah Peak earthquake occurred in Idaho in 1983, and caused extreme surface faulting as well as $12.5 million worth of damage to infrastructure in the surrounding Challis-Mackay area. A 34-kilometer-long (21-mile-long) **fault scarp** formed along the slopes of the Lost River Range; in other areas, the ground was shattered into huge blocks up to 100 meters (330 feet) in width.

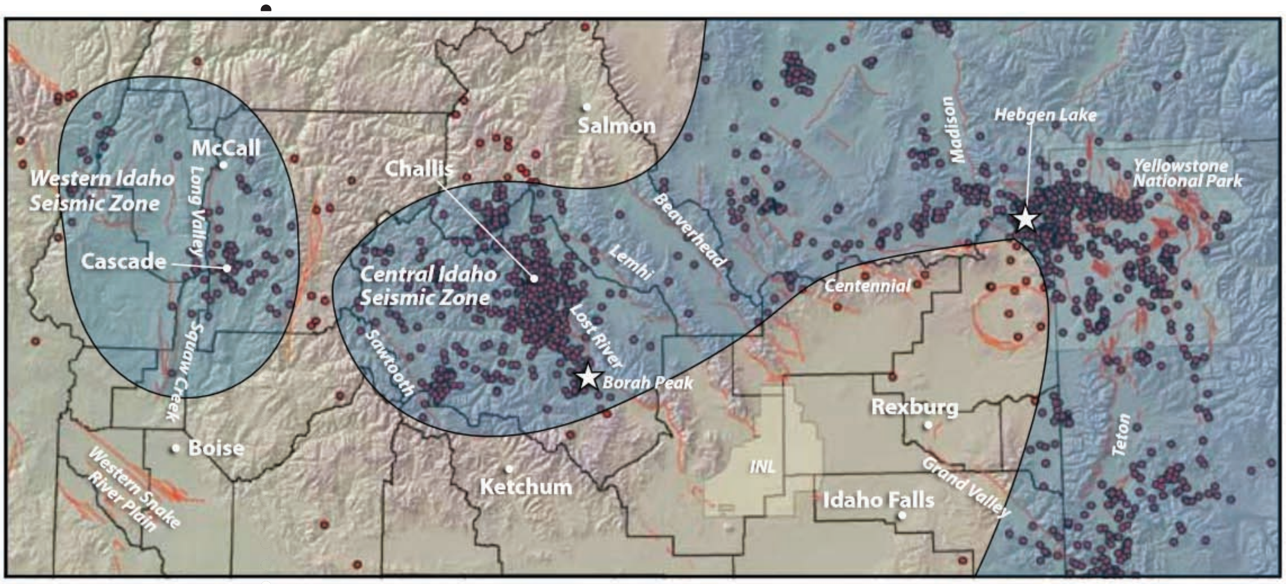


Figure 10.5: Earthquake occurrences in the Central Idaho Seismic Zone and Western Idaho Seismic Zone between 1973 and 2009. Earthquake epicenters are shown in red. The locations of Borah Peak and Hebgen Lake are marked by stars. (See TFG website for full-color version.)

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

accretion • *the process by which a body of rock increases in size due to the addition of further sedimentary particles or of large chunks of land.*

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

A geologically distinct region called the *Western Idaho Seismic Zone* lies between McCall and Boise. It is characterized by prominent north-south-trending basins and ranges that contrast strikingly with the surrounding area. A complex **suture** zone between **accreted terranes** and the ancient North American tectonic **plate** underlies the region and may influence the north-south orientation of the Zone's faults. Major active faults in the Western Idaho Seismic Zone include the Squaw Creek fault and the Long Valley fault zone, which is notable for earthquake swarms. During a swarm, thousands of small shallow earthquakes occur over several weeks to months within a relatively small region.

The *Lewis and Clark Zone* is a **megashear** in the Earth's crust, up to 48 kilometers (30 miles) wide, which runs some 386 kilometers (240 miles) through north Idaho and northwestern Montana. Geologic studies have shown that the North American plate has been **sheared** along this zone repeatedly over the

Figure 10.6: Earthquake damage to State Highway 287 and the Hilgard Lodge near Hebgen Lake, Montana.

past billion years, meaning that the rocks have been continuously **fractured** due to compressive stress. The most obvious manifestation of the zone is a set of parallel valleys that follow brittle fault zones across the grain of the northern Rocky Mountains from Helena and Missoula, Montana to Coeur d'Alene, Idaho. These valleys provided a natural transportation corridor through the mountains used in part by Lewis and Clark in 1806 and the Mullan Trail of the 1850s, and today by Interstate 90. Along the Lewis and Clark Zone in Idaho, many mining-related seismic events, called **rockbursts**, have occurred. Rockbursts are spontaneous, violent fractures of rock in deep mines. The sizable magnitudes of these events, their alignment with the direction of horizontal strain, and their location within the Lewis and Clark Zone suggest that tectonic stress release may be involved in causing them.

See Chapter 1: Geologic History to learn about the tectonic events that formed the North American continent and generated fractures and faults.

Earthquakes have many different effects on the rocks in which they occur, including breaking and movement along faults, **uplift**, and displacement. Earthquakes around Yellowstone National Park have altered the area's extensive **hydrothermal systems** and may help to keep open the fractures and conduits that supply hot water to the surface. For example, both the 1959 Hebgen Lake and 1983 Borah Peak earthquakes caused measurable changes in the output of Old Faithful geyser and other hydrothermal features. Yellowstone is one of the most active seismic zones in the United States, and commonly experiences

Earthquakes

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

megashear • *a large shear formed when rocks have been continuously fractured due to compressive stress.*

shearing • *the process by which compressive stress causes the fracturing and faulting of brittle rocks.*

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

hydrothermal solution • *hot, salty water moving through rocks.*

system • *a set of connected things or parts forming a complex whole.*

geyser • *a hot spring characterized by the intermittent explosive discharge of water and steam.*

earthquake swarms (*Figure 10.7*). The largest swarm occurred in 1985, with more than 3000 earthquakes recorded on the northwest side of the park during a three-month period. Scientists believe these swarms are caused by shifting and changing pressures in the crust due to the migration of hydrothermal fluids, a common occurrence around volcanoes.

See Chapter 4: Topography to learn more about hydrothermal features at Yellowstone National Park.

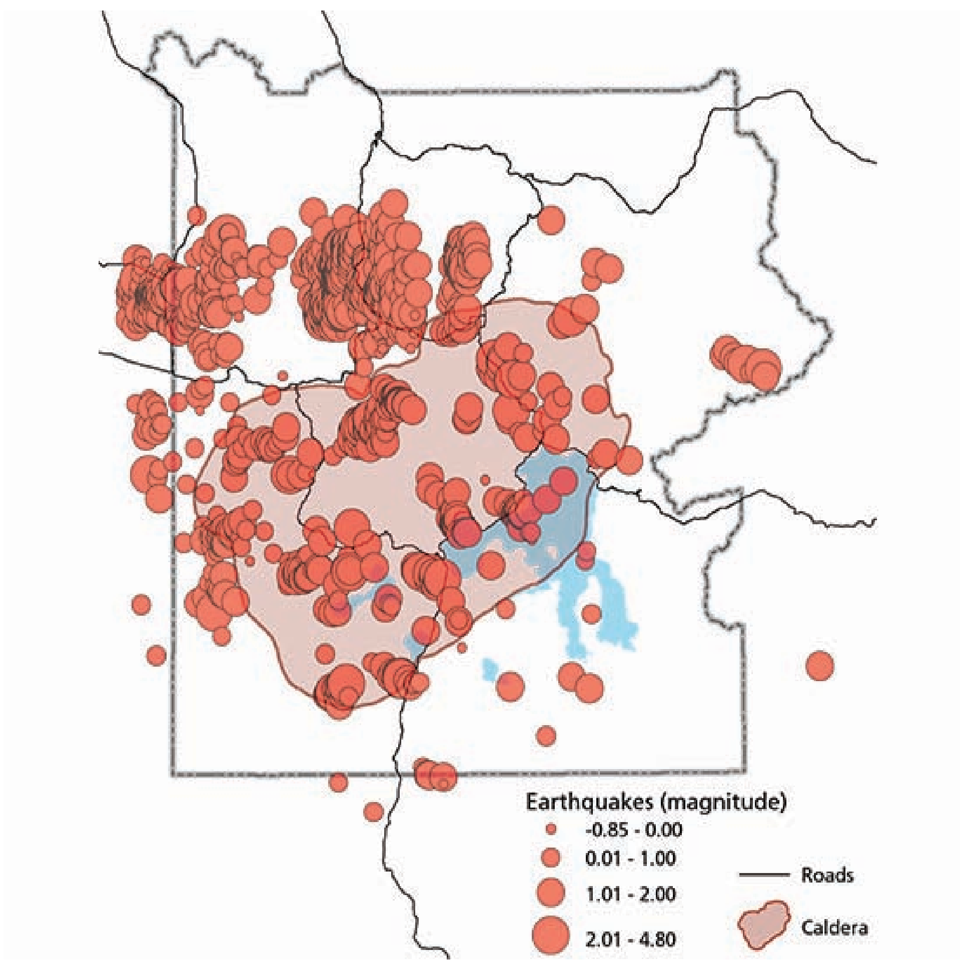


Figure 10.7: Earthquakes in Yellowstone National Park, 2014. Approximately 2000 earthquakes occurred during the course of the year. (See TFG website for full-color version.)

Volcanism

While there are no active volcanoes in the Northwest Central US today, past volcanism has left its mark on the area. Igneous activity continues today in and around Yellowstone National Park in northwestern Wyoming, which overlies a hot spot in the Earth's mantle. During the Cenozoic, as the North American *lava* • *molten rock located on the Earth's surface.*

supervolcano • *an explosive volcano capable of producing more than 1000 cubic kilometers (240 cubic miles) of ejecta.*

plate traveled over this mantle plume, the crust melted and produced a trail of volcanic rock that crosses southern Idaho, forming the Snake River Plain and ending at Yellowstone National Park. The trail of volcanic eruptions from the hot spot works its way east along this path. For example, the rocks at Craters of the Moon National Monument in southeastern Idaho formed during eight major eruptive periods between 15,000 and 2000 years ago. During this time, **lava** associated with the Yellowstone hot spot erupted from the Great Rift, a series of deep cracks that start near Craters of the Moon's visitor center and stretch 84 kilometers (52 miles) to the southeast. Over the course of eruption, the lava field grew to cover 1600 square kilometers (618 square miles).

See Chapter 2: Rocks for more information about the rocks formed by eruptions of the Yellowstone hot spot.

The recent geological history of volcanism at Yellowstone has led the area to be classified as a **supervolcano**—a volcano capable of producing more than 1000 cubic kilometers (240 cubic miles) of ejecta. Supervolcanoes can occur when magma rises under the crust from a hot spot, but is unable to break through. Eventually, the crust ruptures when it can no longer contain the built-up pressure. Although the Yellowstone area contains no active volcanoes today, the Yellowstone hot spot was the source of several prehistoric supereruptions (*Figure 10.8*): the Huckleberry Ridge, 2.1 million years ago, which produced 2450 cubic kilometers (588 cubic miles) of ejecta; the Mesa Falls flow, 1.3 million years ago, which produced 280 cubic kilometers (67 cubic miles) of ejecta; and the Lava Creek flow, 630,000 years ago, which produced 1000 cubic kilometers (240 cubic miles) of ejected material. The Mount St. Helens

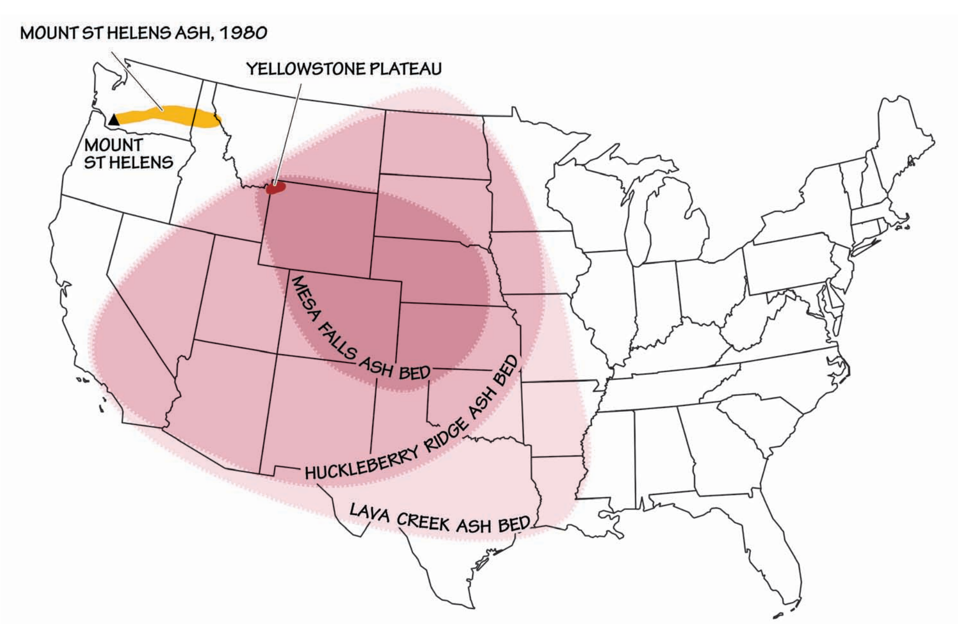


Figure 10.8: The extent of the three most recent ashfalls from Yellowstone supervolcano eruptions, as compared to the eruption of Mount St. Helens in 1980.

mass wasting • *a process in which soil and rock move down a slope in a large mass.*

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

erosion • *the transport of weathered materials.*

eruption in 1980, by contrast, produced only 0.19 cubic kilometers (0.046 cubic miles) of ejecta. While there is concern about another supereruption occurring at Yellowstone, the probability of an explosive eruption within the next few thousand years is very low.

Landslides

The term "landslide" refers to a wide range of **mass wasting** events that result in rock, **soil**, or fill moving downhill under the influence of gravity (*Figure 10.9*). These events occur when friction between the earth material (i.e., rock and soil) and the slope is overcome, allowing the earth material to fail and move downslope. Landslides may be triggered by high rainfall, earthquakes, **erosion**, deforestation, groundwater pumping, or **volcanic** eruptions. They may occur rapidly, such as in some mud and **debris flows**, or they can be as slow as soil **creep**: slow land movement that usually does not cause loss of life, but can still destroy roads and buildings. In mountainous areas, avalanches, landslides,

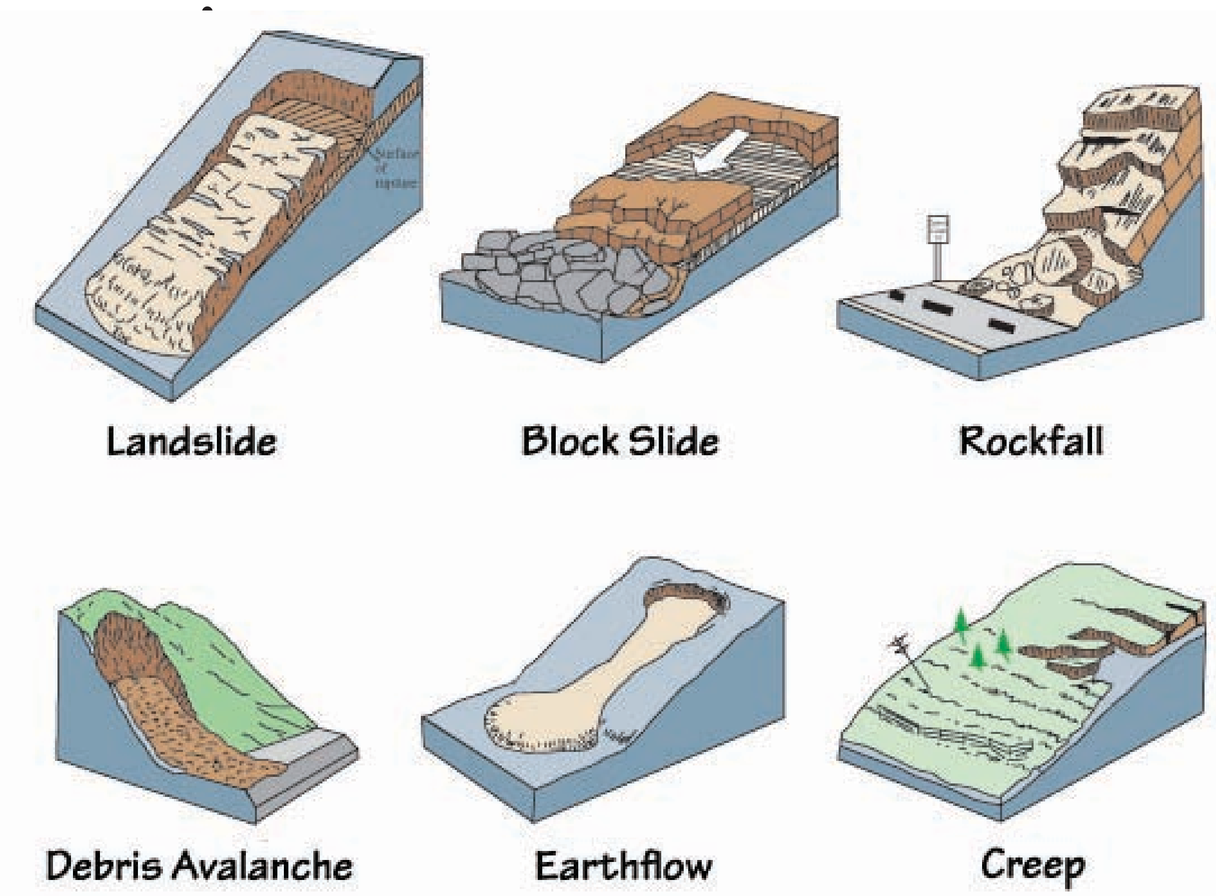


Figure 10.9: Common types of landslides.

and rockfalls can be dangerous, moving downslope and then crossing roads and moving into areas that contain homes and other buildings. In the Rocky Mountains, every year at least one road will be temporarily closed as the result of an avalanche, earth movement, or rockfall event. Mass wasting events can also dam streams and rivers, creating lakes. If such dams fail, a flood will result somewhere downstream.

Landslides are common in mountainous regions of the Northwest Central thanks to a combination of steep terrain, poorly consolidated sediments, and tectonic activity (*Figure 10.10*). They often occur in high glacial valleys with little vegetative cover. In the winter, many of the same mountainous areas that are prone to landslides during the year are subject to avalanches—rapid flows of snow, ice, and rock. Avalanches occur when the strength of the snow is overcome, or when a weak layer in the snow fails. These snow failures can result from storms, warming weather, sunny slopes, earthquakes, and people moving over the snow. Thousands of avalanches occur every winter in the mountains of Idaho, Montana, and Wyoming.

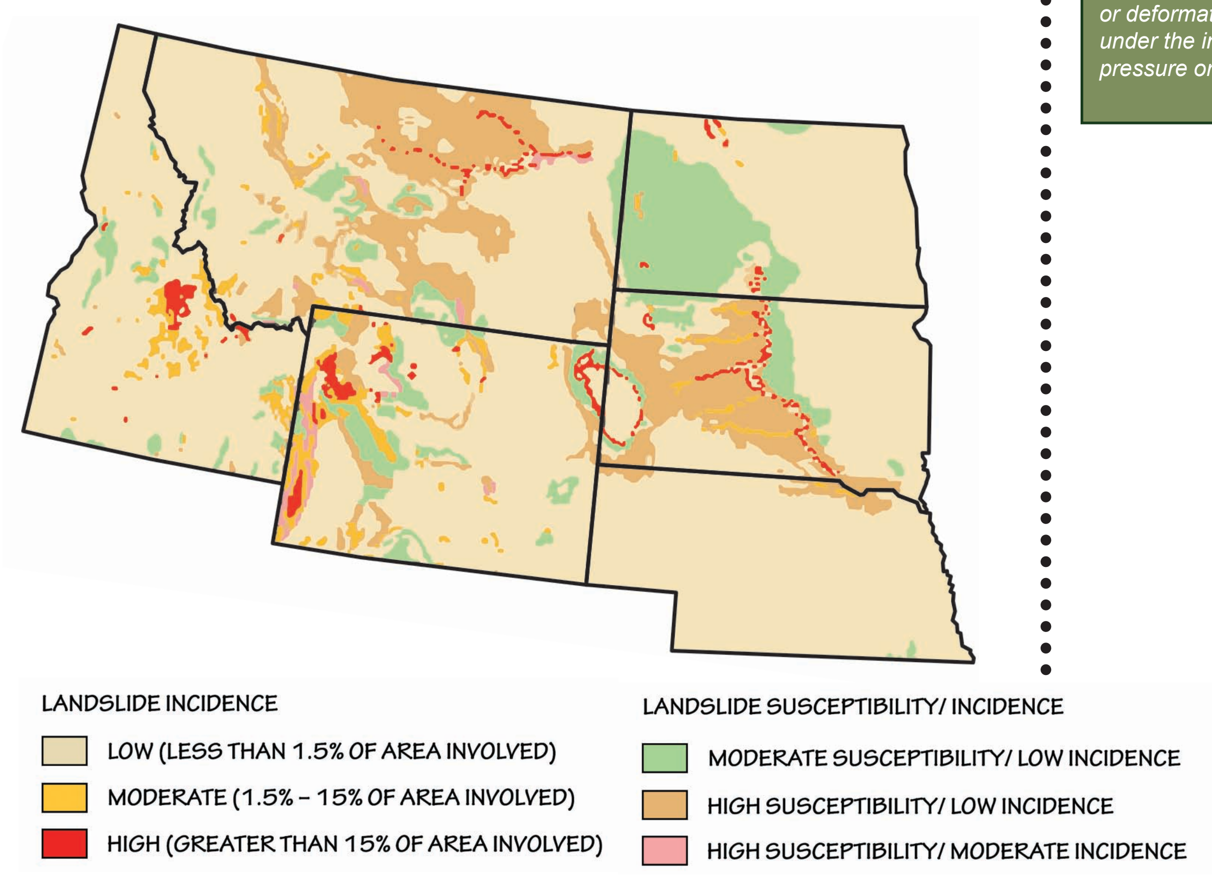


Figure 10.10: Landslide incidence and risk in the Northwest Central. (See TFG website for full-color version.)

Landslides

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

debris flow • *a dangerous mixture of water, mud, rocks, trees, and other debris that can move quickly down valleys.*

creep • *the slow movement or deformation of a material under the influence of pressure or stress.*

Earth Hazards

Landslides

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

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.*

gravel • *unconsolidated, semi-rounded rock fragments larger than 2 millimeters (0.08 inches) and smaller than 75 millimeters (3 inches).*

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

tree • *any woody perennial plant with a central trunk.*

In Montana, landslides are among the state's most common geologic hazards. The largest landslide in Montana history, triggered by the Hebgen Lake Earthquake of August 1959, carried 80 million tons of mud, rock, and debris down Sheep Mountain at an estimated 160 kilometers per hour (100 miles per hour) (*Figure 10.11*). The slide killed 28 people and buried sections of Montana Highway 287 beneath almost 122 meters (400 feet) of rock, as well as formed a major dam across the Madison River (*Figure 10.12*). Landslides are also common occurrences in the mountains of Wyoming. In 1925, more than 38 million cubic meters (50 million cubic yards) of waterlogged soil was dislodged from a mountainside, crossed the Gros Ventre River, and moved 90 meters (300 feet) up the other side of the valley. The landslide blocked the river, creating Lower Slide Lake. Two years later, the dam failed, and the subsequent flash flood killed six people and destroyed a nearby town.

Figure 10.11: Damage from the Hebgen Lake Landslide is still visible today in Madison Valley, Montana.

In Idaho, a variety of geological features combine to increase the likelihood of slope failure. Throughout the Snake River Plain and Columbia Plateau, **basalt** is interbedded with unconsolidated sediments, fractured **metamorphic rocks**, and loose volcanic material along deep canyons. Rocks fractured by folding and faulting are common, and ice-age floods deposited loose **gravel** and **sand** as well as undercut slopes. All these factors contribute to slope instability, and tremors from earthquakes associated with Idaho's several fault lines often produce landslides throughout the state. Intense storms and heavy winter rains, generated by moisture carried eastward from the Pacific Ocean, can also waterlog soils and lead to mudflows or debris flows.

See Chapter 6: Glaciers to learn more about ice-age lakes and outburst floods.

Landslides

Figure 10.12: The landslide dam that led to the formation of Quake Lake (also known as Earthquake Lake). Today, the lake is 58 meters (190 feet) deep and 10 kilometers (6 miles) long.

Mudflows or earthflows are fluid, surging flows of debris that have been fully or partially liquefied by the addition of water. They can be triggered by heavy rainfall, snowmelt or high levels of ground water flowing through cracked bedrock. High groundwater pressures and soil liquefaction due to nearby roadwork are thought to have generated the 1998 mudflow in Bonners Ferry, Idaho, in which 306,000 cubic meters (400,000 cubic yards) of earth materials flowed across Highway 95 and a Union Pacific railway track, burying more than a million dollars' worth of equipment (*Figure 10.13*).

Debris flows are a dangerous mixture of water, mud, rocks, **trees**, and other debris that moves quickly down valleys. The flows can result from sudden rainstorms or snowmelt that creates flash floods. In Glacier National Park, Montana, debris flows regularly occur where rock fragments like **talus** have built up on steep slopes and cliff faces. These debris flows can travel hundreds of meters (feet), and regularly impact trails and roads within the park.

Slumps and creep are common problems in parts of the Northwest Central with a wetter **climate** and/or the presence of unstable slopes, such as North Dakota's Red River Valley, the Fort Randall Reservoir in South Dakota, and the Niobrara River in Nebraska. These areas contain expansive soils generated from **clay**-rich **shales**. Certain clay **minerals** can absorb water and swell up to twice their original volume—an amount of expansion that can exert enough force to cause damage, such as cracked foundations, floors,

See Chapter 8: Soils for more information about Vertisols, soils rich in swelling clays.

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

slump • *a slow-moving landslide in which loosely consolidated rock or soil layers move a short distance down a slope.*

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).*

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

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

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

Landslides

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

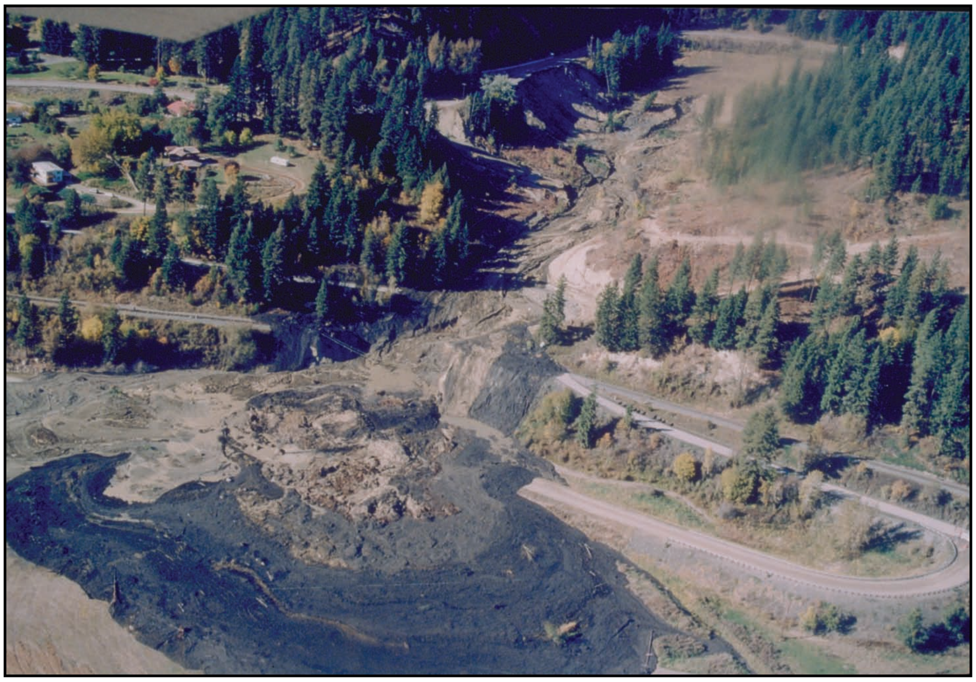


Figure 10.13: Mudflow in Bonners Ferry, Idaho.

and basement walls. An estimated $9 billion of damage to infrastructure built on expansive clays occurs each year in the United States. In addition, when the clay dries and contracts, the particles settle slightly in the downhill direction. This process can cause soil creep, a slow movement of land that causes fences and telephone poles to lean downhill, while trees adjust by bending uphill (*Figures 10.14 and 10.15*). Human development can exacerbate this process when homes are built along river bluffs, disturbing vegetation that would otherwise stabilize the slope and adding water to the land in the form of yard irrigation or septic systems.

Slumping occurs when expansive minerals are present on steeper slopes, and involves the downward movement of a larger block of material along a surface that fails when the weight of the saturated soils can no longer be supported. Thanks to rain and heavy spring snowmelt runoff, slumps are a significant problem in some areas of North Dakota. In 2011 alone, this type of mass wasting caused more than $3 million of damage to roads and trails in Theodore Roosevelt National Park. Slumping is common near roads and highways throughout the state, thanks to the presence of steeper hills, roadcuts, and construction (*Figures 10.16 and 10.17*).

While expansive soils can be found all over the US, nearly every state in the Northwest Central has bedrock units or soil layers that are possible sources, with central Montana, North Dakota's Red River Valley, and South Dakota's **Cretaceous** shales being the most susceptible (*Figure 10.18*). Significant or repeated changes in moisture, which can occur in concert with other geologic hazards such as earthquakes, floods, or landslides, greatly increase the hazard potential of expansive soils. The key to reducing this hazard is to keep the

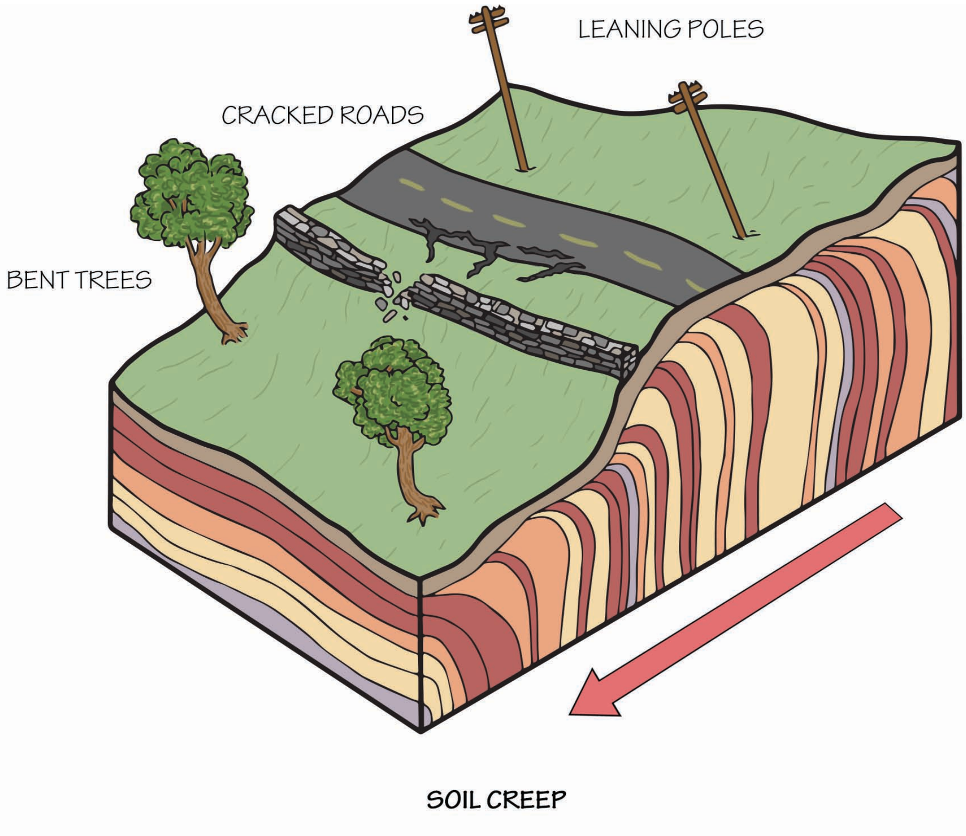


Figure 10.14: Some influences of soil creep on surface topography.

Figure 10.15: These fenceposts along the Sheyenne River Valley in North Dakota lean downhill under the influence of soil creep, while the trees near them bend uphill to compensate.

Earth Hazards

Landslides

lime • *an inorganic white or grayish-white compound made by roasting limestone (calcium carbonate, $CaCO_3$) until all the carbon dioxide (CO_2) is driven off.*

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

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

Figure 10.16: This slump near Interstate 29 in Fargo, North Dakota occurred in clay-rich materials used to construct the nearby overpass.

Figure 10.17: This slump occurred along a North Dakota roadcut after a spring thaw melted piles of snow on the upper bank, saturating the clay-rich soil and increasing its weight.

Karst

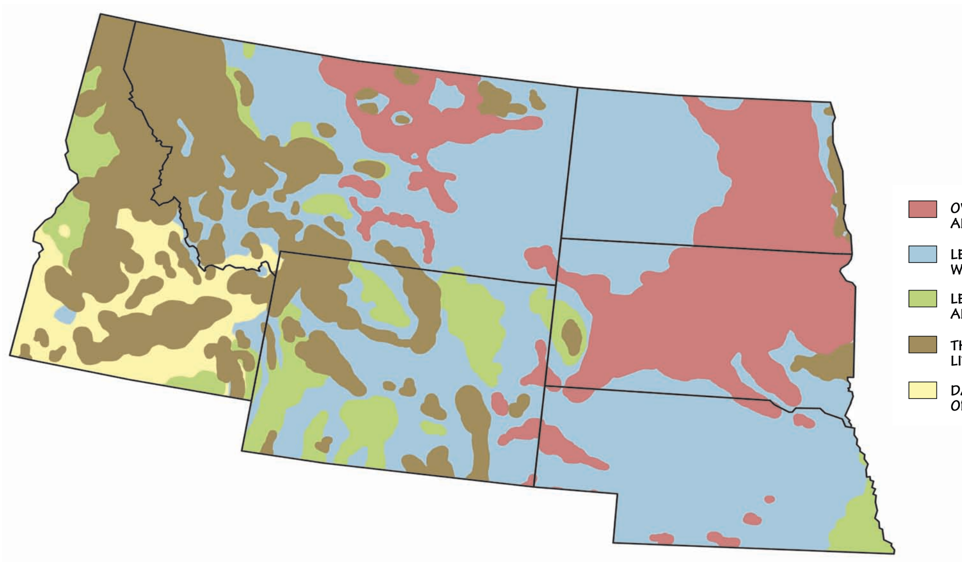


Figure 10.18: Approximate distribution of expansive soils in the Northwest Central US. This map is based on the distribution of types of bedrock, which are the origin of soils produced in place. (Where substantial fractions of the soil have been transported by wind, water, or ice, the map will not be as accurate.) (See TFG website for full-color version.)

water content of the soil constant. There are also chemical stabilizers, including **lime**, potassium, and ionic agents, that can reduce the potential for soil volume changes by increasing the clay's structural stability.

Damage to life and property from mass wasting events can be reduced by avoiding landslide hazard areas or by restricting access to known landslide zones. Hazard reduction is possible by avoiding construction on steep slopes or by stabilizing the slopes. There are two main ways to accomplish stabilization: 1) preventing water from entering the landslide zone through runoff, flooding, or irrigation and 2) stabilizing the slope by placing natural or manmade materials at the toe (bottom) of the landslide zone or by removing mass from the top of the slope.

Karst and Sinkholes

Karst topography forms in areas where the underlying bedrock is composed of material that can be slowly dissolved by water. Examples of this type of **sedimentary rock** include **carbonate rocks** such as **limestone**, **halite**, **gypsum**, **dolomite**, and anhydrite. Carbonate rocks may develop karst and other dissolution features due to the effects of circulating groundwater that has been made slightly acidic through the presence of dissolved carbon dioxide (which creates carbonic acid that reacts with the rock, dissolving it). Sinkholes and caverns can form, creating potential hazards (i.e., the land surface could

carbonate rocks • *rocks formed by accumulation of calcium carbonate, often made of the skeletons of aquatic organisms.*

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

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

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

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

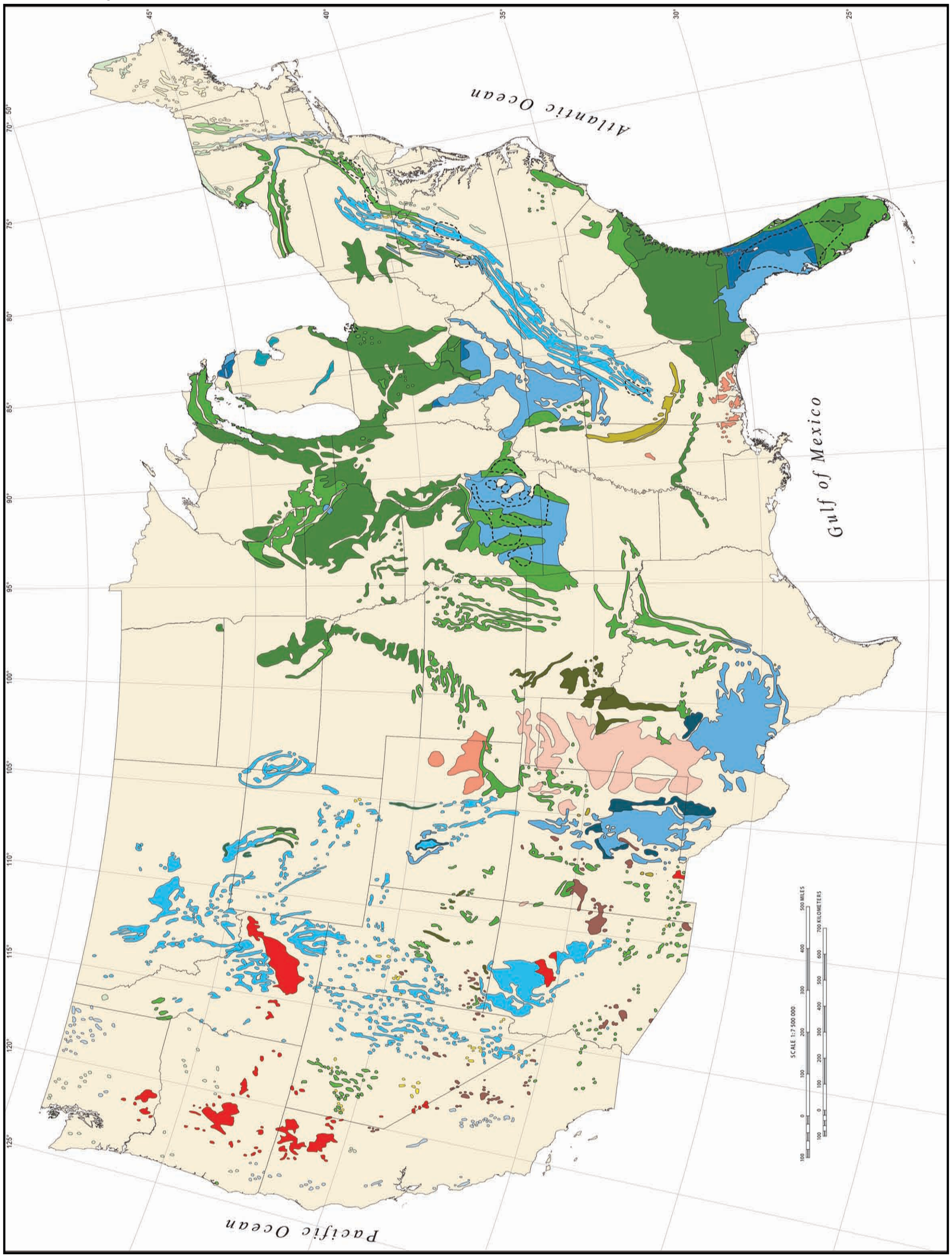


Figure 10.19: Areas of karst in the continental US associated with carbonate and evaporate rocks. (See TFG website for full-color version.)

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 ai 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

Karst

__subsidence__ • the sinking of an area of the land surface.

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

subside or collapse into the underground openings). This may principally occur in areas where cavities filled with water are emptied through groundwater withdrawal or other natural processes, resulting in the cavities being filled with air and reducing support for the overlying rock. Karst is not overly prevalent in the Northwest Central, but it is found in abundance throughout the Black Hills of South Dakota, and is scattered throughout several other states (*Figure 10.19*).

The Black Hills are surrounded and underlain by thick layers of **Mississippian** to **Jurassic** anhydrite and gypsum, which contain abundant karst features due to dissolution from groundwater and rain. Sinkholes are commonplace, ranging in size from small holes of a few meters (feet) across to large pits as wide as 140 meters (460 feet). The presence of other easily dissolved carbonate layers, laid down in **Paleozoic** and **Mesozoic inland seas**, has led to a variety of caves and small sinkholes found throughout the Northwest Central US. For example, the Little Belt Mountains in central Montana are underlain by a thick layer of limestone (the Madison Limestone) laid down in the Mississippian (*Figure 10.20*).

Figure 10.20: The Belt Meteor Crater southeast of Great Falls, Montana, is a sinkhole in the Madison Limestone measuring 10 meters (35 feet) deep and 30 meters (100 feet) across.

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

__Paleozoic__ • a geologic time interval that extends from 541 to 252 million years ago.

In Idaho, volcanic pseudokarst dominates the Snake River Plain. This type of topography is not technically karst—instead of forming through the dissolution on carbonate bedrock, these fissures, sinkholes, and caves were created by the **extrusion** of liquid lava. While sinkholes in volcanic pseudokarst are rare, they tend to be related to the collapse of old **lava tubes**.

Because karst terrain is very **porous** and fractures easily, groundwater pollution can be a serious problem. Contaminants that might otherwise be filtered through the sedimentary rock are quickly transported into **aquifers** by runoff. The hazards of pollution are increased by rampant industrial, agricultural, and residential development over karst features.

Radon

Radon is a naturally occurring **radioactive**, colorless, odorless gas. It is the leading cause of lung cancer in American non-smokers, and the second leading cause of lung cancer overall. It can collect in homes, buildings, and even in the water supply. Radon gas is formed naturally when uranium-238 undergoes radioactive decay, producing energy and several radioactive products such as radon-222 and thorium-232. (The thorium later decays to emit energy and radon-220.) Radon is more commonly found where uranium is relatively abundant in bedrock at the surface, often in **granite**, shale, and limestone. The EPA produced a map of the US showing geographic variation in radon concentrations, divided into three levels of risk: low, medium, and high (*Figure 10.21*).

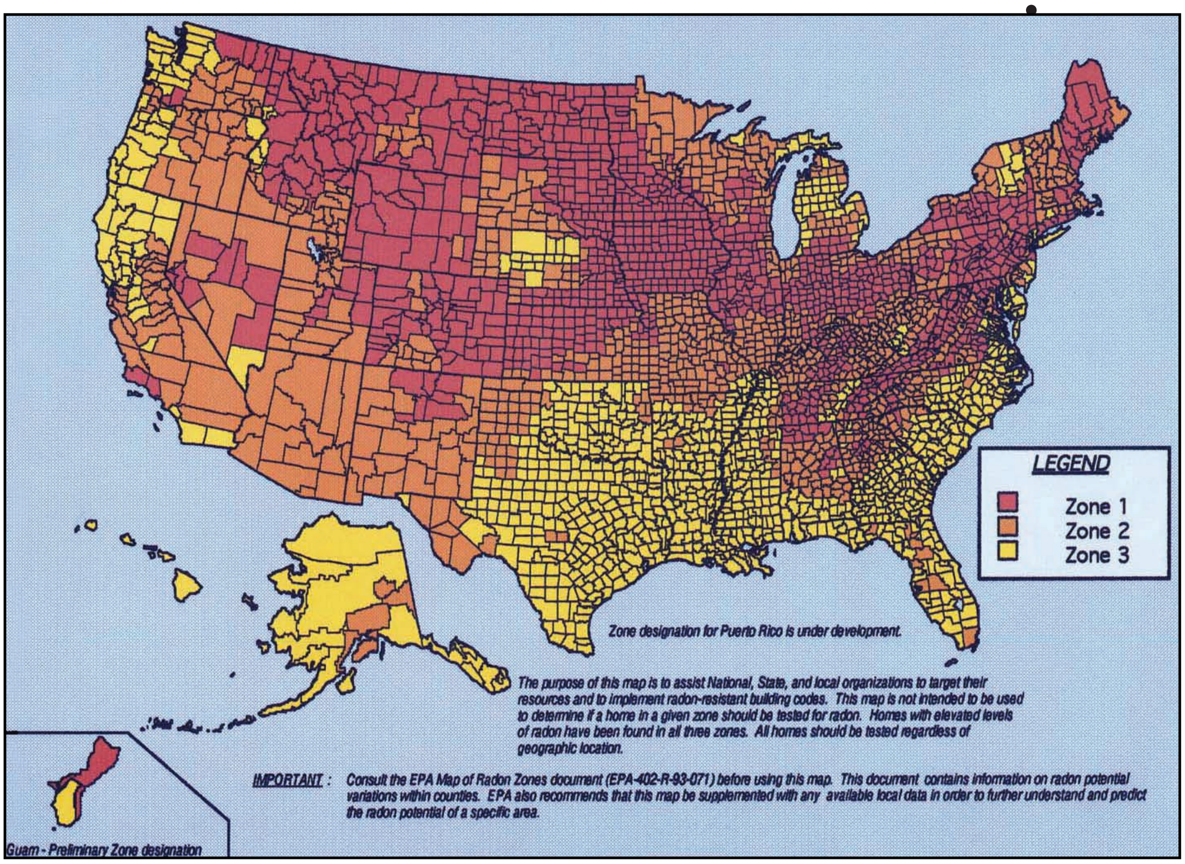


Figure 10.21: Radon zone map of the US. (Note: Zone 1 contains the highest radon levels.) (See TFG website for full-color version.)

Radon

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

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

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

Radon

Paleogene • *the geologic time period extending from 66 to 23 million years ago.*

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

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

Radon concentrations are generally high throughout the Northwest Central US (*Figure 10.22*). Uranium is relatively concentrated in the granites and metamorphic rocks of the Rocky Mountains, Black Hills, and Basin and Range, as well as in the sediments eroded from these areas. Uranium is also concentrated in some **Paleogene sandstones** and **coal** deposits. Taken together, these areas account for a broad part of the Northwest Central. There are, however, areas that are moderate or low in radon—the Sandhills of northwest Nebraska have the lowest radon concentrations in the Northwest Central. This area is composed of windblown sediment that was separated from the clay and heavier minerals that contain relatively high amounts of uranium. In the Columbia Plateau, radon associated with basalt bedrock is also lower in concentration than that found in the mountains farther north.

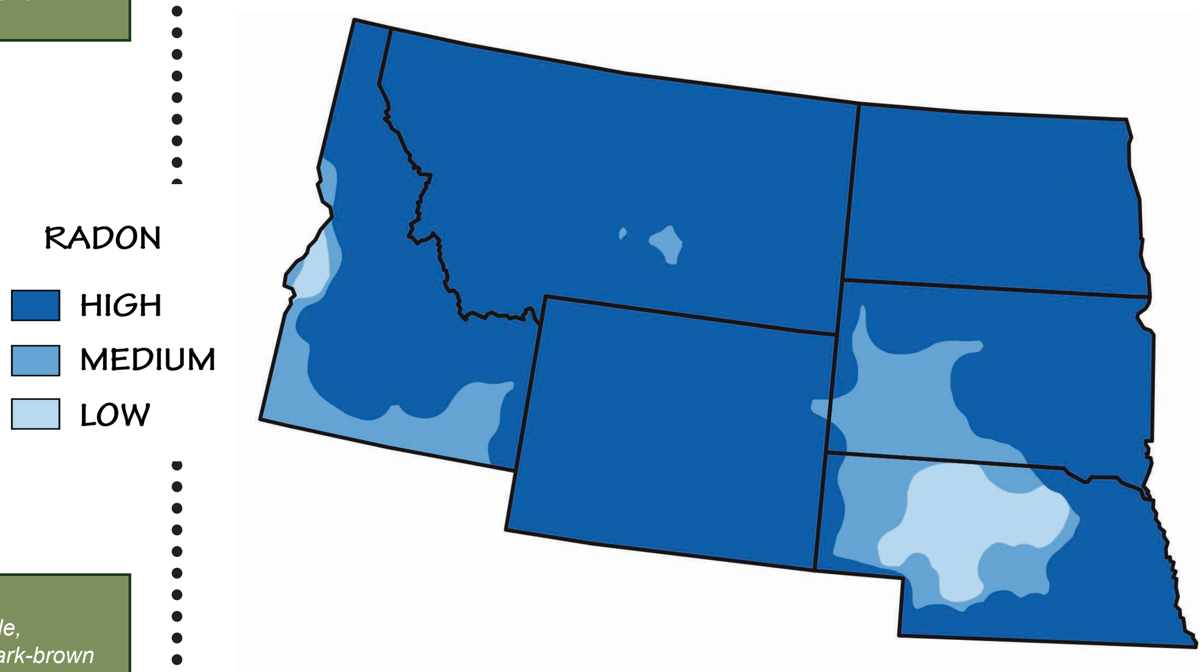


Figure 10.22: Radon risk levels at the surface in the Northwest Central US.

Radon is chemically inert, meaning that it does not react or combine with elements in the ground, and it can move up through rocks and soil into the atmosphere. It is dangerous primarily when it accumulates indoors, creating a health hazard similar to that of secondhand smoke. Radon gas finds its way through cracks in basement foundations, sump pump wells, dirt floor crawlspaces, and basement floor drains. It can also be found in well 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.

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

Radon cannot be detected by sight or smell, so there is no way that the body can sense its presence. 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, 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 also 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.

Floods

Floods are controlled by the rate of precipitation, run-off, stream flow, and shape of the land surface. They may occur when water overflows the banks of a standing water body (such as a lake) or flowing water (such as a stream), or when rainwater accumulates in an area that normally contains neither standing nor flowing water. Areas near rivers, tributaries, creeks, and streams are likely to experience flooding during periods of heavy rainfall.

Flooding can occur at any time of the year and is caused when more water enters a stream/river channel than the channel can contain. This situation can develop when water is unable to soak into the ground and instead runs off into a river channel. Runoff can occur if the ground is already saturated (full of water) or if the ground is too dry, hard, or frozen. The slope of a river (i.e., the topography of the land) can also contribute to flooding. If rivers have a steep slope, water can quickly move through the channel and continue downstream. If rivers have a shallow slope, water moves slowly through the river channel and remains in the area instead of moving downstream. Flash floods—rapid flooding of low-lying areas—are often associated with heavy rain, which can quickly waterlog soil and lead to mudslides on steep terrain, resulting in damage to roads and property. In areas of lower elevation, flash floods can be produced when slow-moving or multiple thunderstorms occur over the same area. When storms move more quickly through an area, flash flooding is less likely.

Floodplains are areas adjacent to rivers and streams that occasionally flood but are normally dry, sometimes for many years. When storms produce more runoff than a stream can carry in its channel, waters rise and inundate adjacent lowlands, leaving behind layers of settled sediment. Significant damage and sometimes loss of human life can occur when buildings and other human infrastructure are built on floodplains, under the assumption that future floods may never occur or will only occur in the distant future. Major floods in the Northwest Central generally occur along the Missouri River or its tributaries (*Figure 10.23*), and these events are more frequent in spring and fall after periods of heavy or sustained rains when stream levels rise rapidly.

Floods

Figure 10.23: The Missouri River and its tributaries. (See TFG website for full-color version.)

Flooding in the Northwest Central generally occurs through flash floods, periods of long-term rainfall, spring snowmelt, or some combination of these factors. While flash floods tend to impact a smaller area than do long-term rainfall and snowmelt, they can be especially dangerous because they arise so suddenly. Famous flash floods include the Republican River Flood of 1935 in Nebraska, when 46–61 centimeters (18–24 inches) of rain fell on May 30th that year; the Cheyenne Flood of 1985, when 18 centimeters (7 inches) of rain fell in three hours on August 1st in Cheyenne, Wyoming; and the Black Hills Flood of 1972 on Rapid Creek in Rapid City, North Dakota, when 38 centimeters (15 inches) of rain—approximately one million metric tons overall—fell over six hours from June 9–10, 1972. The Black Hills Flood is considered to be one of the most significant floods in US history: a surge caused a breach in the Canyon Lake Dam, releasing water into Rapid City and killing 238 people, destroying 1335 homes, and causing over $900 million (adjusted) in damage (*Figure 10.24*).

Floods

hectare • a metric unit of area defined as 10,000 square meters.

Figure 10.24: A pile of cars swept away by the 1972 Black Hills Flood. This event destroyed over 5000 vehicles.

There are numerous recorded instances of flooding on the Missouri River due to long-term rainfall, contributing to subsequent flooding downstream in St. Louis and into the Mississippi. The Great Flood of 1993, when floodwaters traveled down the Missouri River from South Dakota and Nebraska into Iowa, Kansas, and Missouri, flooded over 4 million hectares (11 million acres) and caused at least 50 deaths and over $24 billion (adjusted) in damage. The 2011 Missouri River Flood, caused by high winter snowfall in Montana and Wyoming followed by large spring rainfall on the plains of Montana, inundated roads and buildings (*Figure 10.25*) and threatened towns and cities along the river from Montana to Missouri. The Great Flood of 1881 in South Dakota and Nebraska (notably including Omaha) was caused by ice jams along the Missouri River, and the April 1997 Red River Flood of Grand Forks, North Dakota was due to abundant snowfall combined with heavy rain during the previous fall (*Figure 10.26*).

Devils Lake in North Dakota is known for dramatic annual changes in water level depending on local precipitation, and has gained a net increase of about 40 meters (130 feet) in water depth since 1940. The lake has quadrupled in size over the last two decades, growing from 18,000 **hectares** (44,000 acres) in 1994 to about 82,000 hectares (202,000 acres) today (*Figure 10.27*). Devils Lake is a closed drainage basin with no natural outlets, and water can therefore leave its confines only through evaporation, ground infiltration, or overflow. During one period of especially rapid increase, rainfall between 1993 and 1999 caused the lake's water level to rise about 20 meters (66 feet), flooding 28,000 hectares (70,000 acres) of farmland, displacing 300 homes, and costing about

Floods

Figure 10.25: The Fort Calhoun Nuclear Reactor and surrounding areas of Nebraska were inundated by floodwater during the 2011 Missouri River Flood.

Figure 10.26: Wreckage in Grand Forks, North Dakota, after the 1997 Red River Flood.

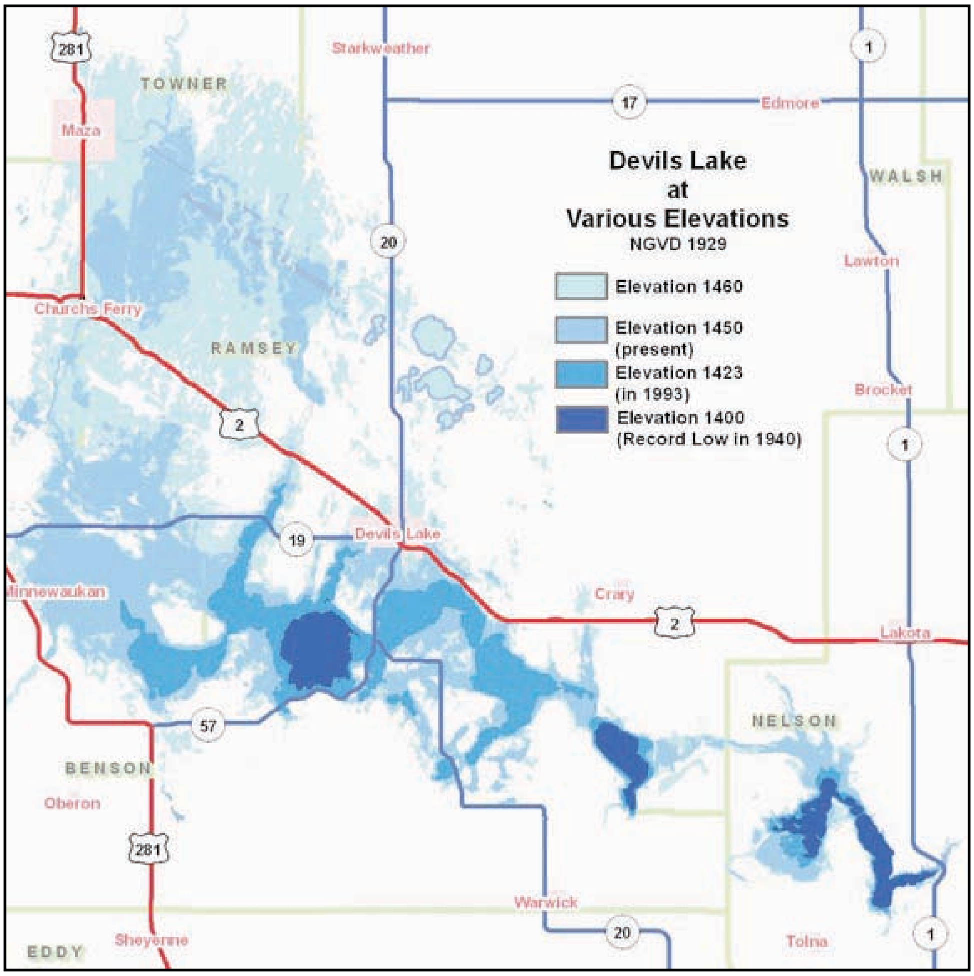


Figure 10.27: The extent of Devils Lake at different water level elevations. (See TFG website for full-color version.)

$450 million to mitigate the flooding. There has been substantial controversy about the ecological impacts of proposed mechanisms to create an outlet that would offset further lake rise, partially focused on where to divert the water and the consequences of potentially moving invasive species into other basins. Flooding from the lake today continues to affect agriculture and infrastructure in the surrounding area.

While floods are always considered a hazard to life and property, they present a compound threat when they trigger mudslides or contribute to the conditions that cause expansive soils and karst topography. While there is no way to completely avoid the destructive impacts of flooding, 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.

10 Earth Hazards

Weather

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

tornado • *a vertical funnel-shaped storm with a visible horizontal rotation.*

cold front • *the boundary between the warm air and the cold air moving into a region.*

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

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.*

Weather Hazards

Weather is the measure of short-term atmospheric conditions such as temperature, **wind** speed, and humidity. The Northwest Central is an active location for atmospheric events such as thunderstorms and **tornados**. It also experiences a variety of other weather hazards, including high temperatures and drought.

Storms, Tornados, and Derechos

Several types of severe storms present challenges to people living in the Northwest Central. Summer brings severe thunderstorms associated with **cold fronts**. Fall and spring can bring ice storms, while winter brings snow and, in some cases, blizzard conditions. In October 2013, for example, a major blizzard affected the Northwest Central and much of the Midwest, dumping up to 1.5 meters (5 feet) of snow across the Great Plains. The snow affected 5000 ranches in South Dakota, scattering and killing herds of cattle and sheep, as well as disabling **power** for more than 20,000 homes and trapping people inside their cars. The storm system's winds blew up to 112 kilometers per hour (kph) (70 miles per hour [mph]), generating 22 separate tornados as well as severe thunderstorms and ice storms.

Rainstorms arise where colder air from higher latitudes abruptly meets warmer air. Severe thunderstorms are a common occurrence for people living in the Northwest Central 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. At the boundary between warmer and cooler air, buoyant warm air rises, and then cools because air pressure decreases with increasing height in the atmosphere. As the air cools, it becomes saturated with water vapor, condensation occurs, and clouds begin to form. Because liquid water droplets in the clouds must be very small to remain suspended in the air, a significant amount of condensation causes small water droplets to come together, eventually becoming too large to remain suspended. Sufficient moisture and energy can lead to dramatic rainstorms. Because 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, the significant difference in air pressure associated with these boundaries and rainstorms also generates strong winds. Flat regions, such as the Great Plains, allow winds to move unimpeded by topography, and are often subject to severe thunderstorms.

While severe thunderstorms are common in some parts of the Northwest Central, two less common storm hazards have the potential to cause serious property damage and endanger lives: **derechos** and tornados. Both of these storm events are associated with **wind shear**, which occurs when the wind's 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 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. Approximately one derecho every two years or so will occur in easternmost South Dakota and Nebraska, and they appear with decreasing frequency as one travels westward (*Figure 10.28*).

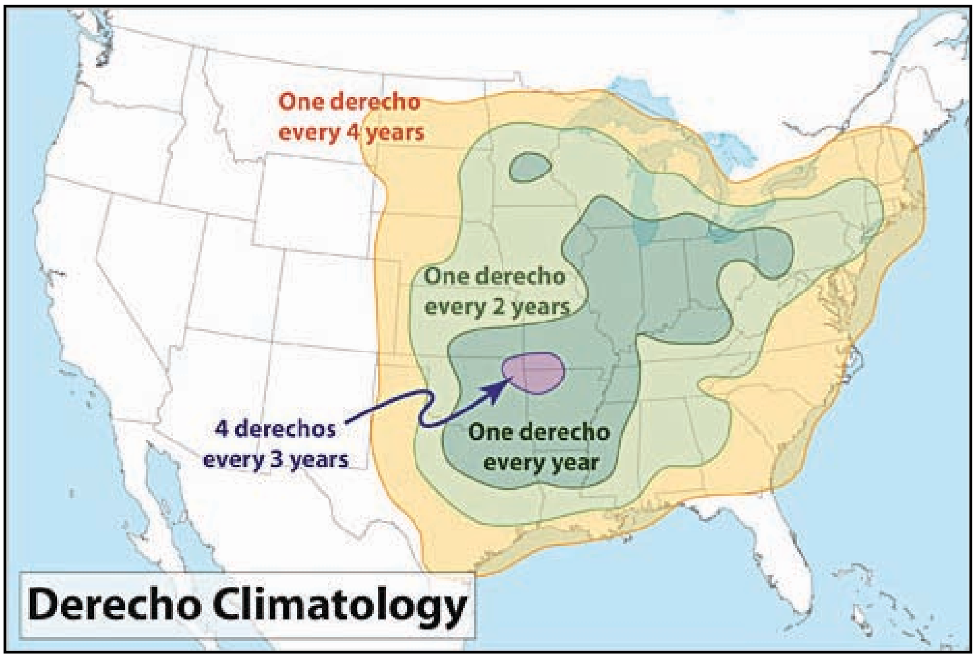


Figure 10.28: Derecho frequency in the continental US. (See TFG website for full-color version.)

The differences between tornados and derechos are indicated in their names: *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 conditions to get started. However, tornado formation is more complicated. 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. Clouds with a visible horizontal rotation can appear, appearing 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. These classifications are estimates of wind speeds based on the type of damage that is observed following the storm.

Measuring Tornado Intensity

Tornado intensity is measured on the Fujita scale, or simply F-scale, based on the amount of damage that a tornado can cause. The scale ranges from F0 to F5. The scale was modified recently to more accurately reflect specific wind speeds; this newer scale is known as the "Enhanced Fujita scale" and ranges from EF0 to EF5.

EF Scale	Estimated Wind Speed (kph)	Estimated Wind Speed (mph)
EF0	104–137	65–85
EF1	138–177	86–110
EF2	178–217	111–135
EF3	218–266	136–165
EF4	267–322	166–200
EF5	> 322	> 200

"Tornado Alley" is the nickname for an area, extending from Texas to Minnesota, that experiences a high number of exceptionally strong tornados due to its flatter topography and high incidence of severe thunderstorms. Both Nebraska and South Dakota reside within Tornado Alley, leading to more tornados in this part of the Northwest Central (*Figure 10.29*). From 1991 to 2010, for example, an annual average of 57 and 36 tornados occurred in Nebraska and South Dakota, respectively (*Figure 10.30*). To the west and north of Tornado Alley, fewer tornado strikes occur, with an annual average of 32, 12, 10, and 5 striking North Dakota, Wyoming, Montana, and Idaho, respectively. The boundaries of Tornado Alley vary in application, depending on whether the frequency, intensity, or number of events per location are used to determine the area's borders.

Although specific tornado paths are not predictable, the conditions that produce them are used to alert people so that they can 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

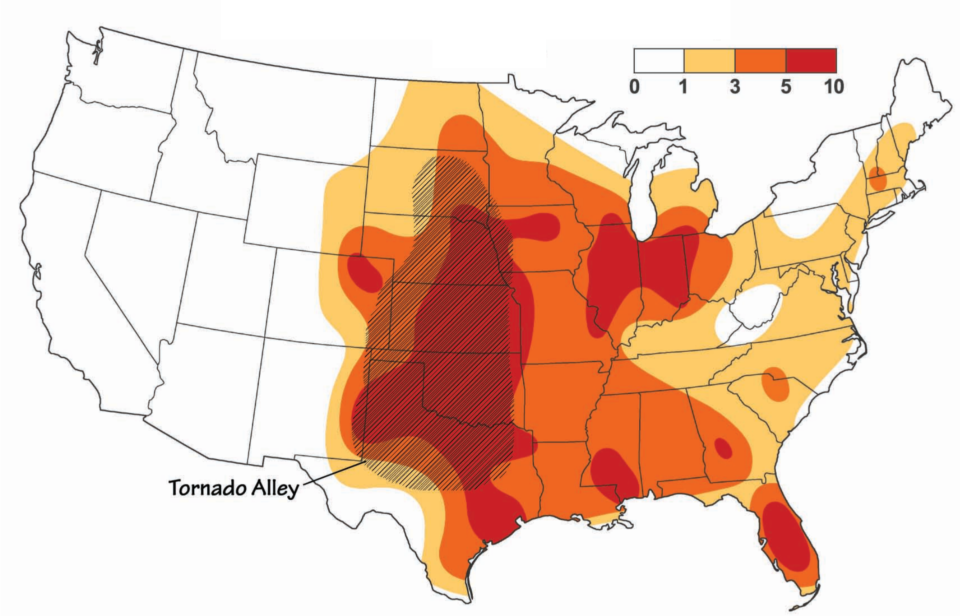


Figure 10.29: Annual tornado reports per 29,500 square kilometers (10,000 square miles) in the continental US, between 1950 and 1995. (See TFG website for full-color version.)

Figure 10.30: Two tornados touch down simultaneously in a South Dakota field between the towns of Enning and White Owl.

Weather

heat wave • *a period of excessively hot weather that may also accompany high humidity.*

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

heat island effect • a phenomenon in which cities experience higher temperatures than do surrounding rural communities.

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

topsoil • *the surface or upper layer of soil, as distinct from the subsoil, and usually containing organic matter.*

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 recent attempt 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.

Extreme Temperature and Drought

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 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 industry also serve to 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 increase 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.

During the first half of 2012, North America experienced a heat wave that set thousands of temperature records, particularly in the Midwest and Northwest Central and parts of central Canada (*Figure 10.31*). Within the Northwest Central, the Great Plains region experienced some of the most anomalous temperatures in the country. The event was attributed to persistent low-level winds blowing warm air from the Gulf of Mexico toward Canada. Like other climate events, the heat wave could not be directly attributed to **global warming**, but climate change is thought to have increased the event's severity by 5 to 10%. The heat wave was also associated with the start of a serious drought in the central United States.

While high temperatures can be directly dangerous, a larger scale hazard arises when these temperatures are coupled with a lack of precipitation in an extended drought period. Most famously, high temperature and drought in the 1930s, combined with deep plowing that removed moisture-trapping grasses,

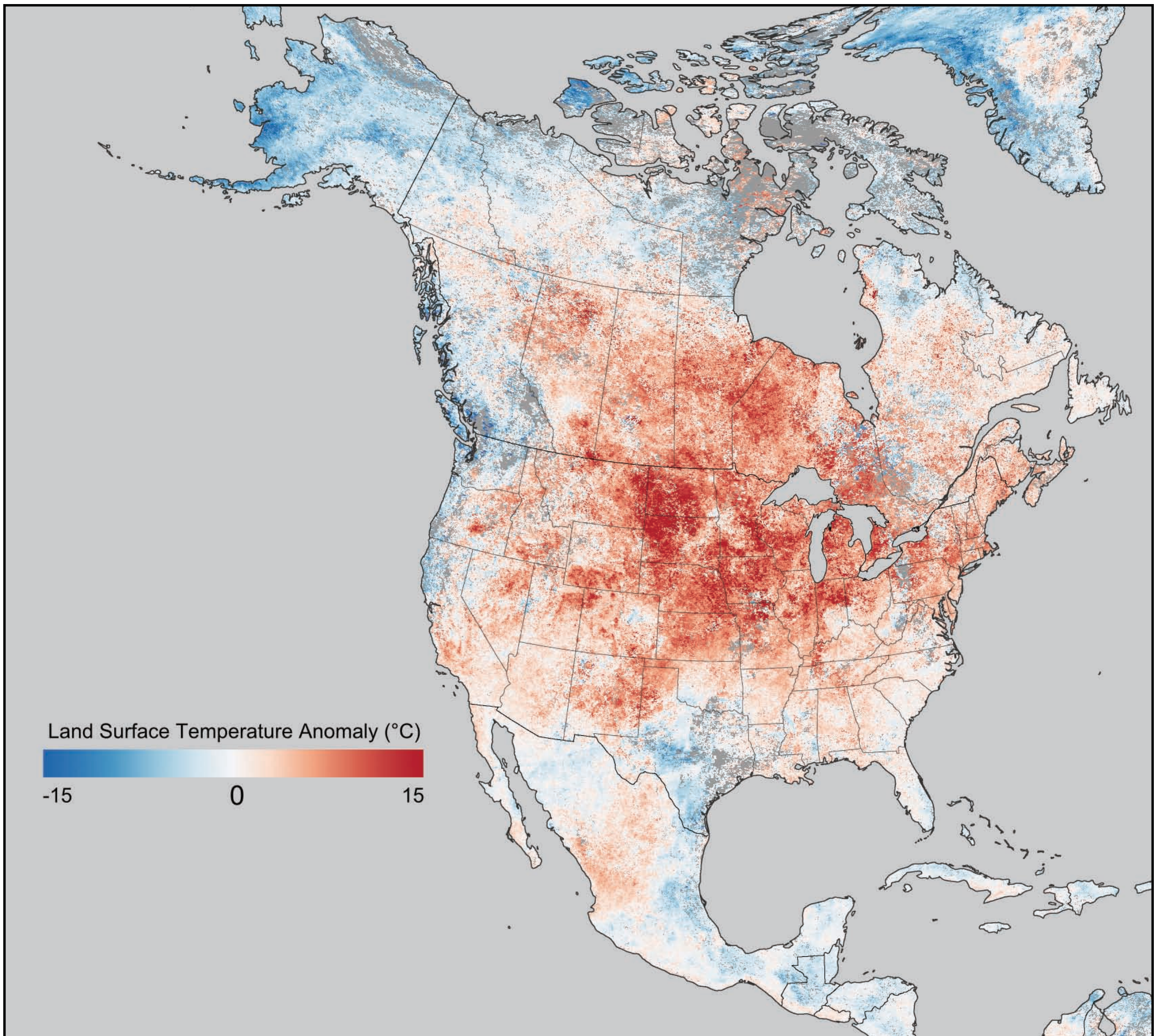


Figure 10.31: Land surface temperature anomalies in March 2011. Red areas represent above average temperatures and blue areas represent below average temperatures. (See TFG website for full-color version.)

led to the Dust Bowl—dust storms that carried vast clouds of black dust across the Midwest and central US, greatly damaging both the ecology and agriculture across that portion of the country (*Figure 10.32*). Although the Dust Bowl was most intense in the panhandles of Texas and Oklahoma, the event impacted agriculture throughout the Great Plains, including Nebraska and South Dakota. Dust storms destroyed **topsoil**, buried equipment and houses, and contributed to the incidence of lung disease.

Weather

polar vortex • *a regularly occurring area of low pressure that circulates in the highest levels of the upper atmosphere.*

jet stream • *a fast-flowing, narrow air current found in the atmosphere.*

Figure 10.32: A car and other farm equipment lies buried following a dust storm near Dallas, South Dakota in 1936.

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 counterclockwise rotating, low-pressure center can break off and shift southward at a lower altitude, covering the northern United States with frigid air. The **jet stream** then shifts to a more southward flow than usual, and its chill can even reach the southern states. A polar vortex can lock the jet stream in this new pattern for several days to more than a week. In early January 2014, the polar vortex dipped low over the upper United States, bringing with it some of the coldest temperatures seen in over 20 years. Temperatures in North Dakota plummeted to −30°C (−23°F), with wind chills of up to −51°C (−60°F). The lowest temperature in the US— −34°C (−30°F)—was recorded near Poplar, Montana. Although the cold temperatures of a polar vortex can be uncomfortable and make traveling dangerous in the winter, the Northwest Central has not yet experienced any major economic or health-related impacts from this type of extreme weather event.

See Chapter 9: Climate to learn more about the jet stream.

Climate Change

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 currently causing a global warming event. The seemingly slight increase in the average annual temperatures in the Northwest Central over the past 25 years has been accompanied by more frequent heat waves, shorter winters, and an increased likelihood of drought and wildfires.

permeability • *a capacity for fluids and gas to move through fractures within a rock, or the spaces between its grains.*

Although wildfires can occur during any season, summer fires are the most common, since increased dryness contributes to fire risk. In June 2012, the Fontenelle wildfire in Wyoming's Bridger-Teton National Forest consumed 25,990 hectares (57,324 acres) of forest after sparks from a downed power line ignited dry, dead timber. In August 2013, a lightning strike ignited the Bear Creek wildfire in Idaho, which burned more than 40,440 hectares (100,000 acres), threatened two popular ski resorts, and required the efforts of more than 1200 firefighters to combat the blaze. The 2012 fire season was among the worst on record in Wyoming, with more than 1300 fires burning about 240,000 hectares (600,000 acres) across the state, thanks to extremely dry conditions and swaths of dead trees killed by pine beetles. Unfortunately, the Rocky Mountains' rugged terrain can make fires even more difficult to extinguish.

Water supply is also a critical issue for the Northwest Central States. Here, most water is obtained from precipitation, snowmelt, and runoff, which will dramatically decrease in quantity as temperature and aridity rise. In addition, Nebraska obtains much of its agricultural and drinking water from the Ogalalla aquifer, an underground layer of water-bearing **permeable** rock. Part of the High Plains aquifer system, this underground reservoir supplies vast quantities of groundwater to Nebraska as well as Texas, Oklahoma, and Kansas. As drought intensifies and temperature rises, the amount of water drawn from the aquifer (especially for agricultural irrigation) has increased, while the rate at which the aquifer recharges has decreased. The aquifer's average water level has dropped by about 4 meters (13 feet) since 1950, and in some areas of heavy use, the decrease is as high as 76 meters (250 feet) (*Figure 10.33*). However, the aquifer only replenishes at a rate no greater than 150 millimeters (6 inches) per year. While the portion of the aquifer beneath Nebraska has yet to be adversely affected, some estimates indicate that at its current rate of use, the entire Ogalalla aquifer could be depleted by as early as 2028, threatening human lives, our food supply, and the entire Great Plains ecosystem.

Increasing temperatures also allow certain pests, such as ticks and mosquitoes, to live longer, thereby increasing the risk of contracting the diseases they carry. In addition, invasive organisms that damage ecosystems, such as the mountain pine beetle, have a better chance of multiplying and outcompeting native organisms because increased temperatures stress local ecosystems and create an environment more favorable to invasive species.

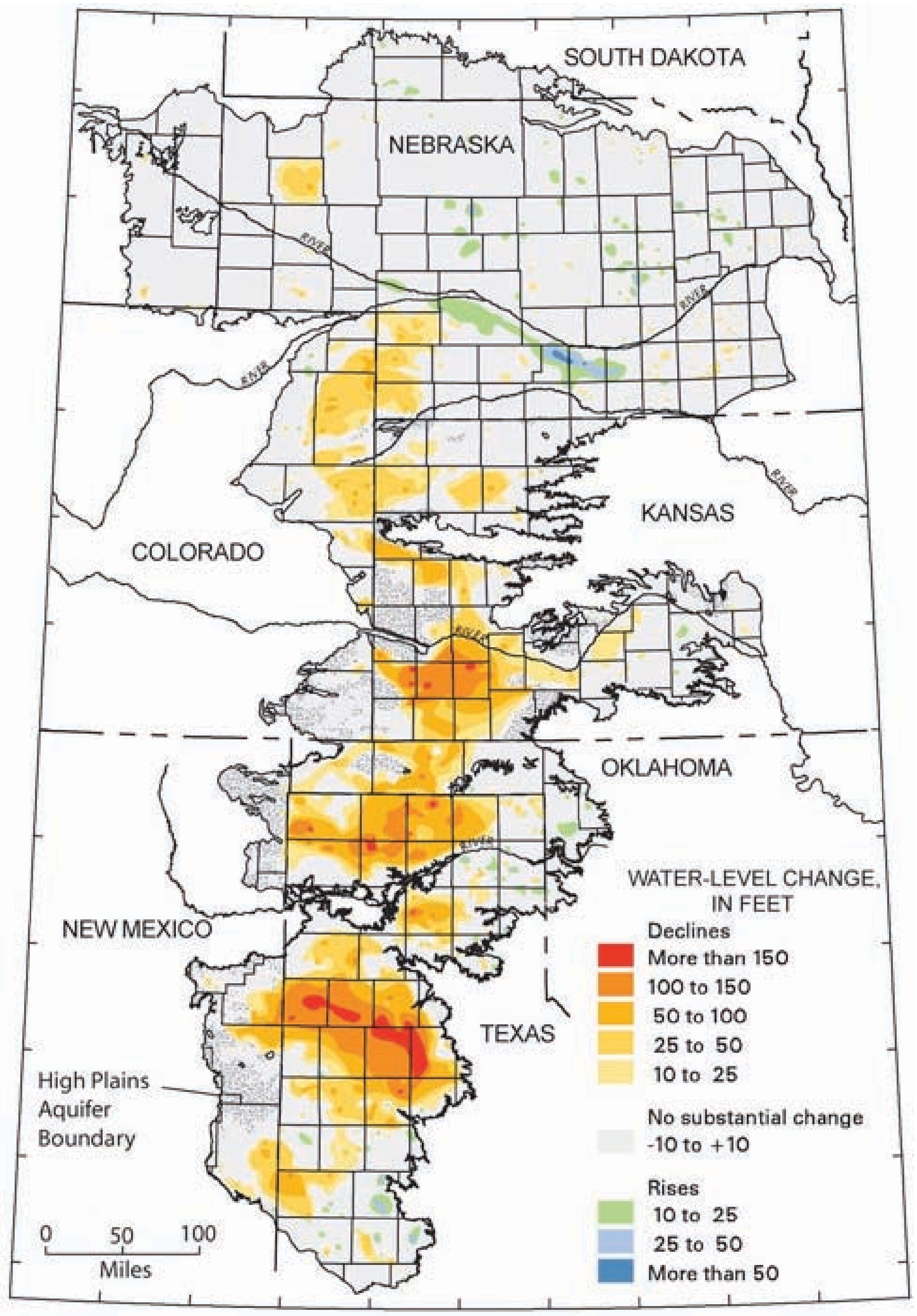


Figure 10.33: Water level change in the Ogalalla aquifer between 1950 and 2005. (See TFG website for full-color version.)

Another concern regarding hazards exacerbated by climate change in the Northwest Central is whether or not there has been or will be an increase in the number or severity of storms, including thunderstorms and tornados. According to NASA, the present data is inconclusive in terms of whether major storms are already more severe, but there is a greater than 66% chance that global warming will cause more intense storms in the 21st century. Since climate is a measure of weather averaged over decades, it might take many years to determine that a change has occurred with respect to these types of storms. Scientists are certain, however, 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 10.34*).

See Chapter 9: Climate for more on the effects of climate change in the Northwest Central.

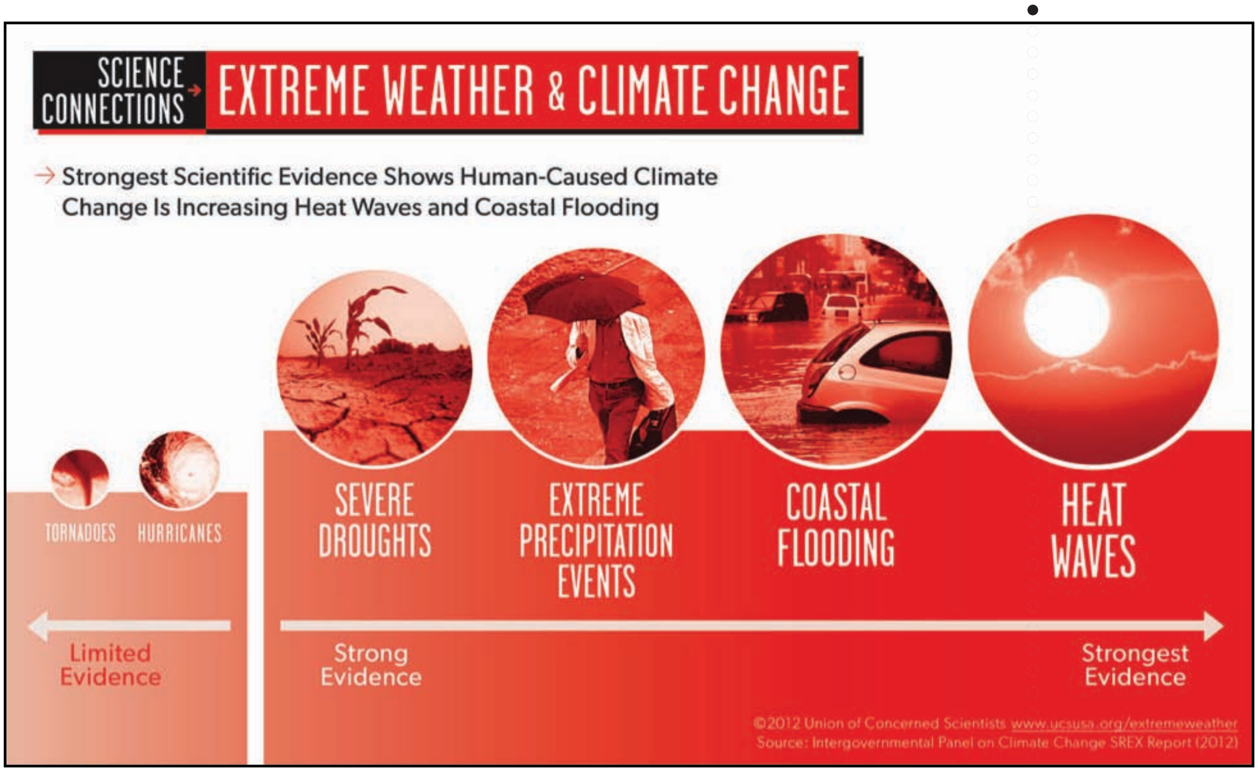


Figure 10.34: The strength of evidence supporting an increase in different types of extreme weather events caused by climate change.

10 Earth Hazards

Resources

Resources

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10 Earth Hazards

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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.

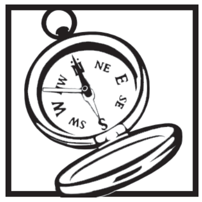
Landslide Hazards Program, US Geological Survey, http://landslides.usgs.gov/.

Natural Hazards and Risks: Hurricanes, by L. Gilbert, J. Galster, and J. Ramage, SERC Module on Hurricane Hazards, http://serc.carleton.edu/integrate/teaching_materials/hazards/index.html.

Radon Activities from the Alabama Radon Program, Alabama and Auburn Universities Extension, http://www.aces.edu/fcs/hndh/radon/alradon.php.

Science Serving Coastal Communities, The National Centers for Coastal Ocean Science (NCCOS), http://coastalscience.noaa.gov/.

Teaching Quantitative Concepts in Floods and Flooding, SERC Resources for Undergraduate Students and Faculty, http://serc.carleton.edu/quantskills/methods/quantlit/floods.html.



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

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(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.

11 Fieldwork

Needs

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

Needs

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 ***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.*	☐ **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
	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.

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Fieldwork

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.

VFEs

> **The framework for understanding how to effectively blend technology, pedagogy, and content knowledge is known by its acronym TPACK.**

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.

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?

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.

> **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.**

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 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

Extraordinary Science Field Trips, Summer 2013, *National Science Teachers Association Reports*, 25(1): 1-2, http://www.nsta.org/docs/NSTAReports201307.pdf.

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My Geologic Address: Locating Oneself in Geologic Time and Process, by K. Ault, SERC InTeGrate workshop "Teaching the Methods of Geoscience" activities, http://serc.carleton.edu/integrate/workshops/methods2012/activities/ault.html.

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Russell, H. R., 1998, *Ten-Minute Field Trips: A Teacher's Guide to Using the School Grounds for Environmental Studies, 3rd edition*, National Science Teachers Association, Alexandria, VA, 163 pp. (Focused on elementary and junior high; chapter on Earth science pp.113–137.)

Shulman, L. S., 2005, Signature pedagogies in the professions, *Daedalus*, 134(3): 52–59.

Teaching in the Field, National Association of Geoscience Teachers, http://nagt.org/nagt/teaching_resources/field/index.html. (Set of resources for teaching field geology.)

Whitmeyer, S. J., E. J. Pyle, and D. W. Mogk (eds.), 2009, Field geology education: historical perspectives and modern approaches, *Geological Society of America Special Papers* 461, http://specialpapers.gsapubs.org/content/461.toc. (29 articles focused on undergraduate education.)

Guides to Fieldwork

(Mostly focused on post secondary education, but useful as references)

Coe, A., T. Argles, D. Rothery, and R. Spicer, 2010, *Geological Field Techniques*, Wiley-Blackwell, Chichester, UK, 336 pp. (This is a current standard.)

Compton, R. R., 1962, *Manual of Field Geology*, John Wiley & Sons, New York, 378 pp. (An old classic.)

Compton, R., 1985, *Geology in the Field*, Wiley, New York, 398 pp. (An updated version of the previous book.)

How to Read a Geologic Map, Wisconsin Geological and Natural History Survey, http://wgnhs.uwex.edu/wisconsin-geology/bedrock-geology/read-geologic map/.

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Lisle, R., P. Brabham, and J. Barnes, 2011, *Basic Geological Mapping*, John Wiley & Sons, Chichester, UK, 217 pp.

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Spencer, E., 2006, *Geologic Maps: A Practical Guide to the Preparation and Interpretation of Geologic Maps, 2nd edition*, Waveland Press, Long Grove, IL, 148 pp.

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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 Genertion 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

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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 Chapter Big Ideas*) 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*™ 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

Appendix

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.

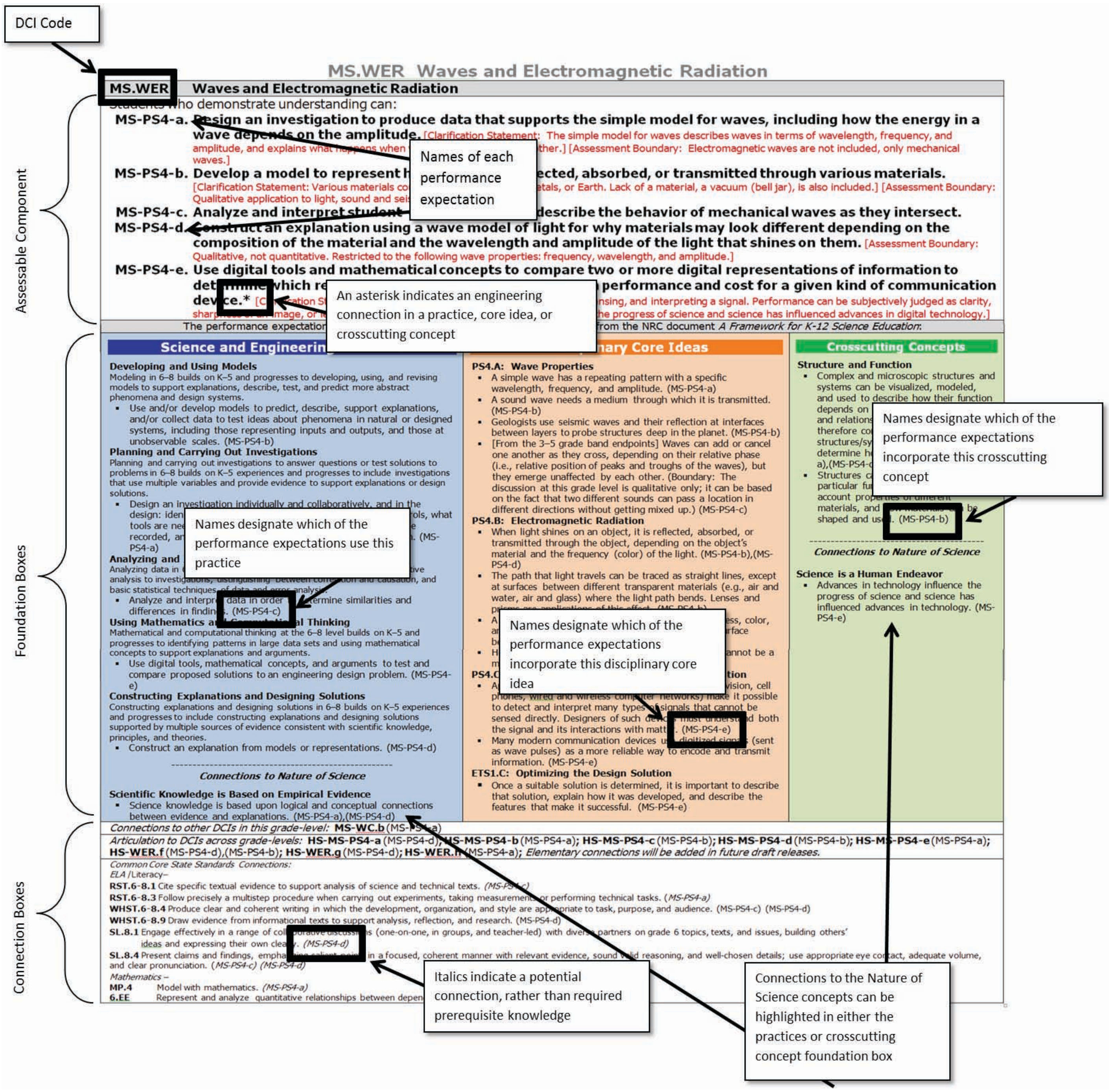


Figure A.1: The architecture of a standard. The NGSS is designed with the web in mind and features of its online architecture make it easier to understand than this diagram might indicate.

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.**

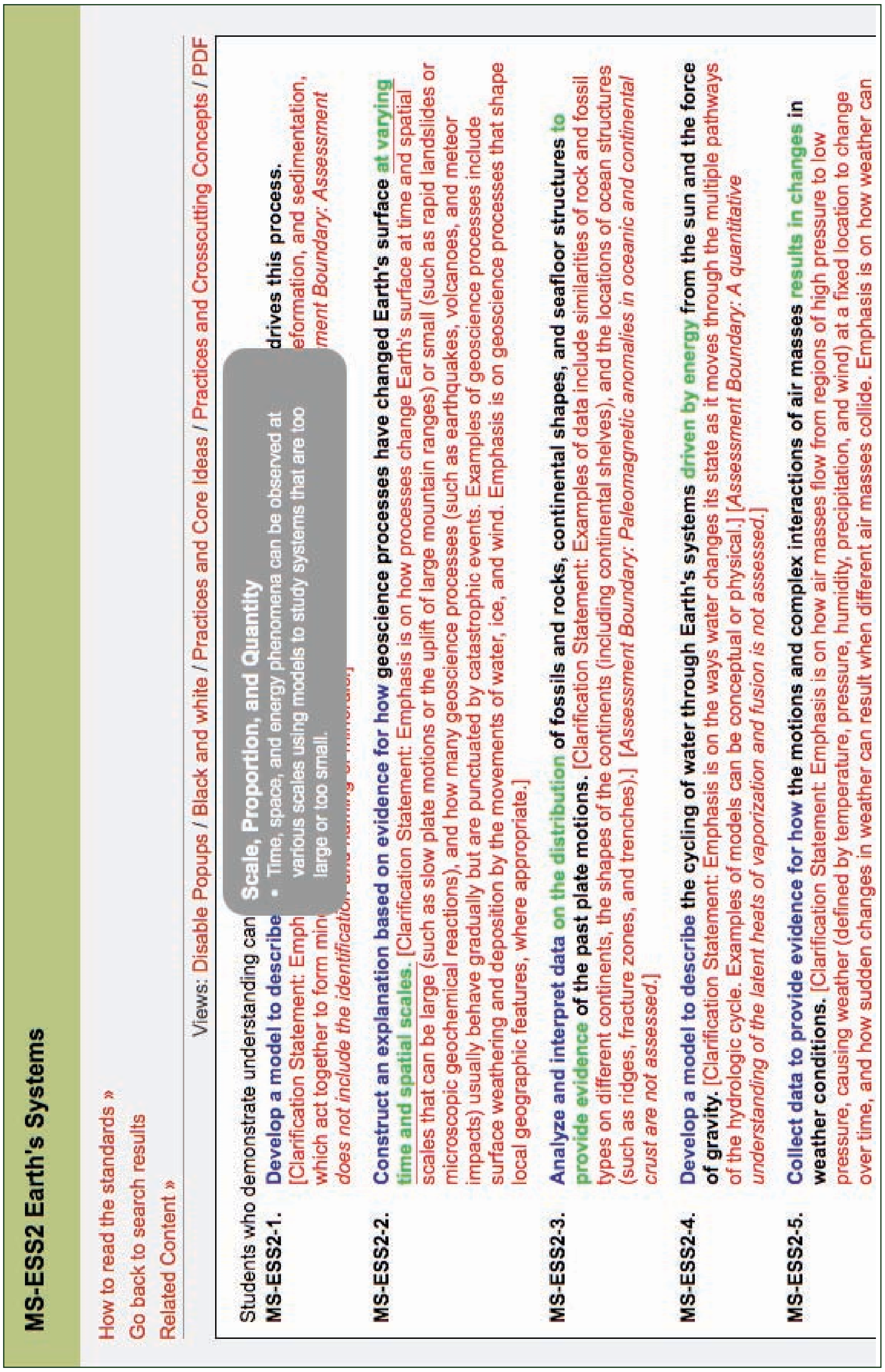
MS-ESS2-4. ***Develop a model to describe*** **the cycling of water through Earth's systems** ***<u>driven by energy</u>*** **from the sun and the force of gravity.**

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 identification and naming of minerals.]

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.

American Association for Advance of Science, 1993, *Benchmarks for Science Literacy*, Oxford University Press, http://www/[rpkect2-61.org/publications/bsl/online/index.php.

Bransford, J. D., A. L. Brown, and R. R. Cocking (eds.), 2000, *How People Learn: Brain, Mind, Experience, and School, expanded edition*, National Academies Press, Washington, DC, http://www.nap.edu/openbook.php?record_id=9853.

Common Core State Standards Initiative, http://www.corestandards.org. (While not focused on science education directly, standards on math and non-fiction reading impact are importantly related.)

National Center for Science Education, 2013, *Evolution and Climate Change in the NGSS*, http://ncse.com/news/2013/04/evolution-climate-change-ngss-0014800.

National Research Council, 1996, *National Science Education Standards*, National Academies Press, Washington, DC, http://www.nap.edu/openbook.php?record_id=4962. (NRC is a body of the National Academy of Sciences.)

National Research Council, 2011, *Successful K-12 STEM Education: Identifying Effective Approaches in Science, Technology, Engineering, and Mathematics*, National Academies Press, Washington, DC, http://www.nap.edu/openbook.php?record_id=13158.

National Research Council, 2012, A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas, National Academies Press, Washington, DC, http://www.nap.edu/openbook.php?record_id=13165.

National Research Council, 2013, *Next Generation Science Standards: For States, By States*. National Academies Press, Washington, DC, http://www.nextgenscience.org/.

NGSS@NSTA Website, National Science Teacher Association, http://ngss.nsta.org/.

Wysession, M., 2013, The Next Generation Science Standards and the Earth and Space Sciences, *The Science Teacher*, April/May issue, http://nstahosted.org/pdfs/ngss/resources/201304_NGSS-Wysession.pdf. (Duggan-Haas, author of this Appendix, worked with Wysession on NRC's Conceptual Framework for New Science Education Standards.)

a

Glossary

	Note: Words in **bold font** are also defined in this glossary.
'a'a	a **dense** and blocky **lava** flow, made up of a massive front of hardened fragments. Cooled 'a'a is a jagged landscape of sharp lava rubble. 'A'a is produced by lava that has a high viscosity and strain rate, as well as high gas effusion.
ablation zone	the front part of a **glacier**, where ice is lost due to melting and calving.
accretion, accrete	the process by which a body of rock increases in size due to the addition of further **sedimentary** particles or of large chunks of land, such as **terranes**.
accumulation zone	the highly elevated part of a **glacier**, where annual snow accumulation outpaces snow loss.
active plate boundary, active plate margin	the boundary between two **plates** of the Earth's **crust** that are colliding, pulling apart, or moving past each other. See also: **plate tectonics**
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.
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.
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**.
alluvium, alluvial	a thick layer of river-deposited sediment.
aluminum	a metallic chemical element (Al), and the most abundant metal in the Earth's crust. Aluminium has a low **density** and an excellent ability to resist corrosion. Structural components made from the metal and its alloys are commonly used in the aerospace industry, transportation, and household goods.
ammonoid, ammonite	a group of **extinct cephalopods** belonging to the Phylum Mollusca, and posessing a spiraling, tightly-coiled shell characterized by ridges, or septa.
amphibole	a group of dark-colored **silicate minerals**, or either **igneous** or **metamorphic** origin.
andesite	a fine-grained **extrusive volcanic** rock, with a **silica** content intermediate between that of **basalt** and **dacite**.

Glossary a

Andisols	a **soil order**; these are highly productive **soils** often formed from volcanic materials. They possess very high water- and nutrient-holding capabilities, and are commonly found in cool areas with moderate to high levels of precipitation.
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.
anthropogenic	caused or created by human activity.
anticline	a layer of rock folded (bent) along an axis, concave side down (i.e., in an upside down “u” or “v” shape). Thus rocks at the center of the anticline, along the fold (crest), are lifted up relative to the rest of the layer.
antimony	a lustrous gray metallic element (Sb), mainly found in nature as the **sulfide** mineral stibnite (Sb_2S_3). Antimony compounds have been known since ancient times, when it was used in cosmetics. Today, the largest applications for the element are as an alloying material for **lead** and tin, and for plates in lead-acid batteries.
Antler Orogeny	a period of mountain building that deformed rocks in a belt extending from the California–Nevada border northward into Idaho. The Antler Orogeny began began in the late **Devonian** and continued into the **Carboniferous**. See also: **orogeny**
aquifer	a water-bearing formation of **gravel**, **permeable** rock, or **sand** that is capable of providing water, in usable quantities, to springs or wells.
archaeocyathid	a vase-shaped organism with a **carbonate** skeleton, generally believed to be a **sponge**. Archaeocyathids were the first important animal **reef** builders, originating in the early **Cambrian**. They were very diverse, but went **extinct** by the end of the Cambrian. Archeocyathids are often easiest to recognize in **limestones**, by their distinctive cross-section.
Archean	a **geologic time** period that extends from 4 billion to 2.5 billion years ago. It is part of the **Precambrian**.
arête	a thin ridge of rock with an almost knife-like edge, formed when two **glaciers erode** parallel valleys.
Aridisols	a **soil order**; these are 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.
arthropod	an invertebrate animal, belonding 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.

Glossary

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.
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.
badlands	a type of **eroded topography** that forms in semi-arid areas experiencing occasional periods of heavy rainfall. Sloping ground composed of **sandstones** and calcareous sediments underlain by **clay** or other soft materials is eroded over time into an intricate series of gullies and ravines. Different layers of rock **weather** at different rates, resulting in a variety of sculpted spurs and buttresses, as well as tall pillars of softer rock with a hard **capstone**.
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.
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**.
batholith	a large exposed structure of **intrusive igneous rock** that solidified at depth, and covers an area of over 100 square kilometers (40 square miles). While batholiths may appear uniform, they are actually composed of multiple **plutons** that converged to form one mass.
bauxite	a whitish, grayish, brown, yellow, or reddish-brown rock composed of hydrous **aluminum oxides** and aluminum hydroxides; the principal commercial source of aluminum.
Belt Supergroup	a 1.45-billion-year-old series of **sedimentary rocks**, found in the Northern Rocky Mountains, that contain **sandstones** and mudstones. The Belt Supergroup is of particular note due to its age and excellent preservation. It is extremely rare that sedimentary rocks of over a billion years in age have not been warped, tilted, **metamorphosed**, or otherwise altered. The Belt Supergroup is also famous for its abundant and well-preserved **stromatolites**.
bentonite	a **clay**, formed from decomposed volcanic ash, with a high content of the **mineral** montmorillonite.

Glossary b

beryl	a white, blue, yellow, green, or pink **mineral**, found in coarse **granites** and **igneous rocks**. It is a source of beryllium and used as a **gemstone**; the green variety is called emerald, the blue is known as aquamarine.
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.
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**.
biomass	organic material from one or more organisms.
biostratigraphy	the branch of geology that uses **fossils** to determine the relative age of **sedimentary** layers.
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.
bituminous coal	a relatively soft **coal** containing a tarlike substance called **bitumen**, which is usually formed as a result of high pressure on **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.
blastoid	an **extinct** form of stemmed **echinoderm**, similar to a **crinoid**. Blastoids possessed a nut-shaped body covered with interlocking plates, which was covered with fine hairlike structures for use in **filter feeding**. The body was held above the sea floor by a stalk of stacked disc-shaped plates.
body fossils	**fossils** that consist of an actual part of an organism, such as a bone, shell, or leaf.

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.
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.
breccia	a **pyroclastic** rock composed of volcanic fragments from an explosive eruption.
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.
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**.
butte	an isolated hill with steep, often vertical sides and a small, relatively flat top.
calcite	a **carbonate mineral**, consisting of **calcium carbonate** ($CaCO_3$). Calcite is a common constituent of **sedimentary rocks**, particularly **limestone**.
calcium carbonate	a chemical compound with the formula $CaCO_3$, commonly found in rocks in the mineral forms **calcite** and aragonite, as well as the shells and skeletons of marine organisms.
caldera	a collapsed, cauldron-like **volcanic** crater formed by the collapse of land following a volcanic eruption.

Glossary

calving	the process by which ice breaks off from the end of a **glacier** (sometimes into a lake or ocean, sometimes over the edge of a cliff).
calyx	the head of a **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.
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**.
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**.
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**.
cementation	the precipitation of **minerals**, such as **silica** and **calcite**, that binds together particles of rock, bones, etc., to form a solid mass of **sedimentary rock**.
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.

Glossary

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.
chalcedony	a crystalline **silicate mineral** that occurs in a wide range of varieties.
chalcopyrite	a yellow **mineral** consisting of a **copper**-**iron** sulfide ($CuFeS_2$). Chalcopyrite is the most common and important source of copper, and can also be called copper **pyrite**.
chalk	a soft, fine-grained, easily pulverized, white-to-grayish variety of **limestone**, composed of the shells of minute planktonic single-celled algae.
chemical fossils	chemicals produced by an organism that leave behind an identifiable trace in the geologic record. Chemical **fossils** provide some of the oldest evidence for life on Earth.
chemical reaction	a process that involves changes in the structure and **energy** content of atoms, molecules, or ions but not their nuclei.
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.
chordate	an animal that possesses the following five traits during at least one stage of its development: a notochord (the flexible rod that, in vertebrates, becomes the backbone), a hollow dorsal nerve cord, pharyngeal gill slits, an endostyle (precursor to the thyroid gland), and a post-anal tail.
chromium	a lustrous, hard, steel-gray metallic element (Cr), resistant to tarnish and corrosion. Chromium is used as a component of certain pigments, as a component of steel (providing resistance and hardness), and in the production of chrome and stainless steel.
cinder	a type of **pyroclastic** particle in the form of gas-rich **lava** droplets that cool as they fall.
cirque	a large bowl-shaped depression carved by **glacial erosion** and located in mountainous regions.
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**.

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.
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.
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** period.
coalification	the process by which **coal** is formed from plant materials through **compression** and **heating** over long periods of time.
coccolithophore	a marine phytoplankton with a skeleton made up of microscopic calcareous disks or rings, and forming much of the content of **chalk** rocks.
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.
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.
Colorado Plateau	a **physiographic** region that covers an area of 337,000 square kilometers (130,000 square miles) of desert and forest within Colorado, New Mexico, Arizona, and Utah. Most of the area is drained by the Colorado River and its tributaries.
columnar joint	five- or six-sided columns that form as cooling **lava** contracts and cracks. Columnar joints are often found in **basalt** flows, but can also form in ashflow **tuffs** as well as shallow **intrusions**. The columns are generally vertical, but may also be slightly curved.
commodity	a good for which there is demand, but which is treated as equivalent across all markets, no matter who produces it.

C

Glossary

compression, compressional force	forces 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.
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 conglomerate must be larger than grains of **sand**.
conifer	a woody plant (**tree**) of the division Coniferophyta. Conifers bear cones that contain their seeds.
conodont	an extinct, eel-shaped animal classified in the class Conodonta and thought to be related to primitive **chordates**. Originally, conodonts were only known from small phosphatic tooth-like micro**fossils**, which have been widely used for **biostratigraphy**. Knowledge about their soft tissues still remains limited.
Conservation of Energy	a principle stating that **energy** is neither created nor destroyed, but can be altered from one form to another.
contact metamorphism	the process by which a **metamorphic rock** is formed through 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.
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.
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: **plate tectonics**
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.
Cordilleran Ice Sheet	one of two continental **glaciers** that covered Canada and parts of the Western US during the last major **Pleistocene ice age**.
corundum	an **aluminum oxide mineral** (Al_2O_3) that is, after **diamond**, the hardest known natural substance. Corundum is best known for its **gem** varieties, ruby (red) and sapphire (blue).

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**.
creep	the slow movement or deformation of a material under the influence of pressure or stress (such as gravity); the slow progression of rock and **soil** down a slope due to the interacting factors of gravity, vegetation, water absorption, and steepness.
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.
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.
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 five-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.
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.
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.

c–d

Glossary

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**.
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.
cyanobacteria	a group of bacteria, also called "blue-green algae," that obtain their energy through photosynthesis.
cycad	a palm-like, terrestrial seed plant (**tree**) belonging to the class Cycadopsida, and characterized by a woody trunk, a crown of stiff evergreen leaves, seeds without protective coatings, and no flowers. Cycads were very common in the **Mesozoic**, but are much reduced in diversity today, restricted to the tropical and subtropical regions of the planet.
cystoid	**extinct**, stalked **echinoderms** related to **crinoids**, but with an ovoid body and triangular pore openings.
dacite	a fine-grained **extrusive igneous rock**, with a **silica** content intermediate between that of **andesite** and **rhyolite**.
debris flow	a dangerous mixture of water, mud, rocks, **trees**, and other debris that can move quickly down valleys. Such flows can result from sudden rainstorms or snowmelt that create flash floods. Areas that have experienced a recent wildfire are particularly vulnerable to debris flows, since there is no vegetation to hold the **soil**.
degrade (energy)	the transformation of **energy** into a form in which it is less available for doing work, such as **heat**.
delta, deltaic	a typically wedge-shaped deposit formed as sediment is **eroded** from mountains and transported by streams across lower elevations. The Mississippi Delta is a modern delta containing sediment being transferred from the Mississippi River into the Gulf of Mexico.
density	a physical property of **minerals**, describing the mineral's mass per volume.
derecho	a set of powerful straight-line **winds** that exceed 94 kilometers per hour (58 miles per hour) and can often approach 160 kilometers per hour (100 miles per hour). 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."
derrick	a lifting device in the form of a framework steel tower that is built over a deep drill hole, typically an oil well. An oil derrick is composed of machinery for hoisting and lowering tools required during the drilling process, and readying the well for extraction of **petroleum**.

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**.
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**.
dike	a sheet of **intrusive igneous** or **sedimentary rock** that fills a crack in a pre-existing rock body.
dimension stone	the commercial term applied to quarried blocks of rock cut to specific dimensions and used for buildings, monuments, facing, and curbing.
dinosaur	a member of 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**.
divergent plate boundary	an **active plate boundary** where two tectonic **plates** are pulling apart from one another, causing the **mantle** to well up at a **rift**. Mid-ocean ridges are the most common divergent boundary and are characterized by the eruption of bulbous pillow-shaped **basalt lavas** and **hydrothermal** fluids.
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.
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.
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.
downwarp	a segment of the Earth's **crust** that is broadly bent downward.
drift	unconsolidated debris transported and deposited by a **glacier**.
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.
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**.

Glossary

echinoderm	a member 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.
effervesce	to foam or fizz while releasing gas. **Carbonate minerals** will effervesce when exposed to hydrochloric acid.
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.
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.
entelodont	an **extinct** family of omnivorous artiodactyl mammals that look somewhat like pigs but are actually thought to be more closely related to hippos. They roamed the forests and plains of North America, Europe, and Asia during the **Eocene** and **Miocene**. Entelodonts had bulky bodies and powerful teeth, and some grew up to 2 meters (7 feet) tall at the shoulder.
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.
Eocene	a **geologic time** period extending from 56 to 33 million years ago. The Eocene is an epoch of the **Paleogene** period.
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.
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.

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.
eukaryotes	organisms with complex cells containing a nucleus and organelles. **Protists** and all multicellular organisms are eukaryotes.
evaporite	a **sedimentary rock** created by the precipitation of **minerals** directly from seawater, including **gypsum**, **carbonate**, and **halite**.
exfoliation	a type of physical **weathering**. When overlying layers are weathered away, the reduction of downward pressure allows the underlying rock to expand toward the surface. This expansion causes **joints**, or cracks, to form parallel to the surface, producing slabs that resemble the curved layers of an onion.
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**.
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.
fault scarp	an escarpment directly beside a **fault** line, where the ground on one side of the fault has moved vertically with respect to the other side, creating step-like **topography**.
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.
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**.
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.

f

Glossary

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.
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.
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.
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.
foraminifera	a class of aquatic **protists** that possess a calcareous or **siliceous** exoskeleton. Foraminifera have an extensive **fossil** record.
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.”
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.
fracture (mineral)	a physical property of **minerals**, formed when a mineral crystal breaks; also a crack in rocks, sometimes known as a **joint**.
frost wedging	**weathering** that occurs when water freezes and expands in cracks.

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**.
gabbro	a usually coarse-grained, **mafic** and **intrusive igneous rock**. Most oceanic **crust** contains gabbro.
galena	an abundant **sulfide mineral** with cubic crystals. It is the most important **ore** of **lead**, as well as an important source of **silver**.
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.
Gellisols	a **soil order**; these are weakly **weathered soils** formed in areas that contain **permafrost** within the soil profile.
gem, gemstone	a **mineral** that has been cut and polished for use as an ornament.
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**.
geyser	a hot spring characterized by the intermittent explosive discharge of water and steam. Superheated water becomes highly pressurized when it enters underground **fractures**; once pressure builds to a certain level, it is released in an eruption of steam and hot water and the process of pressurization begins again.
ginkgo	a terrestrial **tree** belonging to the plant division Ginkgophyta, and characterized by broad fan-shaped leaves, large seeds without protective coatings, and no flowers. Ginkgos were very common and diverse in the **Mesozoic**, but today only one species exists, *Ginkgo biloba*.
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.
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.

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.
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.
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.
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**.
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.
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**.
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.
gravel	unconsolidated, semi-rounded rock fragments larger than 2 millimeters (0.08 inches) and smaller than 75 millimeters (3 inches).
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.
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.
greenstone belt	a series of interlayered **volcanic** and **sedimentary rocks** that have been **metamorphosed** into meta-sedimentary rocks and **amphibolite**. The rocks are called 'greenstones' due to the presence of metamorphic **minerals** that give the rock a greenish-gray color. Many geologists believe these belts are the result of deposition in volcanic arc environments.

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.
halite	See **salt**
hanging valley	a tributary valley that drops abruptly into a much larger and deeper valley. Hanging valleys are most commonly associated with U-shaped valleys that form due to **glacial erosion**.
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: **Moh's Scale of Hardness**
heat	a form of **energy** transferred 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.
heat island effect	a phenomenon in which cities experience higher temperatures than do surrounding rural communities.
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.
hectare	a metric unit of area defined as 10,000 square meters.
helium	a gaseous chemical element (He), which is the second most abundant and second lightest element in the universe. Helium is used in cryogenics, as a coolant; it is also used in industrial applications including pressurizaton, welding, and leak detection. Balloons and blimps, although probably the most well-known and visible application of helium, take up less than an eighth of its total use.
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.
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.
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.

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.
horn	a pointed rocky peak created by **glacial erosion**.
hornblende	a dark silicate mineral that can occur in a variety of forms. Hornblende is a common constituent of many **igneous** and **metamorphic rocks**.
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.
humus	a **soil horizon** containing organic matter.
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.
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.
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.
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.
ice cap	an **ice field** that lies over the tops of mountains.

ice field	an extensive area of interconnected **glaciers** spanning less than 50,000 square kilometers (19,305 square miles). Ice fields are usually constrained by an area's **topography**. Ice fields that lie over the tops of mountains are called **ice caps**.
ice lobe	a broad, rounded section of a continental **glacier** that flows out near the glacier's terminus, often through a broad trough.
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).
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.
Illinoian glaciation	a period of **glaciation** that occurred during the **Pleistocene**, 191 to 131 thousand years ago.
ilmenite	an **ore** of **titanium**, produced for use as a white pigment in paint.
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.
inclusion	a fragment of older rock located within a body of **igneous rock**. Inclusions typically form when igneous rock **intrudes** into and envelopes older material.
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.
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.
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.

i–j Glossary

intensity (earthquake)	a subjective measurement that classifies the amount of shaking and damage done by an **earthquake** in a particular area.
interglacial	a period of geologic time between two successive **glacial** stages.
intermontane	between or among mountains.
intertidal	areas that are above water during low tide and below water during high tide.
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.
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.
isostasy	an equilibrium between the weight of the **crust** and the buoyancy of the **mantle**.
jade	a word applied to two green **minerals** that look similar and have similar properties: jadeite (a kind of **pyroxene**) and nephrite (a kind of **amphibole**). Both minerals are formed during **metamorphism** and are found primarily near **subduction** zones, which explains why jade is abundant in a variety of locations along **active plate boundaries**.
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.
jet stream	a fast-flowing, narrow air current found in the **atmosphere**. The polar jet stream is found at an altitude of 7–12 kilometers (23,000–39,000 feet), and the air within can travel as fast as 160 kilometers per hour (100 miles per hour). Jet streams are created by a combination of the Earth's rotation and atmospheric heating.
joint	a surface or plane of fracture within a rock.
joule (J)	the **energy** expended (or work done) to apply a force of one newton over a distance of one meter.
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**.

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.
kaolinite	a **silicate clay mineral**, also known as china clay. Kaolinite is the main ingredient in fine china dishes such as Wedgwood.
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 **topography** primarily forms in **limestone** bedrock.
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.
kinetic energy	the **energy** of a body in motion (e.g., via friction).
komatiite	**mafic volcanic** rocks richer in magnesium and erupted at a higher temperature than **basalts**. They are restricted to the **Archean**, when the **mantle** temperatures were higher at the depths where **magma** is generated. Komatiites often exhibit “spinifex texture,” an unusual crystallization-cooling texture that produces large, long crystals.
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.
lacustrine	of or associated with lakes.
Lagerstätte (pl. Lagerstätten)	**fossil** deposit containing animals or plants that are preserved unusually well, sometimes even including the soft organic tissues. Lagerstätten 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. Lagerstätten are important for the information they provide about soft-bodied organisms that we otherwise would know nothing about.
lamproite	an **ultramafic volcanic** (**extrusive**) rock with high levels of potassium and magnesium that contains coarse crystals. **Diamonds** can occur in lamproites.
landslide	the rapid slipping of a mass of earth or rock from a higher elevation to a lower level under the influence of gravity and water lubrication. Landslides include rock falls, avalanches, **debris flows**, mudflows, and the **slumping** of rock layers or sediment. See also: **mass wasting**
Laramide Orogeny	a period of mountain building that began in the late **Cretaceous**, and is responsible for the formation of the Rocky Mountains. See also: orogeny

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last glacial maximum	the most recent time the **ice sheets** reached their largest size and extended farthest toward 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.
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.
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.
lava tube	a natural tube formed by **lava** moving beneath the hardened surface of a lava flow.
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: **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.
leonardite	a soft, waxy dark-colored mineraloid found in association with near-surface **lignite** deposits. It is an **oxidation** product of lignite, and is used as a **soil** conditioner, a stabilizer in water treatment, and as a drilling additive.
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**.
lime	an inorganic white or grayish-white compound made by roasting **limestone** (**calcium carbonate**, $CaCO_3$) until all the carbon dioxide (CO_2) is driven off. Originating from limestone, **dolomite**, or **marble**, lime is very important to agriculture, in which it is regularly applied to make **soils** "sweeter" (less acidic).
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.
lithification	the process of creating **sedimentary rock** through the compaction or **cementation** of soft sediment. The word comes from the Greek *lithos*, meaning "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.
loam	a **soil** containing equal amounts of **clay**, **silt**, and **sand**.
loess	very fine-grained, wind-blown sediment, usually **rock flour** left behind by the grinding action of flowing glaciers.
luminescence	the emission of light.
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.
mafic	**igneous rocks** that contain a group of dark-colored minerals, with relatively high concentrations of magnesium and **iron** compared to **felsic** igneous rocks.
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**.
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.
magnitude (earthquake)	a logarithmic scale used to measure the seismic energy released by an **earthquake**. Magnitudes range from 1 to 10, with M3 earthquakes classed as minor and earthquakes of M8 or greater being classified as major.
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.
manganese	a metallic chemical element (Mn). Manganese is used in the production of steel.

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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**.
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**.
marl	a fine-grained **sedimentary rock** consisting of **clay minerals**, **calcite** and/or aragonite, and **silt**.
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.
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**).
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.
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.
megashear	a large **shear**, typically tens to hundreds of kilometers (miles) in length, formed when rocks have been continuously **fractured** due to **compressive** stress.
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.
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.

meteorite	a stony or metallic mass of matter that has fallen to the Earth's surface from outer space.
mica	a large group of sheetlike **silicate minerals**.
microcontinent	a piece of continental **crust**, usually **rifted** away from a larger continent. Microcontinents and other smaller fragments of continental crust (**terranes**) each had their own, often complex, geologic history before they were tacked onto the margin of another continent.
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.
mineral	a naturally occurring inorganic solid with a specific chemical composition and a well developed crystalline structure. Minerals are identified based on their physical properties, including **hardness**, **luster**, **color**, **crystal form**, **cleavage**, **density**, and **streak**. There are over 4900 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**.
mineralogy	the branch of geology that studies the chemical and physical properties and formation of **minerals**.
Miocene	a **geologic time** unit extending from 23 to 5 million years ago. During the Miocene, the Earth experienced a series of **ice ages**, and hominid species diversified. The Miocene is the first epoch of the **Neogene** period.
mirabilite	a saline **evaporite mineral**, sodium sulfate ($NaSO_4$), also known as "Glauber salts" in its processed form. This mineral is used in the manufacture of detergents, paper, and chemical processing, especially in the production of hydrochloric and sulfuric acids.
Mississippian	a subperiod of the **Carboniferous**, spanning from 359 to 323 million years ago.
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.
Mollisols	a **soil order**; these are agricultural **soils** made highly productive due to a very fertile, organic-rich surface layer.
molybdenum	a metallic chemical element (Mo) which has the sixth-highest melting point of any element at 2623°C (4753°F). Molybdenum is mainly used in the creation of alloys, such as stainless steel and cast **iron**, and its strong ability to withstand **heat** makes it useful in applications that utilize extreme heat, such as the manufacture of motors and aircraft parts.

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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**.
mosasaur	an **extinct**, carnivorous, marine vertebrate reptile. 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 12–18 meters (40–59 feet) in length.
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**.
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.
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.
nuclear	pertaining to a reaction, as in fission, fusion, or **radioactive** decay, that alters the **energy**, composition, or structure of an atomic nucleus.
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.
oil	See **petroleum**
Oligocene	a **geologic time** interval spanning from about 34 to 23 million years ago. It is an epoch of the **Paleogene**.

olivine	an **iron**-magnesium **silicate mineral** ($(Mg,Fe)_2SiO_4$) that is a common constituent of magnesium-rich, silica-poor **igneous rocks**.
opal	a **silicate gemstone** lacking a rigid crystalline structure (and therefore a "mineraloid" as opposed to a **mineral**). It forms when silica-rich water precipitates in fissures of almost any type of rock, as well as occasional organic matter.
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**.
ore	a type of rock that contains **minerals** with valuable elements, including metals, that are economically viable to extract.
oreodont	an **extinct** ungulate (hoofed animal) related to modern camels. Oreodonts lived in woodlands and grasslands throughout North America during the **Oligocene** and **Miocene**.
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.
orthoquartzite	a **sandstone** composed nearly entirely of well-rounded **quartz** grains **cemented** by **silica**.
outwash plain	large **sandy** flats created by sediment-laden water deposited when a **glacier** melts. Outwash sediments are also called fluvial material.
oxidation, oxide	a **chemical reaction** involving the loss of at least one electron when two substances interact; most often used to describe the interaction between oxygen molecules and the substances they come into contact with. Oxidation causes effects such as rust and cut apples turning brown.
Oxisols	a **soil order**; these are very old, extremely leached and **weathered soils** with a subsurface accumulation of **iron** and **aluminum oxides**. Commonly found in humid, tropical environments.
pahoehoe	a type of **lava** resulting from the rapid motion of highly fluid **basalt**. It cools into smooth **glassy** flows, or can form twisted, ropey shapes. Pahoehoe is formed from lava that has a low viscosity and strain rate, as well as a low rate of gas effusion.
Paleocene	a **geologic time** interval spanning from about 66 to 56 million years ago. It is an epoch of the **Paleogene** period.
paleoecology	the study of the relationships of **fossil** organisms to one another and their environment.
Paleogene	the **geologic time** interval 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**.

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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.
Pangaea	a supercontinent, meaning "all Earth," which formed over 250 million years ago and lasted for almost 100 million years, during which 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**.
passive margin	a tectonically quiet continental edge, such as the eastern margin of North America, where **crustal** collision or **rifting** is not occurring.
patterned ground	patterns and sorting in the soil caused by repeated freezing and thawing, which causes repeated heaving upward and settling of the rocks and pebbles in the 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 9 meters (30 feet) 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.
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.
pegmatite	a very coarse-grained **igneous rock** that formed below the surface, usually rich in **quartz**, **feldspar**, and **mica**. Pegmatite **magmas** are very rich in water, carbon dioxide, **silicon**, **aluminum**, and potassium, and form as the last fluids to crystallize from magma or the first **minerals** to melt at high temperatures during **metamorphism**.
Pennsylvanian	a subperiod of the **Carboniferous**, spanning from 323 to 299 million years ago.
perennial	continuous; year-round or occurring on a yearly basis.
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.
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. Permafrost is typically defined as any soil that has remained at a temperature below the freezing point of water for at least two years.

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.
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 terrestrial animal species and 90% of all marine animal species.
permineralization	a **fossilization** method in which empty spaces (such as in a bone or shell) are filled by minerals.
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.
Phanerozoic	a generalized term used to describe the entirety of geological history after the **Precambrian**, from 541 million years ago to the present.
phonolite	an **extrusive igneous rock** of intermediate composition, which forms from **magma** with a relatively low **silica** content. The name phonolite comes from Greek meaning "sounding stone" due to the metallic sound it produces if struck.
phosphate	an inorganic **salt** of phosphoric acid, and a nutrient vital to biological life.
physiography	a subfield of geography that studies the Earth's physical processes and patterns, including consideration of the shape (not just the height) of land forms, as well as the bedrock, **soil**, water, vegetation, and **climate** of an area, and how they interacted in the past to form the landscape we see today.
placer deposit	a **mineral** deposit occurring in rivers and streams where less **dense** sediment has been carried downstream but denser minerals such as **gold** have been left behind.
plate tectonics	the process 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.

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plates	large, rigid pieces of the Earth's **crust** and upper **mantle**, which move and interact with one another at their boundaries. See also: **plate tectonics**
playa lakes	ephemeral or dry lakebeds that occasionally contain only a thin layer of quickly evaporating water. Soluble minerals such as **halite**, **gypsum**, and **calcite** precipitate from evaporating playa lakes, leaving behind rock **salt**, gypsum, and **limestone**.
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.
plesiosaur	a member of a group of **extinct** long-necked **Mesozoic** marine reptiles.
Pliocene	a **geologic time** interval extending from roughly 5 to 2.5 million years ago. The Pliocene epoch is a subdivision of the **Neogene** period, and is the time period directly preceding the onset of **Pleistocene glaciations**.
plucking	process by 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.
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.
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
porosity	the percentage of openings in a body of rock such as pores, **joints**, channels, and other cavities, in which gases or liquids may be trapped or migrate through.
porphyry, porphyritic	an **igneous rock** consisting of large grained crystals, or **phenocrysts**, cemented in a fine-grained matrix.
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).
pothole	a shallow, rounded depression **eroded** in bedrock by a **glacier**.
power (energy)	the rate at which **energy** is transferred, usually measured in **watts** or, less frequently, horsepower.

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.
pre-Illinoian glaciation	a grouping of the Midwestern **glacial** periods that occurred before the **Wisconsinian** and **Illinoian glaciations**.
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.
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.
protists	a diverse group of single-celled **eukaryotes**.
protolith	the original parent rock from which a **metamorphosed** rock is formed.
pterosaurs	**extinct** flying reptiles with wingspans of up to 15 meters. They lived during the same time as the **dinosaurs**.
pumice	a **pyroclastic** rock that forms as frothing and sputtering **magmatic** foam cools and solidifies. It is so **vesicular** that it can float. Pumice is a common product of explosive eruptions. Today it is used in a variety of mediums, including construction materials and abrasives.
pyrite	an **iron** sulfide **mineral** (FeS_2). Pyrite's superficial resemblance to **gold** has led to the common nickname "fool's gold."
pyroclastic rocks	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**.
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.

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).
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.
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**.
radioactivity	The emission of radiation (**energy**) by an unstable atom.
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**.
rare earth elements	a set of 17 heavy, **lustrous** elements with similar properties, some of which have technological applications. Although they are relatively common in the **crust**, these metals are not usually found concentrated in economically viable **ore** deposits.
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.
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.
regression	a drop in sea level.

relief (topography)	the change in elevation over a distance.
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.
replacement	a **fossilization** method by which the original material is chemically replaced by a more stable **mineral**.
residual weathering deposit	a **mineral** deposit formed through the concentration of a **weathering**-resistant mineral, in which the other minerals around it have been weathered away.
rhyolite, rhyolitic	a **felsic volcanic** rock high in abundance of **quartz** and **feldspar**.
rift	a break or crack in the **crust** that can be caused by tensional stress as a landmass breaks apart into separate **plates**.
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.
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 **lithified** and preserved, providing information about the flow of water or wind in the paleoenvironment.
rock flour	very fine sediments and **clay** resulting from the grinding action of **glaciers**.
rockburst	spontaneous, violent **fracturing** of rock occurring in deep mines.
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**.
rudist	an **extinct** group of box- or tube-shaped **bivalves** that arose during the **Jurassic**. They were major **reef** formers, but went extinct at the end of the **Cretaceous**.
rugose coral	an **extinct** group of corals that were prevalent from the **Ordovician** through the **Permian**. Solitary forms were most common; these were horn-shaped, leading to their common name, "horn corals."
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.

Glossary

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 and 2 millimeters in diameter.
sandstone	**sedimentary rock** formed by cementing together grains of **sand**.
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**.
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.
scour, scouring	**erosion** resulting from **glacial** abrasion on the landscape.
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**.
seismic belt	a narrow geographic zone along which most **earthquakes** occur.
seismic tomography	a technique for imaging Earth’s sub-surface characteristics, in which the velocity of **seismic waves** is analyzed in an effort to understand deep geologic structure.
seismic waves	the shock waves or vibrations radiating in all directions from the center of an **earthquake** or other tectonic event.
seismic zone	a regional zone that encompasses areas prone to seismic hazards, such as **earthquakes** or **landslides**.

sessile	unable to move, as in an organism that is permanently attached to its substrate.
Sevier Orogeny	a mountain-building event resulting from **subduction** along the western edge of North America, occurring mainly during the **Cretaceous**. During this **orogeny**, compressive forces and **heating** resulted in major **crustal** folding and thrust **faulting**.
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**.
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.
shearing, shear	the process by which **compressive** stress causes the **fracturing** and **faulting** of brittle rocks.
silica, silicon, silicate	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**.
silt	granular sediment most commonly composed of **quartz** and **feldspar** crystals. Particles of silt have diameters of less than 0.074 millimeters.
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**.
silver	a metallic chemical element (Ag). Silver is used in photographic film emulsions, utensils and other tableware, and electronic equipment.
slump	a slow-moving **landslide** in which loosely consolidated rock or **soil** layers move a short distance down a slope. See also: **mass wasting**
snail	See **gastropod**
Snowy Pass Supergroup	a 2.4–2.5 billion year old series of **sedimentary rocks**, located in the Medicine Bow Range in southern Wyoming. These strata, containing thick sequences of **sandstone**, **conglomerate**, and **limestone**, were deposited in a continental shelf environment on the passive margin of proto-North America. The sediments were later **metamorphosed** by an **orogenic** episode accompanied by **volcanic** activity.

Glossary

soapstone	a **metamorphic** schistose rock composed mostly of **talc**. Soapstone has a flaky texture and a greasy or soapy feel, and is an effective medium for carving.
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."
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.
soil taxonomy	the system used to classify **soils** based on their properties.
solifluction	a type of **mass wasting** where waterlogged sediment moves slowly downslope, over impermeable material. Solifluction is similar to a **landslide** or mudslide.
solution mining	the extraction of soluble **minerals** from subsurface strata by the injection of fluids, and the controlled removal of mineral-laden solutions.
Sonoman Orogeny	a period of mountain building along the western edge of North America, in what is now Nevada and eastern Oregon. This **orogeny** is related to **accretion** at the **convergent plate boundary**, and is thought to have occurred around 250 million years ago.
speleothem	an often delicate **mineral** deposit in **limestone** or **dolostone** caves, formed through the dissolution of **carbonate** minerals.
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.
spodumene	a translucent **pyroxene mineral** (lithium aluminum inosilicate) occurring in prismatic crystals, and a primary source of **lithium**. Some varieties of spodumene are also prized as **gems**.
sponge	a marine invertebrate belonging to the Phylum Porifera, and characterized by a soft shape with many pores and channels for water flow. Because they have no nervous, digestive, or circulatory systems, some consider them to be colonies of specialized single cells. Sponges come in a variety of shapes and body forms, and have been around at least since the **Cambrian**. Entire sponges are rarely preserved, but their tiny skeletal pieces (spicules) are common in **sedimentary rocks**. See also: **archaeocyathid**

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.
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**.
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.
subsidence	the sinking of an area of the land surface.
subsoil	the layer of **soil** beneath the **topsoil**, composed of **sand**, **silt**, and/or **clay**. Subsoil lacks the organic matter and **humus** content of topsoil.
sulfur, sulfate	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**.
supervolcano	an explosive **volcano** capable of producing more than 1000 cubic kilometers (240 cubic miles) of ejecta.
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**
syenite	a durable, coarse-grained **intrusive igneous rock**, which is similar to **granite** but contains less **quartz**. It can exhibit **columnar jointing**.
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.

t

Glossary

tabulate coral	an **extinct** form of colonial coral that often formed honeycomb-shaped colonies of hexagonal cells.
talc	hydrated magnesium silicate, formed during **hydrothermal** alteration accompanying **metamorphism**. Talc can be formed from **calcite**, **dolomite**, **silica**, and some **ultramafic** rocks.
talus	debris fields found on the sides of steep slopes, common in **periglacial** environments.
tephra	fragmented material produced by a **volcanic** eruption. Airborne tephra fragments are called **pyroclastic**.
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.
Tertiary	an unoffical but still commonly used term for the time period spanning from 66 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** and **Mississippian** periods all enjoy official status, with the latter pair being more commonly used in the US.)
thorium	a **radioactive rare earth element**, with potential applications in next-generation **nuclear** reactors that could be safer and more environmentally friendly than current uranium reactors.
till	unconsolidated sediment that is **eroded** from the bedrock, then carried and eventually deposited 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.
tillite	**glacial till** that has been compacted and **lithified** into solid rock.
titanium	a metallic chemical element (Ti). Titanium is important because of its lightweight nature, strength and resistance to corrosion.
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.
topsoil	the surface or upper layer of **soil**, as distinct from the subsoil, and usually containing organic matter.

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.”
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.
transform boundary	an **active plate boundary** in which the **crustal plates** move sideways past one another.
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.
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**.
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.
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.
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.

Glossary

Ultisols	a **soil order**; these are **soils** with subsurface **clay** accumulations that possess low native fertility and are often red hued (due to the presence of **iron oxides**). They are found in humid tropical and subtropical **climates**.
ultramafic rocks	**igneous rocks** with very low **silica** content (< 45%), which are composed of usually greater than 90% **mafic minerals**. The Earth's **mantle** is composed of ultramafic rocks, which are dark green to black in color due to their high magnesium and **iron** content.
unconformity	the relation between adjacent rock strata for which the time of deposition was separated by a period of nondeposition or **erosion**; a break in a **stratigraphic** sequence.
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.
vanadium	a metallic element (V) that occurs naturally in **fossil fuel** deposits as well as in a variety of different **minerals**. Vanadium is mainly used to produce specialty steel alloys.
Vertisols	a **soil order**; these are **clayey soils** with a high moisture capacity. During dry periods, these soils shrink and develop wide cracks; during wet periods, they swell with moisture.
vesicular	porous or pitted with vesicles (cavities). Some **extrusive igneous rocks** have a vesicular texture.
volcanic ash	fine, unconsolidated **pyroclastic** grains under 2 millimeters (0.08 inches) in diameter. Consolidated ash becomes **tuff**.
volcanic islands	a string of islands created when molten rock rises upward 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.
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 kilometers / 0.5–6 miles) 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.
water table	the upper surface of groundwater, that is, the underground level at which groundwater is accessible.

watershed	an area of land from which all water under or on it drains to the same location.
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.
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.
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.
Wisconsinian glaciation	the most recent interval of **glaciation**, which occurred during the Pleistocene, 85,000 to 11,000 years ago.
zeolites	**porous** aluminosilicate **minerals**, often formed some time after **sedimentary** layers have been deposited, or where **volcanic** rocks and ash react with alkaline groundwater. Zeolites are often used as catalysts and water softeners, and their microporous surface sturcture makes them useful in concentrating and condensing molecular substances.
zinc	a metallic chemical element (Zn). Zinc is typically used in metal alloys and galvanized steel.

General Resources

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Elements Box: Jane Picconi
Hydrothermal Solutions Box: Jim Houghton

Chapter 6: Glaciers

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Oil and Gas Box: Jim Houghton
Geothermal Box: Wade Greenberg-Brand

Chapter 8: Soils
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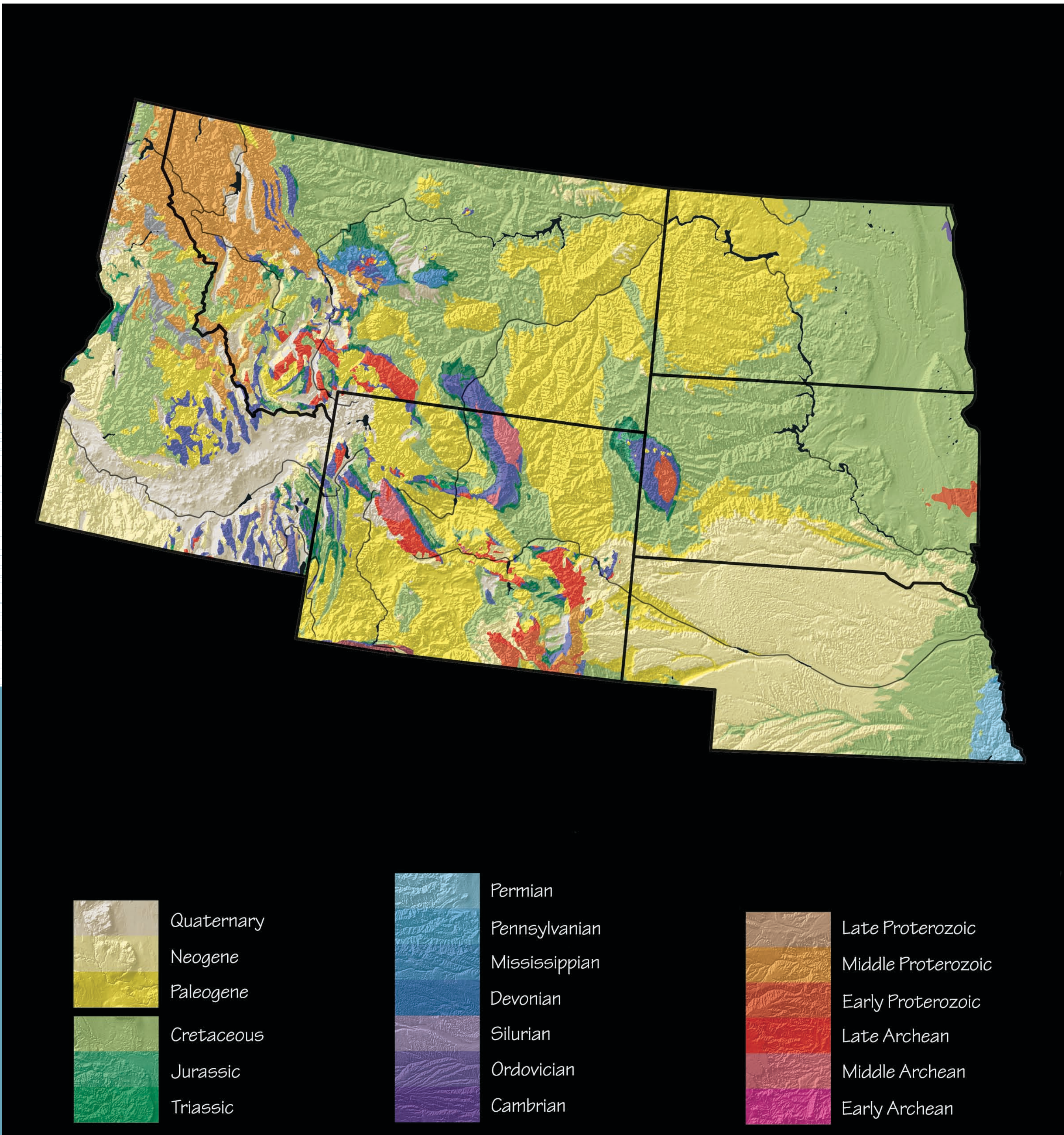
Chapter 11: Fieldwork

11.1–11.2: PRI
11.3: Don Duggan-Haas

Appendix

A.1-A.3: Next Generation Science Standards



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