The Teacher-Friendly Guide™

to the Earth Science of the Western US

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

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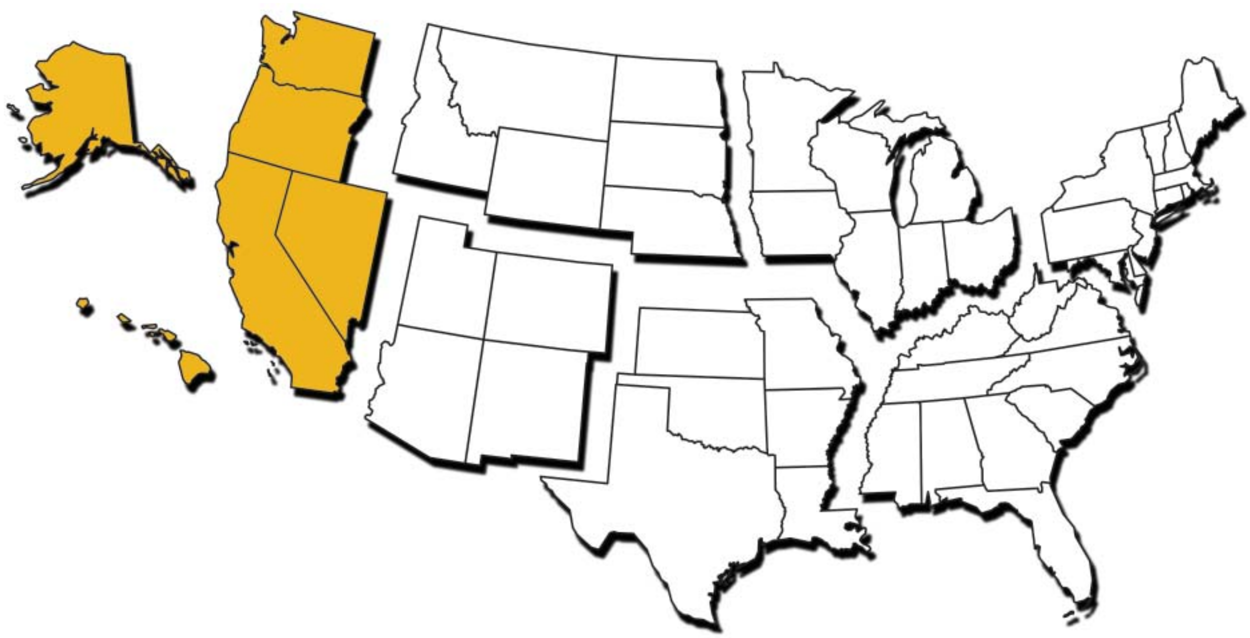

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Paleontological Research Institution
2014

ISBN 978-0-87710-509-1
Library of Congress no. 2014959038
PRI Special Publication no. 47

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

First printing December 2014

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

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

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

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

Cite this book as:
Lucas, M. D., R. M. Ross, & A. N. Swaby (eds.), 2014, *The Teacher-Friendly Guide to the Earth Science of the Western US,* Paleontological Research Institution, Ithaca, New York, xii + 424 pp.

Cite one chapter as (example):
Anderson, B., A. Moore, G. Lewis, and W. D. Allmon, 2014, Fossils of the Western US. Pages 81–123, in: M. D. Lucas, R. M. Ross, & A. N. Swaby (eds.), *The Teacher-Friendly Guide to the Earth Science of the Western US.* Paleontological Research Institution, Ithaca, New York.

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

Preface

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

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

Earth science educators at the Paleontological Research Institution, in working with teachers, have noted that no single source for educators exists that attempts to make sense of the disparate local features of the Western United States in terms of a basic sequence of historical events and processes. Nationally distributed textbooks make few references specifically to the Western region. While a number of reasonably good resources exist for individual states, these do not take enough geographic scope into account to show how it is that, say, volcanoes flow in Hawai'i but explode in Washington, or how tectonic mountain building events and the marine fossil record are related to each other all along the west coast from California into Washington. 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 West (though, like states, an artificial political area), is of the right scale to discuss the evolution of significant portions of sedimentary basins, but also includes ancient igneous and metamorphic rocks. This means that many Earth processes can be illustrated with examples in areas students and teachers might 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 West 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 six natural regions within the West. 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 a 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 *Teacher-Friendly Guides*™ to Earth science, covering all 50 states in seven regions. The West is relatively long because it includes Alaska and Hawai'i, greatly increasing the diversity of Earth science (not to mention area) represented in the region. 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.

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Paleontological Research Institution
December 2014

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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.

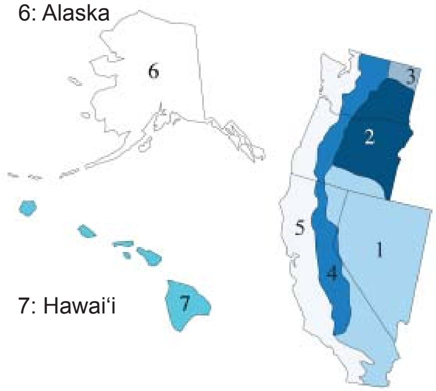
A National Series of Guides

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 West 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 West into seven broad regions (including Alaska and Hawai‘i), 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 seven within the context of Earth history. Chapters on climate and glaciers separately discuss Alaska and Hawai‘i, but are not divided into regions in the contiguous states because these topics involve processes driven 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 maps as a reference tool while you read this Guide. The maps are on the back and inside back cover of the printed Guide are available as downloadable graphics 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 and 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 <u>big ideas</u>. 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 <u>nature of science</u>. 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 way by which the plates of the Earth's crust move and interact with one another at their boundaries.*

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

erosion • *the transport of weathered materials.*

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

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

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

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.*

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

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

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

As **glaciers** extended down from the north, they cut into river valleys in the upper portion of North America. This glacial system shaped the landscape, deepening and widening the river valleys and creating huge lakes that later emptied in great torrents like the Missoula Floods, leaving impressive scars on the landscape as well as huge deposits that accumulated in mere days. Had the glaciers never advanced so far south, the erosional forces that led to the formation and draining of these lakes would have never been set in motion. This interplay 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 lain down by these other systems, furthering the interplay of systems.

See Chapter 4: Topography for more on the Missoula Floods and other ways in which glaciers shaped the Western Landscape.

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

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

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

> One of the fundamental processes known to Earth system scientists is the rock cycle. The rock cycle illustrates the steps involved in the formation of one type of rock from another. It is a system that has operated since the Earth's origin, and it continues today. The energy that drives weathering and erosion, melting, or an increase in heat or pressure, drives the continuation of the rock cycle.
>
> The landscape of the West that we see today has been shaped by the geologic forces of the past, and these forces are still active today. 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 littered throughout the West's terrain tells a story that began billions of years ago with the formation of tectonic plates, and continues today as the Pacific and Juan De Fuca Plates slide underneath and along the North American plates. This plate movement creates the volcanoes of coastal Oregon, Washington, and Alaska, **earthquakes** along the Pacific's Ring of Fire, and features on the seafloor, like the Juan De Fuca Ridge off the coast of Oregon and Washington.
>
> During the most recent **ice age**, glaciers advanced and retreated many times during the past two million years. One of the great questions in the Earth sciences revolves around the causes of these glacial cycles, with the general consensus pointing toward cyclic variations in the planet's tilt, movement about its axis, and its orbital shape around the sun. These variations lead to changes in the amount of solar radiation that reaches the Earth, which in turn affect global climate.

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

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

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.*

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.*

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

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.*

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

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.

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.
>
> The San Andreas Fault is a **transform boundary** that separates the North American plate from the Pacific plate and runs almost the entire length of California, from the Salton Sea in the south to Cape Mendocino in the north. The relative motion of the plates shifts most of the continent to the southeast, while a relatively thin sliver of California (and the very large Pacific plate to which it is connected) shifts to the northwest. While the **fault** itself is relatively young (thought to be between 5 and 30 million years old at different points along its length), the processes at play have been at work in the same way for billions of years, opening and closing oceans and building up and tearing down landscapes.
>
> Today, the **ice sheets** of Greenland and Antarctica make up some 95% of all the current glacial ice on Earth. The study of these modern glaciers and their influences on the environment, such as through the formation of U-shaped valleys, is key to interpreting glacial deposits of the past, which are thought to have formed under the same processes as those operating today.

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).*

transform boundary • *an active plate boundary in which the crustal plates move sideways past one another.*

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

ice 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).*

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

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

The use of models is fundamental to all of the Earth sciences. Maps and models 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 below Earth's surface, but modeling of convection currents brings us closer to the true nature of these monumental geologic phenomena.
>
> The observation of natural phenomena today, such as deposition along a streambed, is critical for interpreting the geologic record. But for processes that operate on much larger, slower scales, modeling within the lab is required. The formation of mountain ranges, such as the Cascades, is better understood by examining the effects of stress and strain in the laboratory.
>
> What is the effect of a two-kilometer-thick (1.2-mile-thick) glacier on the terrain? In addition to changes related to deposition, the shear weight of such an object depresses the continental mass. Understanding this **compression**—and the rebound that occurs upon the 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

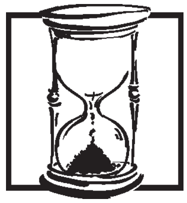
Donovan, S., & J. Bransford, 2005, *How Students Learn: Science in the Classroom,* National Academies Press, Washington, DC, http://books.nap.edu/catalog.php?record_id=10126.

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 Western US:

Reconstructing the Geologic Past

We often wonder: What will the places we live in look like a millennium from now? A vision of "what might be" is critical for making the big decisions that will shape our future and that of our descendants. But to look forward, we have to first look back in time.

The shape and position of North America has changed dramatically over the last billion years, and geologic processes continue these changes today. The Earth is estimated to be approximately 4.6 billion years old. The oldest rocks known are located in northern Quebec and date to 4.3 billion years ago. These are part of Canada's **Precambrian** shield, the ancient core of the North American continental landmass. Rocks more than 3.5 billion years old are found on every continent.

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

The Earth is dynamic, consisting of constantly moving **plates** that are made of rigid continental and oceanic **lithosphere** overlying a churning, plastically flowing **asthenosphere** (*Figure 1.1*). These plates pull apart, collide, or slide past one another with great force, creating strings of volcanic islands, new ocean floor, **earthquakes**, and mountains. The continents likewise continuously

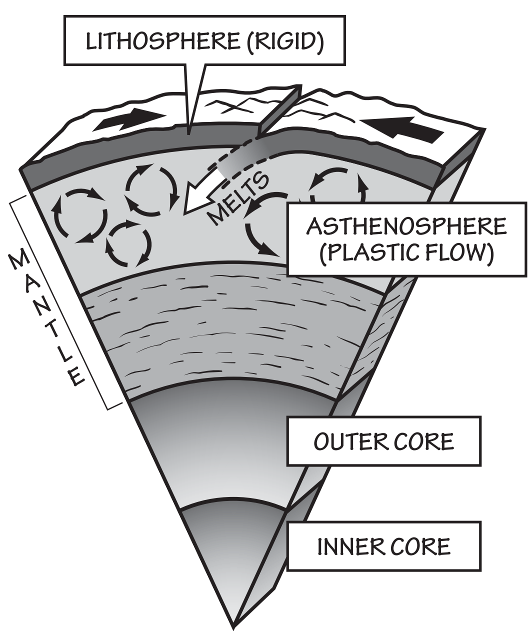


Figure 1.1: The layers of the Earth include the rigid crust of the lithosphere, which is constantly moving over the plastically flowing asthenosphere.

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).*

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

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.*

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

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Reconstructing

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

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).*

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

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

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

shift position because they are part of the moving plates. This not only shapes the land over time, but it 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.

- *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 past volcanism. By looking at both their texture and chemistry we can determine the tectonic setting and whether or not the rocks formed at the surface or deep underground. Likewise, **metamorphic rocks**, created when sediment is subjected to intense **heat** and pressure, provide important clues of 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 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 West.

- *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 entire 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 are easily preserved as fossils, and many environments also do not lend themselves to preserving organisms as fossils. As a result, the clues that fossils give provide only glimpses of the ancient world, with many important details missing.

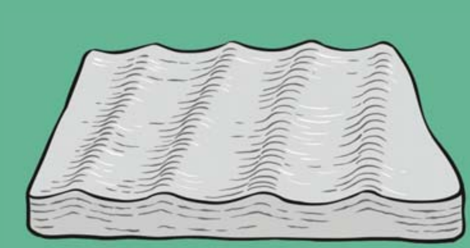
See Chapter 3: Fossils for more information about the West's prehistoric life.

- *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 moved 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.

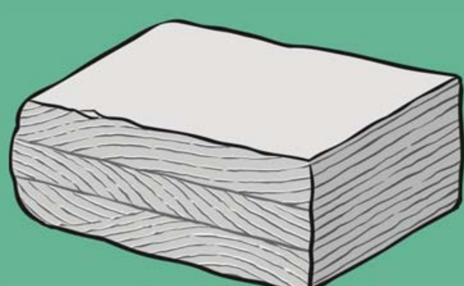
See Chapter 4: Topography for more detail about the landscapes found in the Western States.

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.

Reconstructing

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

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

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

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.*

1 Geologic History

Reconstructing

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, the Earth's recent history is better known than its ancient past. Although preserved geologic clues are indeed fragmented, geologists have become increasingly skilled at interpreting them and constructing ever more detailed pictures of the Earth's past.

Organizing and Presenting the Case

There are two important tools that geologists use to portray the history of the Earth: the **geologic time scale** and **paleogeographic maps**.

The geologic time scale is 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 typically divided into four principle divisions.

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

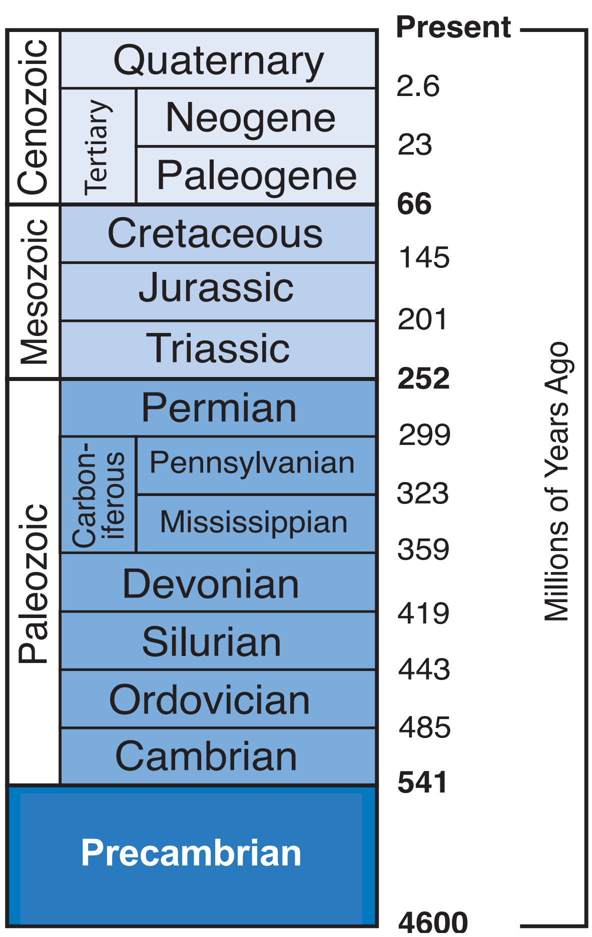


Figure 1.2: The Geologic Time Scale (spacing of units not to scale).

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

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

The last and current division, the **Cenozoic**, extends from the **extinction** of the dinosaurs, nearly 66 million years ago, to the present. With the demise of the dinosaurs, mammals became dominant and, subsequently,

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

paleogeographic maps • *maps that portray the estimated ancient geography of the Earth.*

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.*

Pangaea • *supercontinent, meaning "all Earth," which formed over 250 million years ago and lasted for almost 100 million years.*

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

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

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

Geologic Time

How did geologists come up with the timeline for the history of the Earth? Over the course of many years and through the combined work of geologists around the world, the geologic time scale was developed (*Figure 1.2*). 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.

more diverse and highly developed. We humans don'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!

Paleogeographic maps portray the probable ancient geography of the Earth. They often appear in sequences designed to show the geologic development of a region. The process of constructing these maps is based on first looking at the rocks and landscapes to develop the geologic history of a specific area. Then, by comparing the histories of neighboring areas, geologists can determine how much of an area experienced a similar history. Because an enormous amount of data is required to construct even a small paleogeographic map, completed sections often show only general details and are frequently subject to considerable debate. Maps of the distant past are particularly difficult to piece together since the important clues are so fragmented.

Geologic History

Reconstructing

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

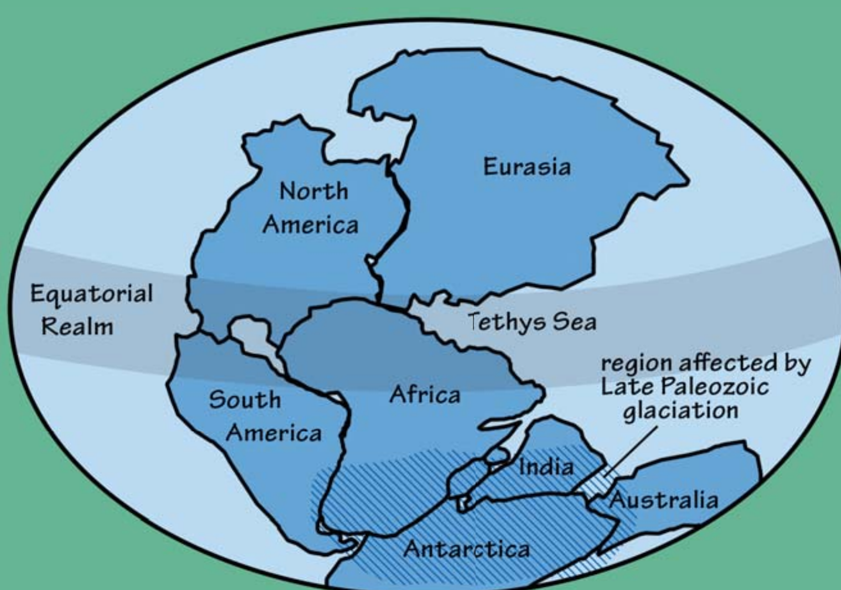
plate tectonics • *the way by which the plates of the Earth's crust move and interact with one another at their boundaries.*

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.*

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, slowly moving toward their present-day positions over the following 150 million years.



Pangaea during the late Paleozoic era

The Western States:
The Big Picture

The geologic history of the Western United States is a saga of moving continents and climate change that produced shifting coastlines, rising and eroding mountain chains, and ever-changing ecosystems. Though much of it is geologically young, its rocks and landscapes record over half a billion years of Earth history. Furthermore, it is a place where nearly all the processes that shaped it are still visible at some level.

The Western States are divided up into seven different geologic provinces (*Figure 1.3*): The Basin and Range (1), Columbia Plateau (2), Northern Rocky Mountains (3), Cascade-Sierra Mountains (4), Pacific Border (5), Alaska (6), and Hawai'i (7).

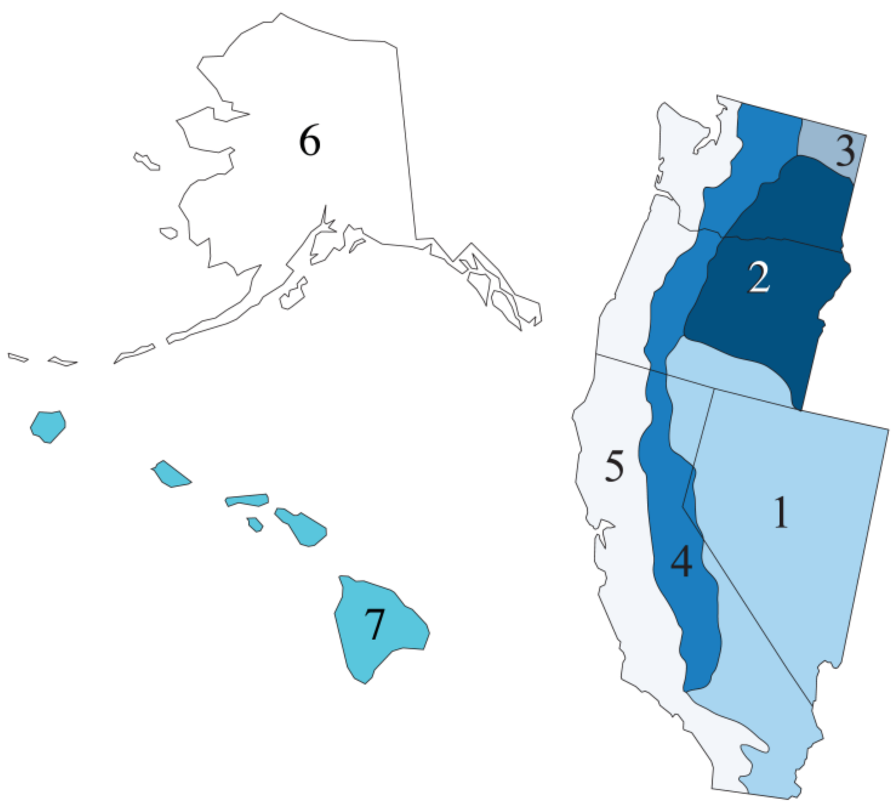


Figure 1.3: Geologic regions of the West.

With the exception of Hawai'i (which will be handled separately at the end of this chapter), the Western States are all on **active plate margins** (*Figure 1.4*). In the case of Alaska, Oregon, and Washington, thin oceanic **crust** is colliding with the thicker continental crust of the North American plate. As it does so, sediment, sedimentary rock, and even bits of the oceanic crust itself are scraped off the descending crustal plate and pushed onto the overlying

Big Picture

active plate margin • *the boundary between two plates of the Earth's crust that are colliding, pulling apart, or moving past each other.*

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

Big Picture

plate. Just as a rug develops folds when pushed from the side, these rocks are wrinkled up into mountains like the Coast Range of Oregon and the Olympic Mountains of Washington in a process known as **accretion** (*Figure 1.5*).

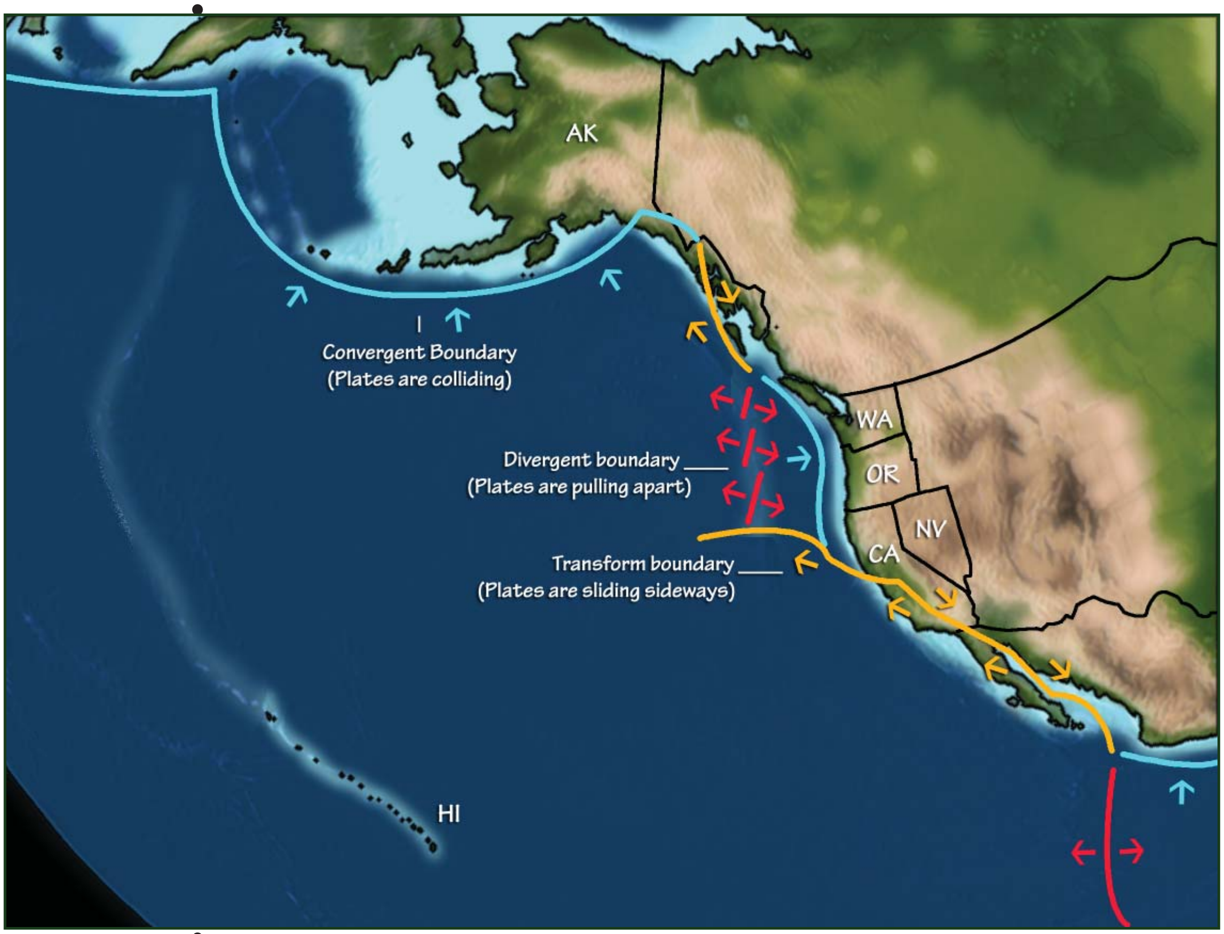


Figure 1.4: Active plate margins of western North America. (See TFG website for full-color version.)

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.*

transform boundary • *an active plate boundary in which the crustal plates move sideways past one another.*

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

Farther inland, as the oceanic crust descends deep into the upper **mantle**, the rock above the descending crust melts and forms a line of volcanoes on the surface. This process, called **subduction,** is responsible for creating the Cascades of Oregon and Washington as well as the Aleutian Islands and Wrangell Mountains of southern Alaska. Though they are also located on an active margin, the crustal plates in California are moving sideways past one another rather than colliding. This **transform boundary**, which includes the San Andreas Fault, is in reality a wide zone of north-south oriented **faults** with frequent and destructive earthquakes. Although **volcanic** activity is rare in this area, long, straight mountain ranges and troughs, such as Bodega Bay in northern California, are formed as blocks of crust are wrenched sideways.

In addition to tectonic activity, climate is a major player in the West's geologic history. The past two million years, a time span called the **Quaternary**, have

Big picture

been a time of radical shifts in the Earth's climate. Though we are currently in a period of rising global temperatures, much of the Quaternary has been characterized by **ice ages** in which glaciers repeatedly expanded to cover the northern half of North America, Europe, and Asia. During the most recent

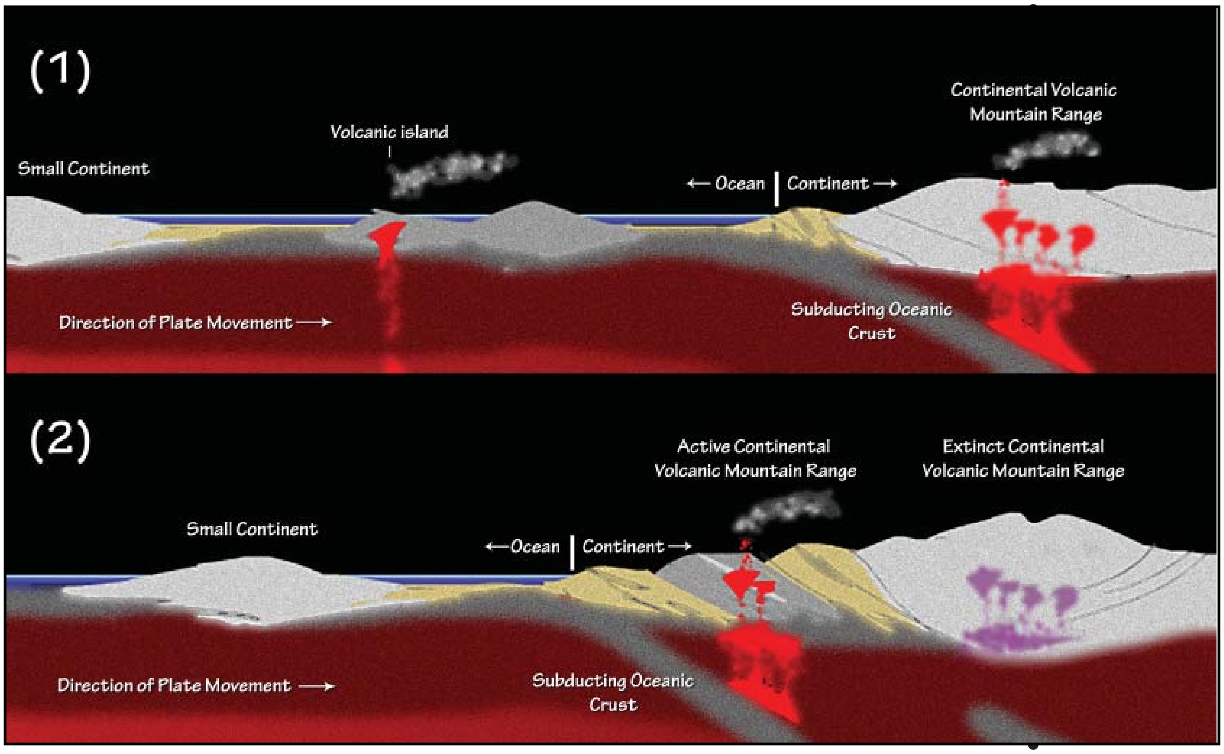


Figure 1.5: An idealized cross section of an active margin where an island arc (1) is added to the edge of a continent (2). (See TFG website for full-color version.)

glacial advance, approximately 20,000 years ago, portions of the **Cordilleran Ice Sheet** buried southern Alaska and northern Washington under a mile of ice, carving deep **fjords** and glacial valleys. This **ice sheet** deposited huge quantities of glacial sediment in low-lying areas such as Puget Sound and also carved rugged mountain landscapes (*Figure 1.6*). Farther to the south, what are now modest mountain glaciers grew to become **ice caps** covering entire mountain ranges such as the Sierra Nevada and the Blue Mountains of Oregon. Even Hawai'i, which is now ice-free, saw small glaciers on the summit of Mauna Kea, its highest peak.

See Chapter 6: Glaciers to learn more about how glaciers have sculpted Western landscapes.

During each ice age, sea level dropped as more and more seawater became locked up in glacial ice. As the oceans fell, coastlines moved farther out to sea. Later, as the climate warmed and sea level rose, the former coastal lands were flooded, drowning river valleys, glacial valleys, and coastal plains.

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.*

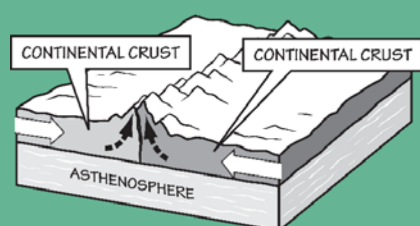
fjord • *a deep, narrow, glacially scoured valley that is flooded by ocean water.*

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

Big Picture

Continental and Oceanic Crust

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



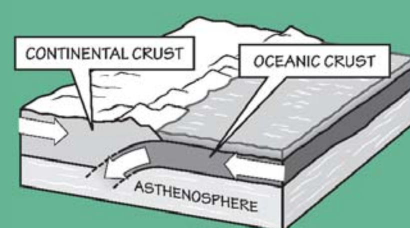


Figure 1.6: Continental glaciers originating in Canada spread across North America, including Alaska and Washington, during the Quaternary period.

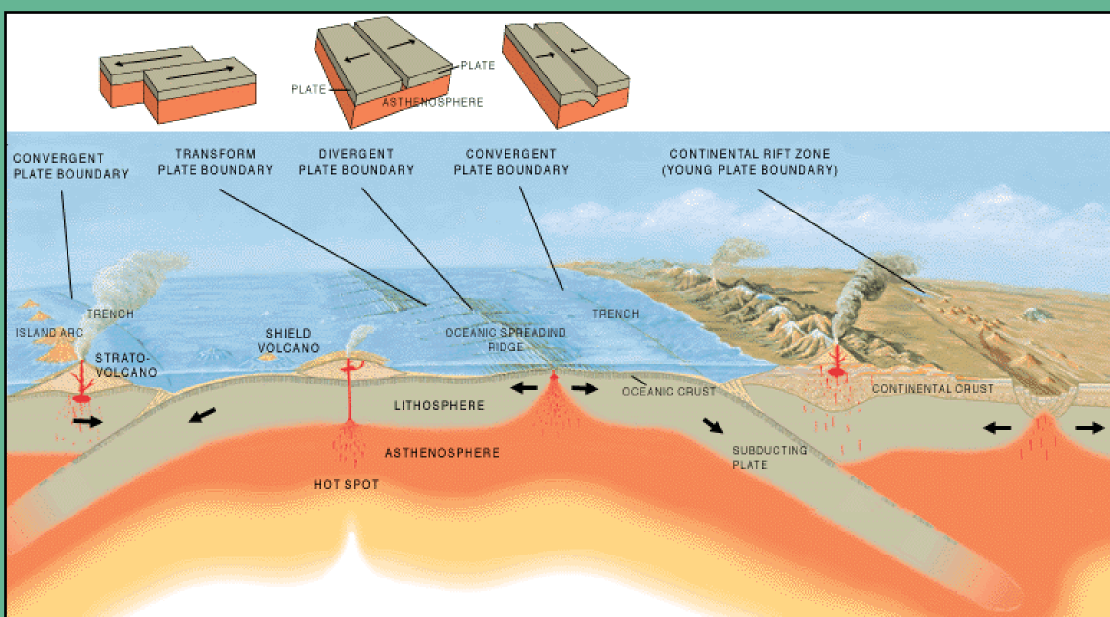
Geologic History 1

Big Picture

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.)

1 Geologic History

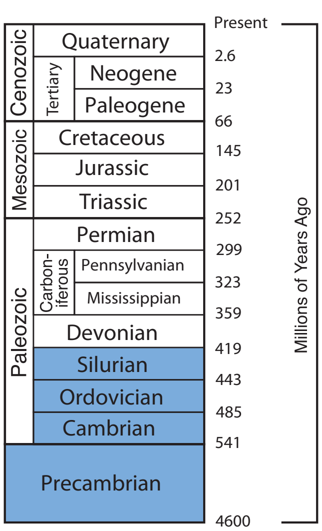
Paleozoic

passive margin *• a tectonically quiet continental edge where crustal collision or rifting is not occurring.*

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

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

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



The Paleozoic and Precambrian:
Looking to the Distant Past

Over 600 million years ago, the entirety of what is now the Western States was either underwater or had not yet become part of North America. Seafloor sedimentary rocks found in the Klamath Mountains, the Sierra Nevada, the Basin and Range, and the central mountains of Alaska indicate that the entire region was underwater during the early Paleozoic and that the coastline of ancient North America was somewhere to the east, near Arizona, Utah, and Idaho (*Figure 1.7*).

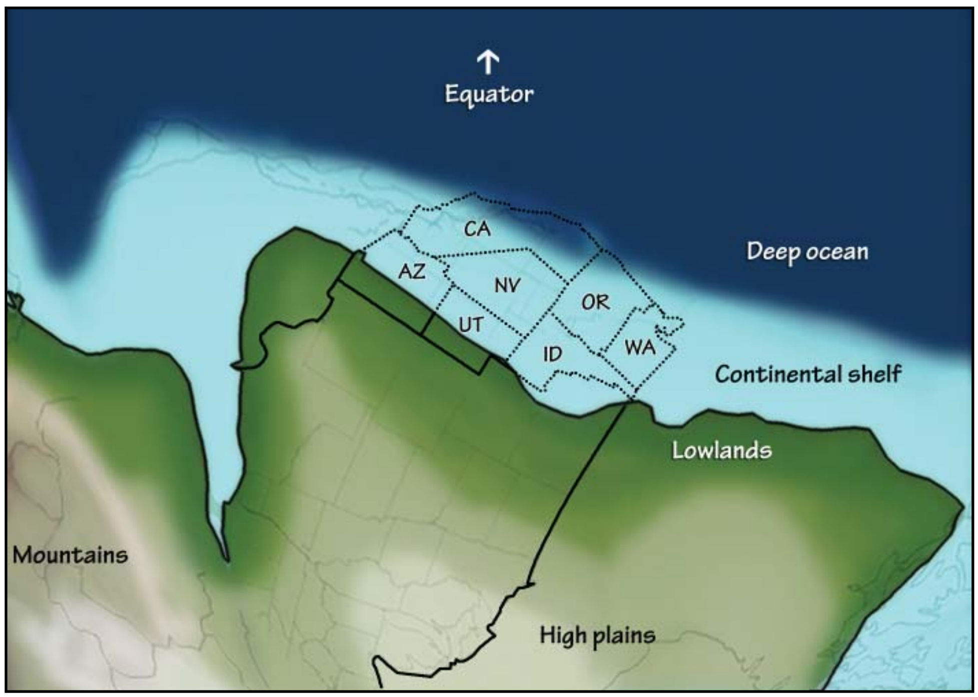


Figure 1.7: The Western United States at 600 million years ago. The entire region is located in the southern hemisphere. (See TFG website for full-color version.)

In the early Paleozoic, about 500 million years ago, what is now the west coast of North America was a **passive margin**—little or no volcanic activity, earthquakes, large mountain ranges, or plate boundaries were found in the Western States at that time. As the Earth's continents began moving towards one another to eventually form the supercontinent Pangaea, the Western States became an active subduction zone, which began **uplifting** new mountains. Subduction also led to accretion, adding **volcanic islands** and seafloor sediment to the edge of the continent. One such episode created much of the present-day **basement rock** in Nevada and southern Oregon. Other periods of accretion created the Okanogan Highlands and sections of Alaska's central mountains. By 400 million years ago, large mountain ranges had risen in parts of Alaska and the Basin and Range of Nevada and Oregon. As accretion continued over time, the coastline moved farther seaward. The landmass also began to rotate, moving the North American plate into a more modern orientation.

The Mesozoic

For much of the Mesozoic, large sections of the Western States were underwater. Around 300 million years ago, the Western States were part of the continental margin surrounding the supercontinent Pangaea. However, that changed once Pangaea began splitting apart 250 million years ago. As the supercontinent **rifted** apart, subduction, volcanism, and accretion in the Western States accelerated, adding more land to the continental margin (*Figure 1.8*). Land did not build up continuously—accretion in these states delivered packages of rock known as accreted or exotic **terranes**. Each terrane consists of sedimentary rock made from former seafloor sediment, slabs of oceanic crust (**ophiolites,** *Figure 1.9*), the remains of volcanic islands, and, in some instances, shards of continental crust. The terrane is pressed against the edge of the continent in a process sometimes described as "docking."

Figure 1.8: The Western United States at 135 million years ago. The terrane contains an island arc in the process of docking with the Western States. This arc will eventually become part of Alaska and British Columbia. (See TFG website for full-color version.)

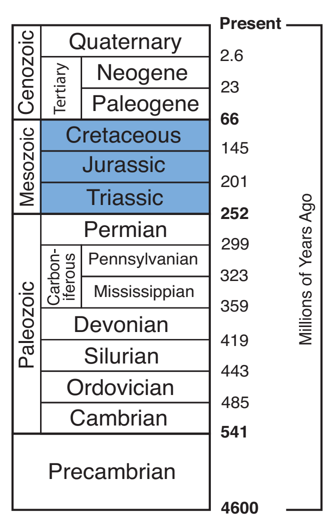
In general, accretion was accompanied by volcanism, which resulted in several major **orogenies** (episodes of mountain building). During the Mesozoic, three such episodes were particularly important in the development of western North

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

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

ophiolite • *a section of the Earth's oceanic crust and the underlying upper mantle that has been uplifted and exposed above sea level and often thrust onto continental crustal rocks.*

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



Mesozoic

__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.

__bathymetry__ • the topography of an underwater landscape.

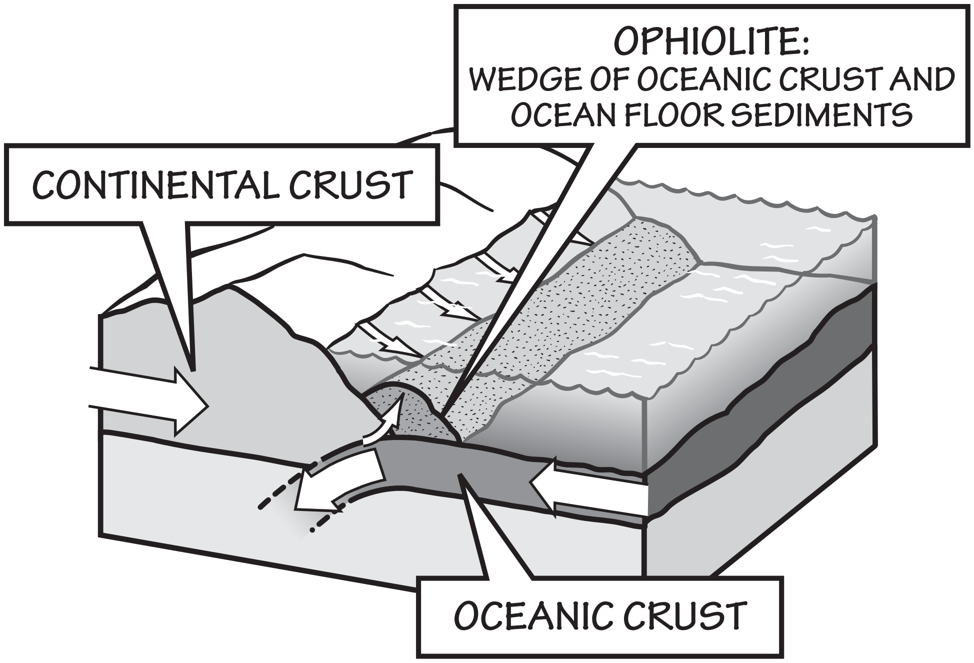
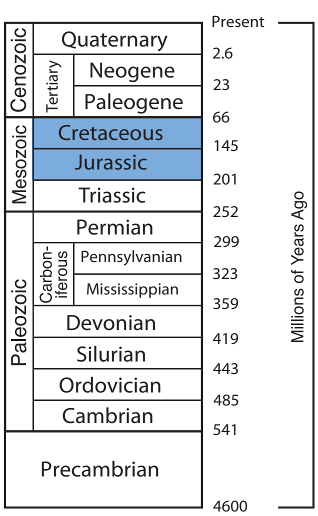


Figure 1.9: Formation of an ophiolite.

America. The Nevadan, Siever, and **Laramide orogenies** took place between 180 and 50 million years ago. The remnants of these mountain-building events can still be seen as bodies of **intrusive rock** embedded in the West's present-day ranges.

While the addition of land to the continental margin was a general theme throughout the Mesozoic, it was by no means a consistent process. Sedimentary rock found in the Midwest indicates that shallow seas episodically inundated the interior of North America, turning major parts of the Western States into a broad isthmus (*Figures 1.10* and *1.11*). The exact reasons for this periodic flooding are not known, but there are two possibilities: sea level rise or a change in the elevation of the continental plain. Although sea level change is often associated with climate change, it can also be driven by changes in the **bathymetry** of the ocean floor. Increased volcanic activity at mid-ocean ridges could have increased the size of the ridges, displacing seawater and causing the sea level to rise. Additionally, as Pangaea began to drift apart, the crust underlying the Interior Plains most likely stretched, causing it to thin and making the land surface drop below sea level.



Mesozoic

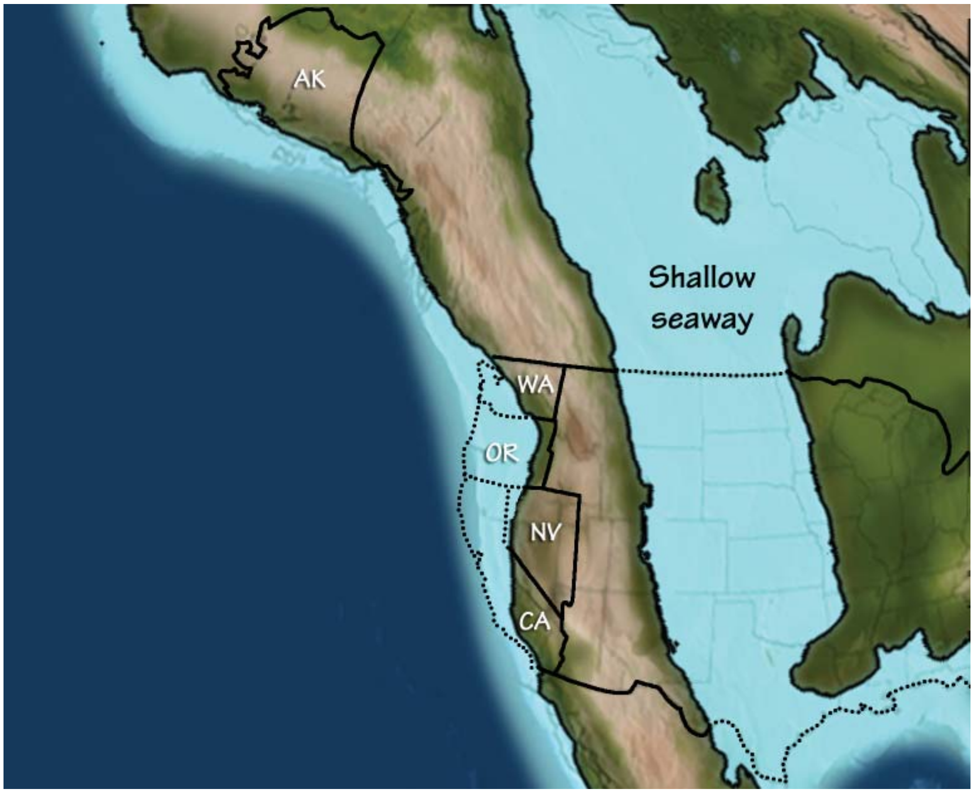


Figure 1.10: North America 90 million years ago. During this time, a shallow seaway covered much of central North America.

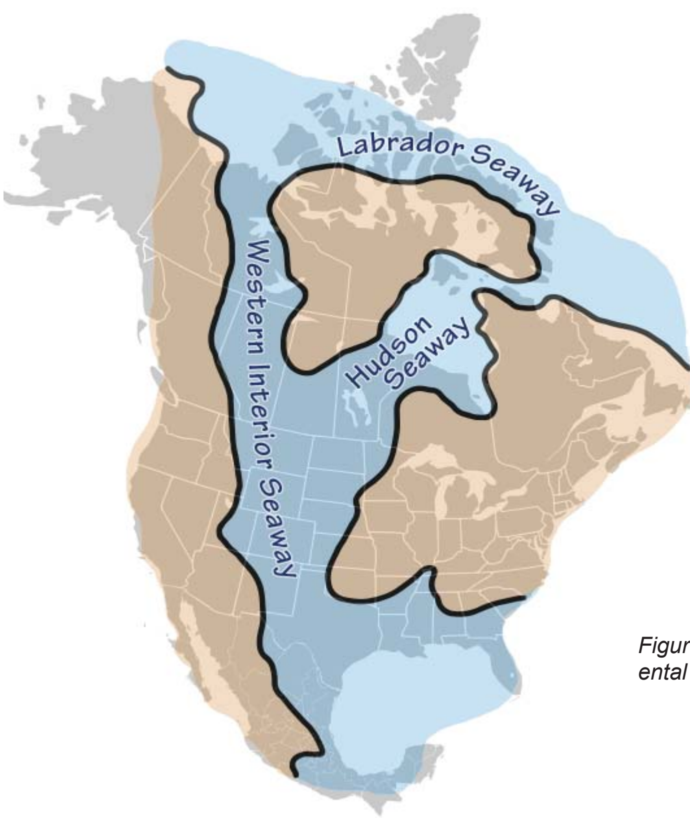
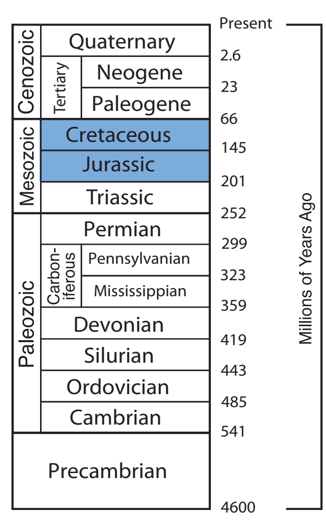


Figure 1.11: Cretaceous continental seas over North America.



1 Geologic History

Cenozoic

convergent boundary • *an active plate boundary where two tectonic plates are colliding with one another.*

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

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

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.*

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

Era	Period		Millions of Years Ago (base)
			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**

The Cenozoic

The geography of the Western States became progressively more recognizable during the Cenozoic. Around 66 million years ago, the entire west coast of North America was a **convergent boundary**, where subduction created volcanic mountain ranges. Although some of the volcanic ranges from this time span remain active today, all of the earliest ranges have ceased to erupt, often being replaced by newer ranges farther seaward (see *Figure 1.5*). As more land accreted to the edge of the continent, subduction became increasingly more difficult, until it finally stopped, forming a new convergent boundary farther seaward. When this happened, the source of **magma** for the old volcanic arcs was cut off, and a new arc formed closer to the new boundary. This accretion caused the western edge of North America to expand outward, towards its present configuration (*Figure 1.12*).

A major change in the plate boundary along California also contributed to the extinction of the older Cenozoic volcanic arcs. Beginning about 30 million years ago, a mid-ocean ridge called the East Pacific Rise collided with the North American continent. As this ridge subducted, the plate boundary adjacent to California gradually changed, becoming a transform or sideways-moving boundary. As a result, subduction ceased, as did the last of the volcanic activity in what we now know as the Sierra Nevada. An important byproduct of this change in plate motion was that Nevada and southern Oregon began to pull apart, forming the collection of north-south trending mountains and valleys known as the Basin and Range.

Much of the present-day Sierra Nevada is a large exposure of **granite** called a **batholith**—the remains of the magma chambers that previously fueled volcanic mountain ranges that are exposed once the ancestral ranges have been eroded away. In the case of the Sierra Nevada, the stretching of the Basin and Range uplifted the solidified magma chambers of the ancestral range as rivers, **landslides**, and glaciers eroded away the overlying rock. The continued erosion of this rock is the source of much of the **gold**-laden **gravel** found in the rivers of California's Central Valley.

The present-day Cascade Range, which extends all the way from southern British Columbia to northern California, is made up of a series of volcanoes that have built up a large platform of volcanic debris. These volcanoes, the Cascade Volcanic Arc, began to arise 36 million years ago due to the subduction of the Pacific plate beneath North America. However, the major volcanic peaks that make up what we call the High Cascades today formed more recently, within the **Pleistocene**. As long as subduction continues, the Cascades will remain volcanically active, although there is evidence that the rate of subduction is slowing, and as a result, volcanism in the Cascades will eventually cease.

Farther north, accretion and volcanism continued to add more land to Alaska's coastline. As mountain ranges rose and eroded, sediment washed from the land, mixed with the remains of microscopic marine life, and settled onto the continental shelf fringing the state. As this organic material was buried by even

Cenozoic

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

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

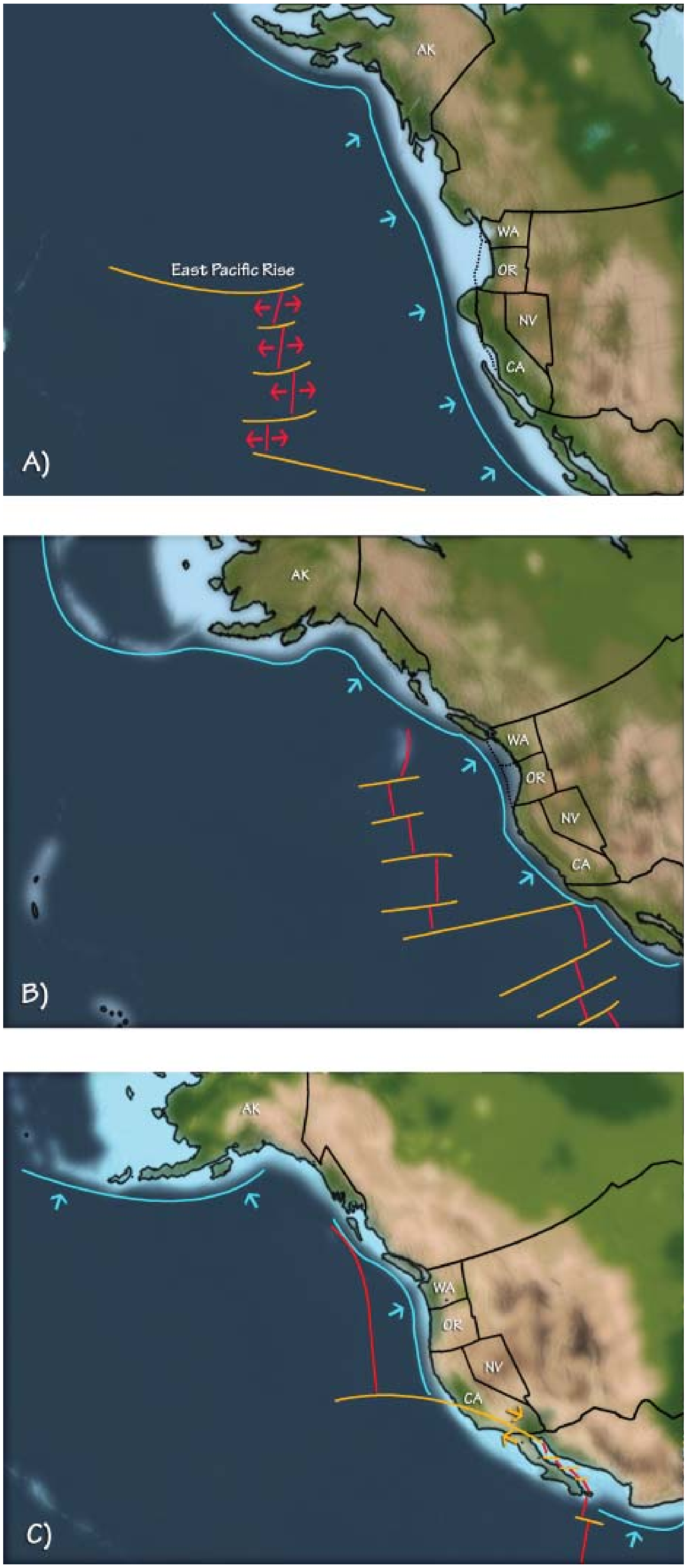
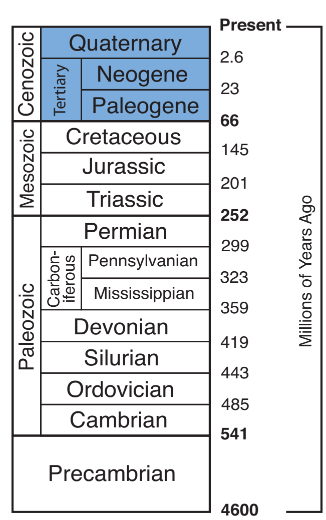


Figure 1.12: (A) North America 50 million years ago—the entire west coast of North America is a subduction zone. (B) North America 30 million years ago—the East Pacific Rise is approaching the subduction zone. (C) North America 5 million years ago—by this time California is a transform boundary and the Basin and Range begins stretching.
(See TFG website for full-color version.)



more sediment, it was slowly converted into the large **petroleum** deposits on which much of Alaska's economy now relies.

Fossils found in Alaska tell us that during parts of the Cenozoic, its climate was temperate, perhaps even subtropical. Although plate motion can account for some of this change—North America has been slowly moving north throughout the Cenozoic—other important factors also played a role in Alaska's changing climate history. The majority of the Cenozoic was characterized by **greenhouse conditions**, during which sea levels are generally higher and glaciers diminish. During periods of changing global climate, polar areas tend to see a greater shift in climate than do areas close to the equator. During a shift to greenhouse conditions, tropical climate zones could have moved into areas that are now temperate or even subpolar.

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

greenhouse conditions • *time periods when atmospheric greenhouse gas concnetrations are high and global temperatures are elevated.*

Geologic History of Hawai'i

Hawai'i is located thousands of kilometers from the nearest plate boundary, but it is volcanically active and geologically very young. The oceanic crust on which the Hawaiian Islands reside is nearly 90 million years old, yet the oldest of these islands was formed a mere 5 million years ago. In fact, the youngest is less than a half million years old. The Hawaiian Islands are the surface expression of a mantle **hot spot**—a place where a large slab of crust rides over the top of a rising plume of hot rock in the underlying mantle. The Hawaiian hot spot has its origin deep within the Earth, near the core-mantle boundary, where an area of anomalously high temperature creates a **thermal plume**: a zone of solid mantle material that moves slowly upward toward the surface. Thermal stress drives the motion of the plume; the hotter material rises because it is less dense and therefore more buoyant than its surroundings. As magma created by the plume erupts onto the seafloor, repeated **lava** flows build a massive volcano that eventually reaches the surface of the ocean and becomes a volcanic island.

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

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

The Hawaiian hot spot lies beneath the Pacific plate, where it maintains a relatively fixed position within the mantle. The overlying Pacific plate moves to the northwest at the tectonically rapid rate of 8.5 centimeters per year (3 inches per year). The northwest motion of the plate eventually carries each island away from the hot spot, creating a chain of volcanic islands whose age increases with increasing distance from the hot spot (*Figure 1.13*). The Hawaiian Islands are the southernmost part of a string of islands and undersea mountains stretching from the middle of the North Pacific to the Aleutian Islands of Alaska. The Emperor Seamounts, the northernmost end of these undersea mountains, are the oldest. The youngest islands are currently over the hotspot, and still volcanically active, whereas the older, extinct islands reveal the track of oceanic crust moving over the hotspot.

The Hawaiian hot spot has been active for at least 80 million years, based on the age of the oldest island, Meiji Seamount, now far to the north near the Aleutian trench. The hot spot remains active today, erupting new lava at Kīlauea volcano and the still-submerged Lō'ihi seamount—the youngest volcano in the chain.

As each volcano forms above the hot spot and moves away, it undergoes a sequence of constructive and then destructive geological processes. These processes, detailed below, have created a chain of volcanoes that extend 5800 kilometers (3600 miles) from the Hawaiian Islands to the Emperor Seamounts.

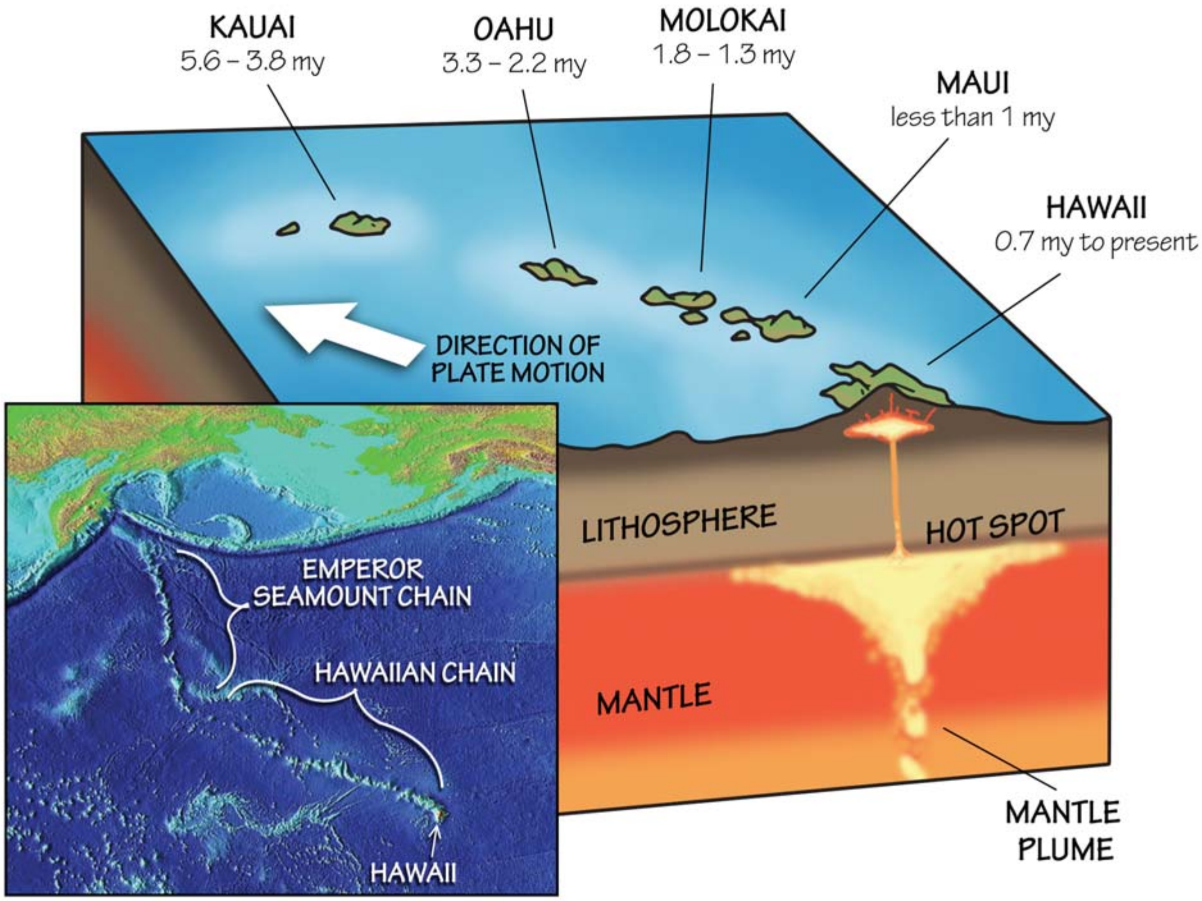


Figure 1.13: Interaction of the Pacific plate and the Hawaiian hot spot produces a chain of volcanic islands that increase in age with increasing distance from the hot spot. The Emperor Seamounts are the continuation of the Hawaiian Islands, and formed while the plate was moving directly north. (See TFG website for full-color version.)

Lifecycle of Hawaiian Volcanoes

For more than 50 years, geologists have recognized that Hawaiian volcanoes exhibit a relatively consistent set of features reflecting events in the island's lifecycle. These events are typically divided into nine stages, although (as with all natural processes) there may be overlap and gradation between them. Over time, the volcanoes exhibit changes in morphology and behavior, as well as chemical changes in the lavas they erupt. Early lavas are derived from near the edge of the thermal plume, a magmatic source that is chemically different from lavas derived from the center of the plume.

1 Geologic History

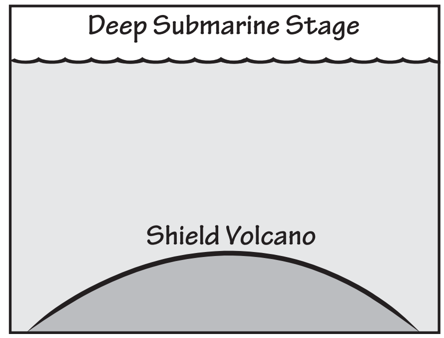
Hawai‘i

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

silica • *a chemical compound also known as silicon dioxide (SiO2).*

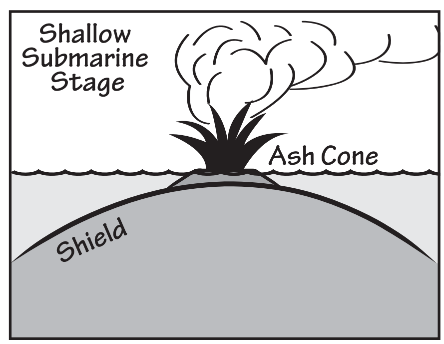
As one of the best-developed examples of an oceanic hot spot **system**, the Hawaiian Islands provide a unique window into geologic processes—a time machine through which we can look either forward or backward at the creation and evolution of the islands.

(1) Deep Submarine Stage



While not all Hawaiian volcanoes go through every stage of development described here, we assume that all volcanoes begin with a deep submarine stage, where magma erupts through the seafloor and solidifies. During the deep submarine stage of volcano formation, the magma is made up of **alkalic basalt**, which is derived from the edge of the thermal plume. Alkalic basalts contain around 47% **silicates**, and are relatively high in sodium and potassium. On the seafloor, they erupt as dense lava flows form the initial volcanic shield. Lō‘ihi, currently forming off the south coast of Hawai‘i Island, is an example of the deep submarine stage.

(2) Shallow Submarine/Early Shield Stage

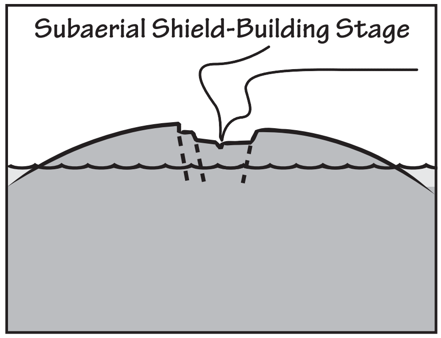


After layers of early dense lava flows have accumulated, they create a broad submarine shield. When lavas erupt on the deep sea floor, the pressure of the overlying water column keeps gases like oxygen, carbon dioxide, and hydrogen sulfide dissolved in the magma. However, as the growing volcanic shield approaches the ocean surface, the gases begin to form bubbles in the magma, or **exsolve**. These bubbles can be preserved in the chilled lava as **vesicles**. The exsolving gasses can also contribute to a more violent style of eruption. When the summit of the growing volcano approaches the sea surface, the interaction of seawater with the erupting magma can be quite spectacular, characterized by jets of steam, shattered rock, and vaporized lava. No eruptions of this type occur in modern Hawai‘i, although from similar eruptions observed in Iceland and elsewhere in the Pacific, we hypothesize that they must have been part of Hawai‘i's past.

(3) Subaerial Shield-Building Stage

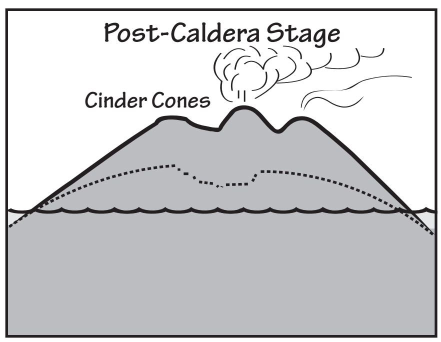
The submarine and subaerial shield-building stages are the main constructive phases of Hawaiian volcanism. By the time the volcano has emerged above sea level, the lavas have undergone a change in chemistry. Movement over the center of the hot spot produces lavas with fewer alkali elements and more silicates, creating **tholeiitic basalt**, the second major type of Hawaiian lava, This highly fluid lava erupts voluminously over 0.5–1 million years, continuing to build a classic shield-shaped volcano. These volcanoes erupt from shallow

magma reservoirs located a few kilometers beneath their summits, and also from radial rift zones that channel magma lower onto the flanks of the active volcano. High-volume eruptions that rapidly empty the magma reservoir often lead to summit collapse and the formation of a volcanic **caldera**: the large steep-walled crater that crowns many **shield volcanoes**. While a summit caldera is characteristic of the shield-building stage, some volcanoes do not appear to have one (e.g. Hualālai, West Molokaʻi), and the well-developed summit caldera on Lōʻihi shows that caldera formation may also occur earlier in the life cycle of a volcano. Mauna Loa and Kīlauea, which both have large summit calderas, are examples of volcanoes in the subaerial shield-building stage.



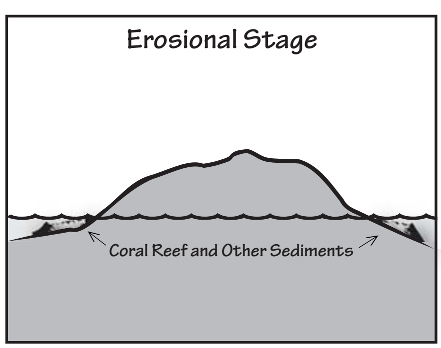
(4) Post-Caldera Stage

Most summit calderas are eventually filled and buried by continuing eruptions of tholeiitic lavas. As the volcano moves away from the center of the hot spot, the eruptions change composition again, returning to alkalic basalt. These later eruptions cap the older shield, and their slightly more explosive nature gives rise to lava fountains that produce **cinder** cones on the summits and flanks of the volcanoes. These cones give older volcanoes a bumpy profile, in contrast to the smooth, younger shield. Alkalic cap lavas often contain numerous **phenocrysts**: early-formed crystals that are entrained in the magma as it erupts. The growth of crystals changes the composition of the remaining liquid magma, and late-stage eruptions can sometimes produce unusual lavas that are so silica-rich they are no longer called **basalts**. Mauna Kea and Hualālai are in the post-caldera stage, and the Puʻu Waʻawaʻa cinder cone on Hualālai's north flank produces high-silica eruptions called **trachyte**.



(5) Erosional Stage

While the first four stages in the volcanic life cycle are predominantly constructional, it is important to recognize that erosional processes begin as soon as a volcano rises above the sea floor. Submarine landslides that drape the flanks of Lōʻihi, and prominent **fault scarps** (*pali* in Hawaiian) on Kīlauea and Mauna Loa are evidence that even young volcanoes begin to experience gravitational collapse. Once eruptive



Hawaiʻi

shield volcano *• a volcano with a low profile and gradual slope, so named for its likeness to the profile of an ancient warrior's shield.*

cinder *• a type of pyroclastic particle in the form of gas-rich lava droplets that cool as they fall.*

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

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 topgraphy.*

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

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

tsunami *• a series of ocean waves that are generated by sudden displacement of water, usually caused by an earthquake, landslide, or volcanic explosions.*

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.*

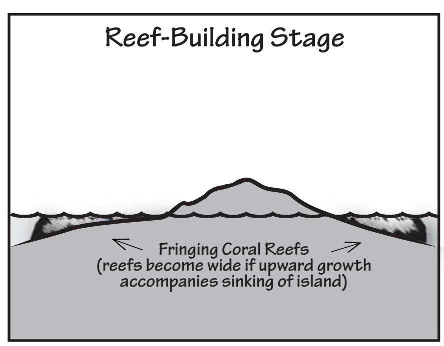
leeward *• downwind; facing away from the wind.*

Figure 1.14: Sunrise view of Hawai‘i Island from the summit of Haleakalā, Maui. Four of Hawai‘i’s five subaerial volcanoes are visible. On the leftmost side is Mauna Kea, in the post-caldera stage, and smaller, eroded Kohala peeks through the clouds directly in front. Mauna Loa, a giant shield volcano is on the right, and on its flank is smaller Hualālai, also a post-caldera volcano. Although the topography appears gentle and subdued, both Mauna Kea and Mauna Loa rise more than 4,000 meters (13,100 feet) above sea level.

activity slows, erosion and **weathering** become dominant forces in shaping the evolution of the islands. **Soils** form, and streams—absent on very young volcanoes—begin to incise the surface of the shield. Hawaiian volcanoes are also subject to episodic, catastrophic, erosional events, when mega-landslides rip apart the unsupported seaward flanks of the islands. These landslides scatter enormous blocks of material for hundreds of kilometers (miles) across the seafloor and generate **tsunamis** with local run-up heights up to 300 meters (980 feet) above sea level. Kohala and Haleakalā are examples of erosional stage volcanoes.

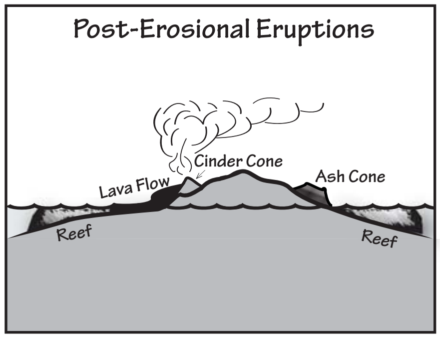
(6) Reef-Building Stage

Hawai‘i’s tropical latitude permits the growth of **reef**-building corals. The reefs are found principally on the **leeward** side of each island where there is little river runoff and thus very clear water. Many of these corals live at or near sea level, making the reefs excellent indicators of sea level rise and fall. As the islands age, the coral reefs expand, eventually encircling each island. Volcanoes as

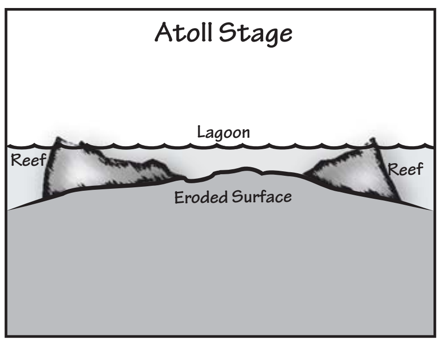


young as Mauna Loa are host to incipient reefs, while the older islands of O‘ahu and Kaua‘i have extensive, well-developed fringing reefs.

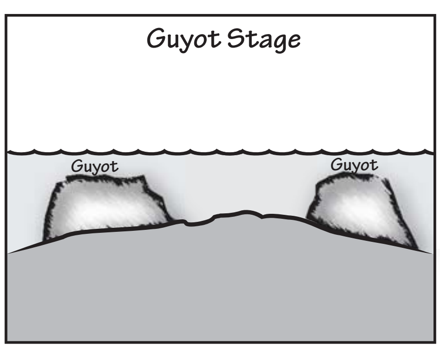
(7) Rejuvenated Post-Erosional Eruptions
After a long period of quiescence, most Hawaiian volcanoes experience a final episode of eruptive activity. This rejuvenated stage typically produces cinder cones and associated **volcanic ash** deposits. Many of the cinder cones are located near the shoreline. One hypothesis for the origin of these late-stage eruptions is that mass loss due to erosion decompresses the magma below, triggering further melting and eruption. Rejuvenated volcanism is found on all islands except Hawai‘i.



(8) Atoll Stage
As the volcanoes drift farther from their hot spot origin, they cool and eventually become extinct. The lithosphere on which the islands sit also cools, becoming denser. This leads to a gradual subsidence of the volcanic ridge, causing the islands to slowly sink. As subsidence drags the islands down from below, erosion by waves, streams, and **mass wasting** works to diminish the islands from above. Fringing reefs expand to encircle the eroded volcano. Ultimately, the volcanic edifice is eroded to sea level and only the circular reef remains, forming an **atoll**. Many of the Northwestern Hawaiian Islands are in the atoll stage.



(9) Guyot Stage
Continued subsidence pulls even the coral atolls below sea level. Eventually, the living coral reefs literally “drown,” becoming flat-topped seamounts called **guyots**. The Emperor Seamounts exemplify this final stage in the life cycle of Hawaiian volcanoes. Ultimately, each of the Emperor Seamount and Hawaiian islands will return to the mantle via subduction at an active plate boundary, millions of years in the future.



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

mass wasting *• a process in which soil and rock move down a slope in a large mass.*

atoll *• a circular or horseshoe-shaped coral reef, surrounded by deep water and enclosing a shallow lagoon.*

Hot Spot Volcanoes and Hawaiian Tradition

Some changes that occur as hot spot volcanoes evolve through their life cycle—for example, the transition from alkalic to tholeiitic lavas—are evident only by conducting chemical tests. But many other changes are visible to the naked eye. Smooth volcanic shields are dissected by erosion, large canyons are carved through the landscape, and the size of the islands decreases with increasing age. The original inhabitants of the Hawaiian Islands were acute observers of nature. Their survival in the isolated islands depended on their understanding of natural phenomena, and their cosmology reflected what they saw in the world around them. The ancient Hawaiian story of Pele, the goddess of fire and volcanoes, describes her arrival on the islands of Kauaʻi and Niʻihau: the oldest of the eight main Hawaiian Islands. Pele found these islands to be unsuitable for her fiery temperament, as they were dominated by her sibling rival, Nāmaka, goddess of the ocean. Pele traveled to Oʻahu, the next youngest island, but here too she could not escape the influence of her sister. Pele moved from island to island, to Molokaʻi, Lānaʻi, and on to Maui, where she thought she might be safe. But she was forced to flee even from the giant volcano Haleakalā, coming at last to Hawaiʻi Island and Kīlauea. On Kīlauea she searched the earth with her digging stick and found a fire that Nāmaka could not extinguish. Here, within the youngest volcano, Pele made her home. This oral tradition accurately reflects the age progression of Hawaiian volcanoes, passing along the islands' geologic history through a colorful narrative.

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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.)

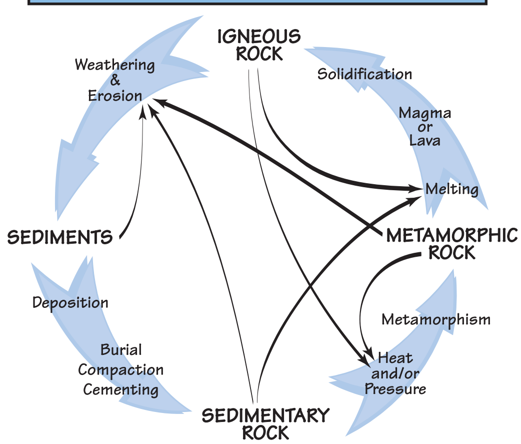
Chapter 2: Rocks of the Western US

Approximately 200 million years ago, the western edge of what is now North America contained only Nevada and a small sliver of Washington State. As the supercontinent **Pangaea** split up, the western edge of the continent became an **active plate boundary**. The Western States were built by violent eruptions, **subductions**, collisions, and accretions as well as by the processes of **erosion**, deposition, and **lithification**. As a result, there are a wide variety of rocks to be found throughout the Western US (*Figure 2.1*).

Igneous Rocks of the West

rhyolite	granite
obsidian	tuff
pumice	diorite
andesite	dacite
basalt	gabbro
peridotite	pyroclastic rocks

Sediments of the West
(not consolidated into rocks)
gravel
sand
silt
clay



Metamorphic Rocks of the West
schist
slate
gneiss
phyllite
quartzite
marble
serpentine

Sedimentary Rocks of the West

conglomerate	sandstone
greywacke	siltstone
shale	limestone
travertine	tufa
gypsum	chert
halite (rock salt)	

Figure 2.1: The rock cycle.

Pangaea • *supercontinent, meaning "all Earth," which formed over 250 million years ago and lasted for almost 100 million years.*

active plate boundary • *the boundary between two plates of the Earth's crust that are colliding, pulling apart, or moving past each other.*

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

erosion • *the transport of weathered materials.*

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

CHAPTER AUTHORS

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2 Rocks

Review

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

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

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

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

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	--

As rocks at the Earth's surface erode and **weather**, the sediment that forms can be compacted and **cemented** into **sedimentary rock**. Generally, these sediments are transported by **wind**, water, or ice to a depositional environment such as a lakebed or ocean floor; here they build up, burying and compacting

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

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 springs, playas (dry lake beds), drying seas
gypsum	rock gypsum	playas, drying seas
halite	rock salt	playas, drying seas

lower layers. As water permeates the sediment, dissolved minerals may precipitate out, filling the spaces between particles and cementing them together. Sedimentary rocks can also **accrete** from fragments of the shells or skeletal material of marine organisms such as clams and coral.

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 recrystallize and realign. The pressure to transform a rock may come from burial by sediment, or from **compression** due to plate movements, while the heat may be from very deep burial or from contact with magma.

Review

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.*

heat • *the transfer of energy 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.*

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.*

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

2 Rocks

Review

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

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.*

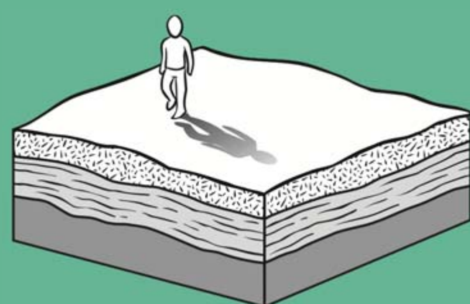
schist • *a medium grade metamorphic rock with sheet-like crystals flattened in one plane.*

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

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

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 Basin and Range
Region 1

While the formation of the Basin and Range province is a recent event that began only 30 million years ago, the bedrock that makes up the up-thrust ranges and down-dropped basins is very old. Since its formation, the bedrock of the basins has been covered by young deposits such as loose sediment washed down from the mountains and **evaporite** deposits from dried- out lakes. The ranges, however, expose rocks whose ages span from **Precambrian** to **Cenozoic**. Many of the sedimentary rock layers exposed in the mountains of the Basin and Range are the same as the rocks exposed by the Colorado River in the Grand Canyon, such as the Coconino Sandstone, Hermit Shale, and Kaibab Limestone, all of which are **Permian** in age.

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

The oldest rocks in the Basin and Range can be found in southern Nevada and the eastern Mojave Desert of California. They include **granite** as well as 1.7-billion-year-old metamorphic rocks such as **gneiss**, **schist**, and **marble**. The Pahrump group of rocks in Death Valley and nearby Nevada contains limestone in which **stromatolites** may be found.

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

An excellent place to see both **Paleozoic** and **Mesozoic** rock is near Las Vegas, Nevada. The dark gray limestone of the Bonanza King Formation formed in the **Cambrian** sea during a time period when the land that is now the Western States was still completely submerged—or not even yet part of North America. Today, the Paleozoic limestone has been thrust over the younger **Jurassic** Aztec Sandstone along a reverse **fault** that was created in the Mesozoic when the western edge of North America became a **convergent plate boundary**. The red Aztec Sandstone gives Red Rock Canyon its name (*Figure 2.2*). The **sand** that makes up this stone was deposited as sand dunes, which is evident from the **cross-bedded** layers that result from sand sliding down the side of a dune.

See Chapter 1: Geologic History for more details about the position and formation of the Western states during the Paleozoic.

Region 1

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

convergent boundary • *an active plate boundary where two tectonic plates are colliding with one another.*

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

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

2 Rocks

Region 1

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

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.*

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

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 the Fossils chapter in this Guide.

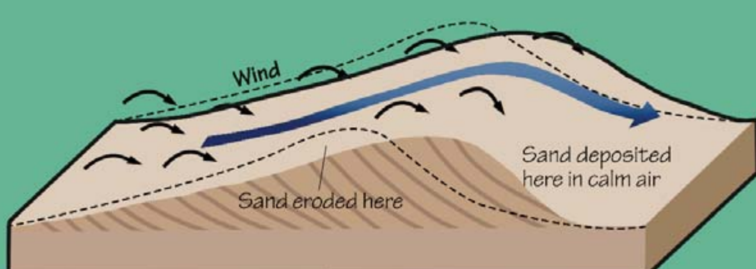
During the Mesozoic, subduction occurred along the western coast. The resulting volcanoes are long since gone, but the granite that formed beneath those volcanoes remains, especially in the western parts of the Basin and Range. The stacked towers of granitic boulders found in Joshua Tree National Park (*Figure 2.3*), the Granite Mountains of the eastern Mojave, and Granite Peak in Nevada are all examples of granitic **intrusions** that formed during the Mesozoic.

The formation of the San Andreas Fault around 30 million years ago ended the compression of southern California and Nevada, and a period of extension

Figure 2.2: The Aztec Sandstone in Nevada.

Cross-bedded Sand Dunes

Cross-bedded sand dunes form as air movement pushes sediment downwind, 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.



2 Rocks

Region 1

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

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

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

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

felsic • *igneous rocks with high silica content and low iron and magnesium content.*

Figure 2.3: "Giant Marbles" in Joshua Tree National Park.

began, leading to the wide-spread formation of basins and ranges. The extensional forces thinned the **crust**, allowing magma to reach the surface, which resulted in a period of intense volcanism This volcanic activity continues to the present day. In addition to creating the faults that make up the fault-block mountains of the Basin and Range, the tension resulted in a period of intense volcanism, which still continues today.

This volcanic activity gave rise to a wide variety of igneous materials. Hole in the Wall and Wild Horse Mesa of the eastern Mojave National Park provide evidence for an explosive eruption of **rhyolitic** ash, which created an ash-flow **tuff** (*Figure 2.4*). Ash-flow tuffs are the result of pyroclastic flows—explosions that contain pulverized rock and superheated gases, which can reach temperatures of up to 1000 °C (1830 °F). 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** in nature. High **silica** content makes the magma quite viscous, preventing gas bubbles from easily escaping, thus leading to pressure build-ups that are released by explosive eruptions. The ash flows from these violent explosions tend to hug the ground, eventually solidifying into tuffs. Tuffs and other pyroclastic materials are **vesicular** (porous) due to gases expanding within the material as it cools.

See Region 2: Rocks of the Columbia Plateau in this chapter for more details about columnar jointing.

The largest deposit of ash-flow tuff in the West is the Bishop Tuff from California's Long Valley Caldera eruption

Understanding Volcanism

Most volcanic eruptions occur along tectonic plate boundaries. At *divergent boundaries*, the mantle wells up where two plates pull apart, creating new crust. Mid-ocean ridges are the most common type of divergent boundary and are characterized by the eruption of bulbous pillow-shaped basalt lavas and hydrothermal fluids. Conversely, convergent plate boundaries destroy old lithosphere at subduction zones, where the ocean floor descends into the mantle. Volcanism here results from the subduction of seawater and seafloor sediments that descend into the mantle with the subducting slab, which lowers the melting temperature of mantle rocks enough to generate magma. Explosive eruptions characterize subduction zone volcanism and create arrays of cone-shaped stratovolcanoes that mark the position of the convergent boundary.

Volcanism can also occur at a hot spot, where superheated magma plumes well up from a point directly underneath the plate. Large shield volcanoes are produced as a direct result. The mechanics of hot spot volcanism are still largely unknown.

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.

760,000 years ago. The Bishop Tuff is pink in color, vesicular, and contains pieces of **pumice** (*Figure 2.5*). Along the Owens Gorge, just north of Bishop, California, the Bishop Tuff can be found in **columnar joints**.

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

pumice • *a pyroclastic rock that forms as frothing and sputtering magmatic foam cools and solidifies.*

divergent boundary • *an active plate boundary where two tectonic plates are pulling apart from one another, causing the mantle to well up at a rift.*

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

2 Rocks

Region 1

mafic • *igneous rocks that contain a group of dark-colored minerals, with relatively high concentrations of magnesium and iron.*

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

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

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

Figure 2.4: Hole in the Wall ash-flow tuff.

Figure 2.5: Bishop Tuff.

Not all volcanic rocks of the Basin and Range were created under such explosive conditions. **Mafic** magmas, which create rocks such as basalt, are less viscous and therefore can flow more easily. These gentler, effusive eruptions create features such as cinder cones and basalt flows. Lunar Crater in Nevada contains cinder cones and basalt lava flows that date from the **Miocene** to the **Pleistocene**, 20,000 years ago. Amboy Crater, Pisgah Crater, and the Cima Volcanic fields of the eastern Mojave also produced **basalt** and **scoria.**

In addition to the ancient stromatolites preserved in **limestone**, the Basin and Range also contains younger sedimentary rocks. Because the region is part of the Great Basin, water does not flow to the ocean, but instead evaporates from many **playa lakes** in the basins. At Mono Lake, a large playa lake located in Mono County, California, bubbling hot springs create a spongy limestone called **tufa**, which composes the strange towers that can now be seen since the water level of the lake has fallen (*Figure 2.6*).

Figure 2.6: Tufa towers at Mono Lake, California.

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.*

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

playa lake • *ephemeral or dry lakebed that occasionally contains only a thin layer of quickly evaporating water.*

tufa • *a carbonate sedimentary rock, formed by evaporation of water around the mouth of a hot spring or other seep, causing calcium carbonate to precipitate out of solution.*

Rocks of the Columbia Plateau
Region 2

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. 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 2.7*). The thickness of the lava flows reached 1800 meters (6000 feet), burying almost all of the older rock in the area.

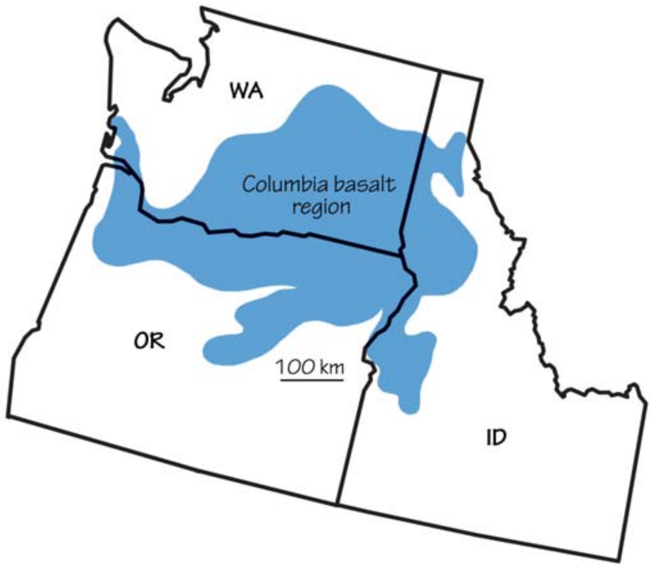


Figure 2.7: Extent of Columbia Basin Flood Basalt.

The Columbia River has eroded deep into the lava flows of the Columbia Plateau, revealing layers of columnar jointed basalt. Layers of these jointed lava flows have been exposed at the Moses Coulee in Douglas County, Washington (*Figure 2.8*). The rhyolitic ash flows of the Bishop Tuff in California and Devil's Tower (an igneous intrusion) in Wyoming (*Figure 2.9*) also exhibit columnar jointing.

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.

Figure 2.8 Moses Coulee exposure of lava flows in Douglas County, Washington.

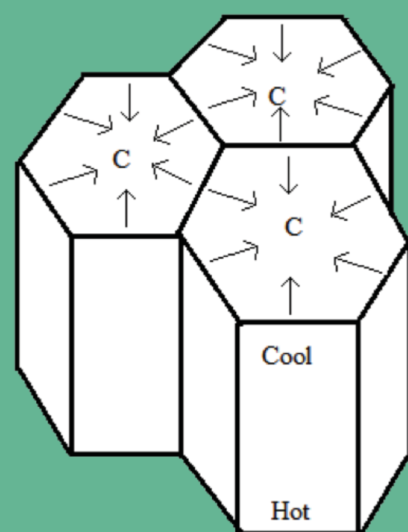
Figure 2.9: Devil's Tower National Monument in Wyoming.

Regions 2–3

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

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.



Rocks of the Northern Rocky Mountains

Region 3

The oldest rocks of Washington State can be found in the Northeastern Highlands, which contain the Northern Rocky Mountains as well as the Kootenay Arc and the Okanogan Highlands (*Figure 2.10*). The Northern Rocky Mountains defined the ancient edge of the North American continent during the Precambrian. The oldest rocks are granite, gneiss, and schist of the ancient continental crust. Above them lies the **Belt Supergroup**, a 1.45-billion-year-old series of sedimentary rocks that contains **sandstones** and mudstones.

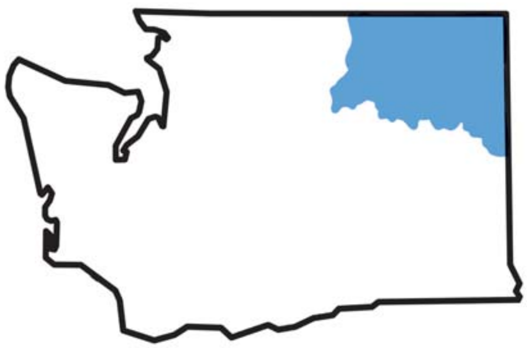


Figure 2.10: Washington State with highlighted Northeastern Highlands region.

For millions of years, the edge of the continent deposited sediments onto its continental shelf. About 200 million years ago the Okanogan micro-continent, an island about the size of California, slammed into the coast, folding and compressing the coastal sediments. The resulting sedimentary rocks, known as the Kootenay Arc, were compressed like an accordion, so that today they lie nearly vertical. They can be viewed between Chewelah and Kettle Falls, Washington. Kettle Falls, now below Franklin D. Roosevelt Lake, marks the **suture** line between the sedimentary rocks of the Kootenay Arc and the granites and gneisses of the Okanogan micro-continent.

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.

Granite can also be found throughout the Northeastern Highlands, due to Mesozoic-era magmatic intrusions that cooled at depth. These intrusions are notable for their uranium content, and uranium mines operated in the region between the 1950s and 1980s.

During the early **Paleogene** (50–66 million years ago), the Okanogan Highlands were subjected to further volcanic and tectonic events, resulting in the development of gneiss domes. As the granitic rocks of the highlands were subjected to heat and stress, they melted and rose, dragging underlying gneiss up with them to form the domes. During the same time period, massive **ore** deposits formed as igneous intrusions. Significant deposits of **gold** and **silver** can be found in the Okanogan area. In addition, Mt. Tolman near Keller, Washington holds one of the largest **molybdenum** reserves in the United States, containing over 2.4 billion tons of ore.

See Chapter 5: Mineral Resources to learn more about valuable ores found in the Western States.

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

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

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

silver *• a metallic chemical element (Ag).*

molybdenum *• a metallic chemical element (Mo) which has the sixth-highest melting point of any element.*

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

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

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).*

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

Rocks of the Cascade-Sierra Mountains
Region 4

The rocks of the Cascades and the Sierra Nevada are primarily igneous, since they resulted from melting above a subduction zone. The Cascades are younger mountains, having first appeared 36 million years ago, and are still forming today. In contrast, the plutonic core of the Sierra Nevada began to form over 200 million years ago during the Nevadan **Orogeny**. Oceanic **lithosphere** at the edge of the North American continent melted while subducting at a steep angle, and the magma rose back through the continental crust to form a volcanic arc. While these volcanoes ruptured the surface, massive bodies of magma slowly cooled deep below, creating a huge granite **batholith**. During the **Laramide Orogeny** in the late **Cretaceous** (70–80 million years ago), the angle of subduction became shallower, possibly due to an increased rate of plate convergence. As a result of this shallow subduction angle, volcanism slowed and the North American plate was heavily **uplifted**. The original volcanoes are long since worn away, and their sediments can now be found in the Central Valley of California.

Part 1: The Sierra Nevada

The Sierra Nevada that we see today is composed of the once-deep granite batholith, uplifted with the North American plate and exposed by erosion. The uplifted granitic intrusion is 640 kilometers (400 miles) in length, and lies mostly within California, although one small spur resides in Nevada (*Figure 2.11*). The Sierra Nevada batholith is composed of over 100 different plutons. Each pluton has a slightly different chemistry, but all of the rock is made up of some form of granite. The White Mountains and the Alabama Hills are considered part of the same batholith, but they have been separated from the main body by faulting.

Figure 2.11: Extent of the Sierra Nevada range.

Region 4

Mt. Whitney and the other high peaks of the Sierra experience frequent freezing and thawing, which creates a process called **frost wedging**. At these high elevations, water seeps into cracks in the rocks and then freezes, expanding as it transitions from liquid to solid. This forces the cracks to widen, and the process is repeated as temperatures rise and fall, finally shattering the rocks (*Figure 2.12*).

Figure 2.12: On Mt. Whitney, frost wedging causes rocks to crack in sharp patterns.

The rounded rocks of the Alabama Hills appear markedly different from the jagged granite peaks of Mt. Whitney above them, not because they are made of a different rock, but because they weather differently (*Figure 2.13*). At lower elevations where freezing is infrequent, the granite experiences **spheroidal weathering.** The rough edges of the rock wear away evenly, gradually revealing a smooth surface. The rocks tend to look browner because chemical weathering**,** which is enhanced at warmer temperatures**,** produces **iron** oxides, or rust.

A different weathering process, known as **exfoliation**, formed the impressive rounded granite domes of Yosemite National Park. Although granite is under tremendous pressure when it forms deep underground, it is at equilibrium with the surrounding rock because the pressure is equal in every direction. However, when it is uplifted*,* there is no longer any significant downward pressure on it, so it expands towards the surface. This expansion causes **joints**, or cracks, to form parallel to the surface, producing slabs that resemble the curved layers of an onion (*Figures 2.14 and 2.15*). The most famous example of an exfoliation dome is Half Dome of Yosemite (*Figure 2.16*).

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

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

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

exfoliation *• a type of physical weathering in which overlying layers are weathered away, and the reduction of downward pressure allows the underlying rock to expand toward the surface.*

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

Figure 2.13: Rounded Granite of the Alabama Hills with the Sierra Nevada in the background.

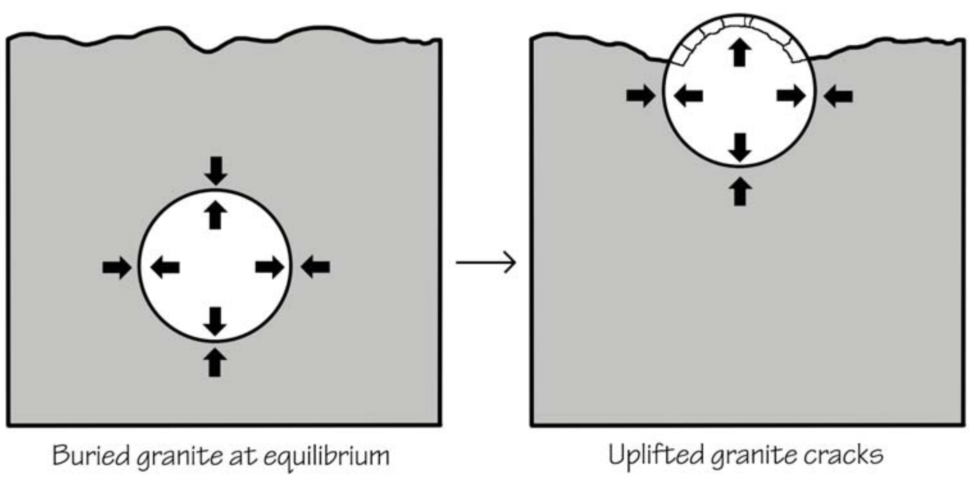


Figure 2.14: Exfoliation process diagram.

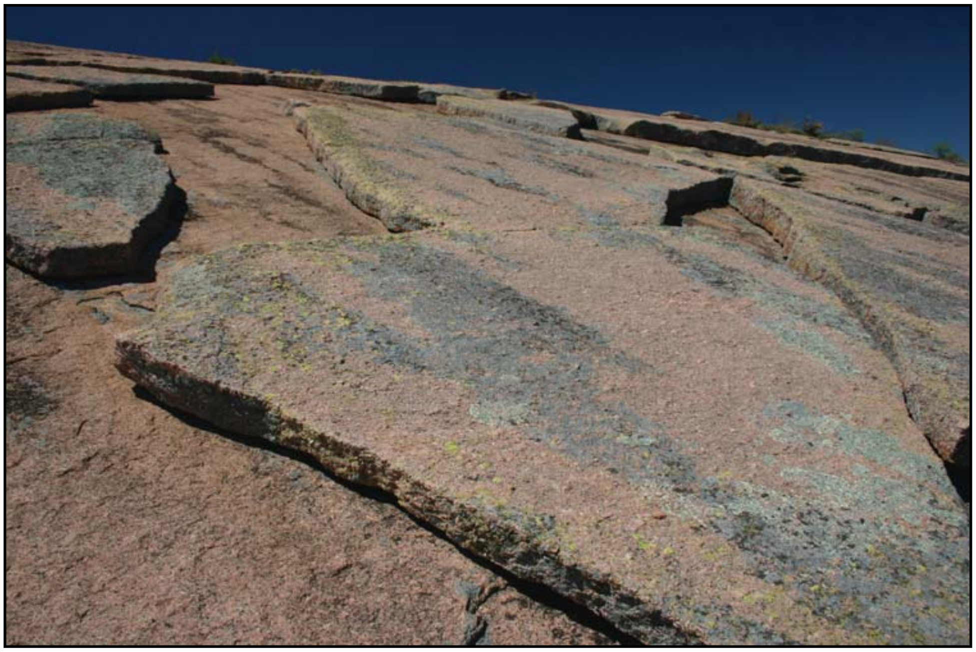


Figure 2.15: Exfoliation joints on granite dome.

Figure 2.16: Half Dome of Yosemite.

Region 4

roof pendant *• a downward projection of metamorphosed basement rock that hangs exposed above an uplifted igneous intrusion.*

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

contact metamorphism *• a metamorphic rock that has been altered by direct contact with magma.*

inclusion *• a fragment of older rock located within a body of igneous rock.*

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

The superheated intrusions of granitic magma that formed the Sierra batholith also affected the surrounding rocks. One classic example is called a **roof pendant**, which forms when the intruding magma turns the surrounding sedimentary **basement rock** into metamorphic rock through the process of **contact metamorphism**. After uplift and erosion, the remnant of the metamorphic rock hangs above the granitic intrusion (*Figure 2.17*).

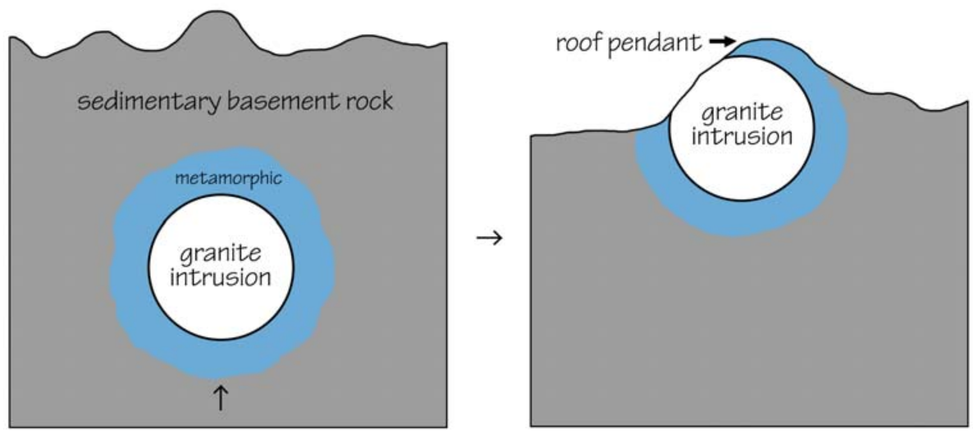


Figure 2.17: Formation of a roof pendant. (See TFG website for full-color version.)

Besides the famous felsic granite of the Sierra Nevada, there are prominent mafic rocks as well, particularly in the Tehachapi Mountains at the southern end of the range. These mountains contain plutonic igneous and metamorphic rocks that are highly mafic due to their iron and magnesium content. The most abundant rock is mafic gneiss. Sometimes this dark rock can be found as **inclusions** within the lighter granite of the Sierra, indicating the presence of older rock enveloped by a newly hardening intrusion.

Several parts of the Sierra Nevada are composed of accreted **terranes** from the subducting Farallon plate along the western continental margin. The Western Foothills contain highly metamorphic rock that is the result of terranes colliding. The rocks here include serpentinite from the subduction zone as well as **hydrothermally** formed veins of **quartz** that contain gold. The Klamath Mountains, also composed of accreted terranes, are oldest in the east and youngest in the west, representing the continuing accretion of island arcs and continental fragments from the Pacific Ocean. The rocks of the eastern Klamath are Cambrian to **Triassic** in age, and are mostly metamorphic and **ultramafic**. The western Klamath, located along the California-Oregon coast, is formed of marble. These rocks began as a limestone **reef** in a shallow ocean. After they accreted onto the edge of the continent, they were

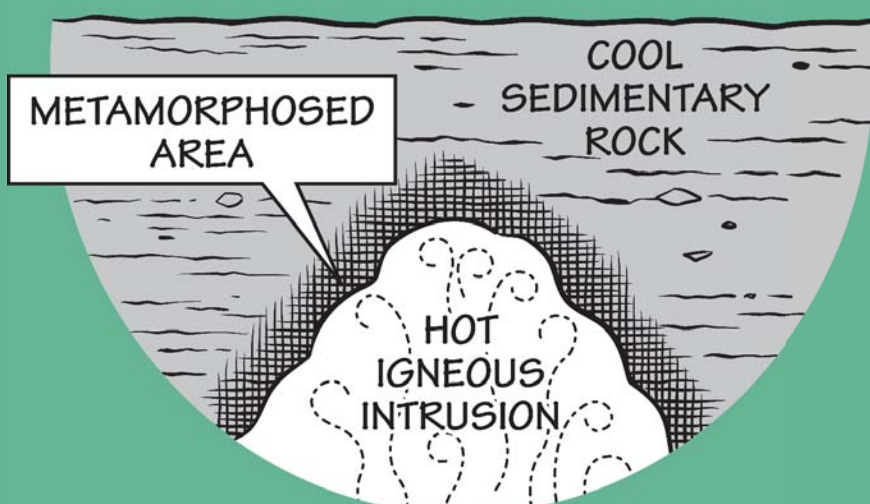
***Terranes* are fragments of crustal material that have been broken off from one plate and accreted to a different piece of crust through tectonic forces. Each fragment in a large grouping of accreted terranes shows a distinct geologic history.**

Region 4

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.

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

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

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

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

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.*

shield volcano *• a volcano with a low profile and gradual slope, so named for its likeness to the profile of an ancient warrior's shield.*

finally metamorphosed into marble by the heat from intruding magma during the Mesozoic. The intrusions cooled into granite and diorite, which are visible at the Oregon Caves National Monument.

See Chapter 5: Mineral Resources to learn more about Alaskan gold.

Part 2: The Cascades

The Cascade Range extends all the way from southern British Columbia to northern California, and is made up of a series of volcanoes that have built up a large platform of volcanic debris (*Figure 2.18*). These volcanoes, the Cascade Volcanic Arc, arose due to the subduction of the Pacific plate beneath North America. As long as subduction continues, the Cascades will remain volcanically active.

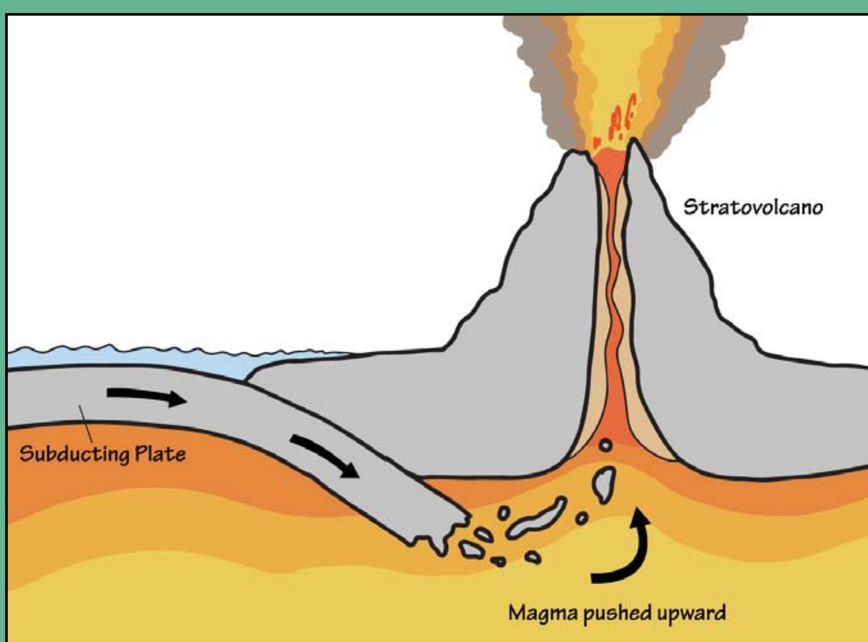
The Cascades are primarily composed of volcanic igneous rock, the youngest of which is found in the active volcanoes of the High Cascades—strikingly large **stratovolcanoes** that rise high above the landscape of the range. The tallest of the High Cascades is Mt. Rainier, which rises to 4392 meters (14,410 feet) above sea level. The most common rock produced by these volcanoes is **andesite**, a fine-grained rock of intermediate silica content. Another common rock is **dacite**, a gray volcanic rock that lies between andesite and rhyolite in terms of its silica content.

The Cascades also contain a few ancient **shield volcanoes.** A shield volcano has a low profile and gradual slope because it is made of lava flows that were more fluid than the "sticky" silica-rich lavas that build up stratovolcanoes. Newberry Volcano in Oregon is the widest volcano of the Cascades, with a

Figure 2.18: The Cascade Range. (See TFG website for full-color version.)

Stratovolcanoes

A *stratovolcano* is a conical volcano made up of many lava flows as well as layers of ash and breccia from explosive eruptions. In fact, stratovolcanoes are often characterized by their periodic violent eruptions, which occur due to their presence at subduction zones. While young stratovolcanoes tend to have steep cone shapes, the symmetrical conical shape is readily disfigured by massive eruptions, such as at Mt. Saint Helens in 1980. Older stratovolcanoes like Mt. Rainier further lose their symmetry due to erosion, especially because volcanoes are inherently unstable mountains. Many older stratovolcanoes contain collapsed craters called *calderas*.



diameter of 32 kilometers (20 miles). This broad shield volcano emitted a wide range of flows, ranging from basalt to rhyolite. The volcano's caldera is thought to have first formed 500,000 years ago, when the original cone collapsed following a particularly large eruption that emptied the underlying magma chamber. Today, the caldera forms a lake that contains a few smaller volcanic

Region 4

obsidian • *a glassy volcanic rock, formed when felsic lava cools rapidly.*

basaltic andesite • *a dark, fine-grained rock that is intermediate between basalt and andesite in silica content.*

slate • *a fine-grained, foliated metamorphic rock derived from a shale composed of volcanic ash or clay.*

phyllite • *a metamorphic rock that is intermediate in grade between slate and schist.*

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

cones as well as the Big Obsidian Flow (*Figure 2.19*), a 1300-year-old patch of volcanic glass that covers about 10 square kilometers (4 square miles). The **obsidian** from this flow was commonly used to make tools, and it has been traced to Native American sites all over the region.

See Region 7: Hawai‘i in this chapter for more information about shield volcanoes.

Figure 2.19: Newberry Caldera showing the lake, central cones, and the Big Obsidian Flow.

Belknap Crater in Oregon (*Figure 2.20*) is another large shield volcano. It produced basaltic lava flows 3000 years ago, but its last eruption, 1500 years ago, produced **basaltic andesite** lava flows. Overall, the flows from Belknap Crater—and its sister craters, Little Belknap and Yapoah—cover nearly 200 square kilometers (77 square miles) of the surrounding area.

The Western Cascades are made up of old, extinct, and highly eroded volcanoes. The oldest outcrops, 18–40 million years old, contain many pyroclastic rocks. The old volcanic remnants of the Western Cascades provide us with a glimpse of what the current High Cascades will look like in about 18 million years.

The North Cascade Range, although it has a few prominent volcanoes, is predominantly an uplifted block of accreted terranes. The collision that accreted these terranes created intense pressure, leading to metamorphic conditions that formed rocks such as **slate**, **phyllite**, schist, gneiss, and marble. Numerous magmatic intrusions left behind intrusive rocks such as granite, diorite, and **gabbro**, as well as causing contact metamorphism. The volcanoes of the North Cascades, such as Mt. Baker and Glacier Peak, are

Figure 2.20: Belknap Crater.

made of basalt and andesite as well as volcanic **breccia**, a pyroclastic rock composed of volcanic fragments from an explosive eruption. There are some sedimentary rocks in the North Cascades as well; the Methow Valley contains a thick layer of Cretaceous sedimentary rocks such as **shale**, sandstone, and **conglomerate**.

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

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

transform boundary • *an active plate boundary in which the crustal plates move sideways past one another.*

greywacke • *a variety of dark-colored sandstone that contains angular grains of quartz and feldspar embedded in clay.*

Rocks of the Pacific Border
Region 5

Stretching from Mexico to Alaska, the Pacific Border is a chaotic jumble of compressed land and ocean sediments, subducted plate scrapings, accreted terranes, and even errant pieces of ocean plate plastered against the western edge of the continent. Many different parts of the range contain a wide variety of rocks, but all of the ranges share one thing in common: they are the leading edge of an active plate boundary.

Southern California lost its subducting plate boundary 20 million years ago. The junction between the subducting Farallon plate and North America has been shifting northward, leaving the Pacific plate directly next to the North American plate. This new boundary is defined by the San Andreas Fault, a **transform boundary** (*Figure 2.21*).

Evidence of past subduction can be found along the California coast in what is called the Franciscan Assemblage (or formation). Some parts of it are called a **mélange**, a mixture of fragmented rocks produced in a subduction zone. Approximately 90% of the Franciscan Assemblage is composed of **greywacke**, a form of sandstone deposited in deep marine basins by submarine landslides called **turbidity currents**. This dark-colored rock has layers that transition from

Region 5

coarse grains to fine grains as a result of the submarine turbidity currents coming to rest. The Franciscan Assemblage has also been intruded by **serpentinite**, a metamorphic rock formed when **peridotite** from the subducting plate reacts with water, producing a light, slippery, green rock.

The rocks of the Franciscan Assemblage stand in stark contrast to the Salinian block, a terrane that contains granite as well as metamorphic rocks such as gneiss, schist, **quartzite**, and marble. The Salinian block is a segment of the

serpentinite *• a metamorphic rock formed when peridotite from a subducting plate reacts with water, producing a light, slippery, green rock.*

peridotite *• a coarse-grained plutonic rock containing minerals, such as olivine, which make up the Earth's mantle.*

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

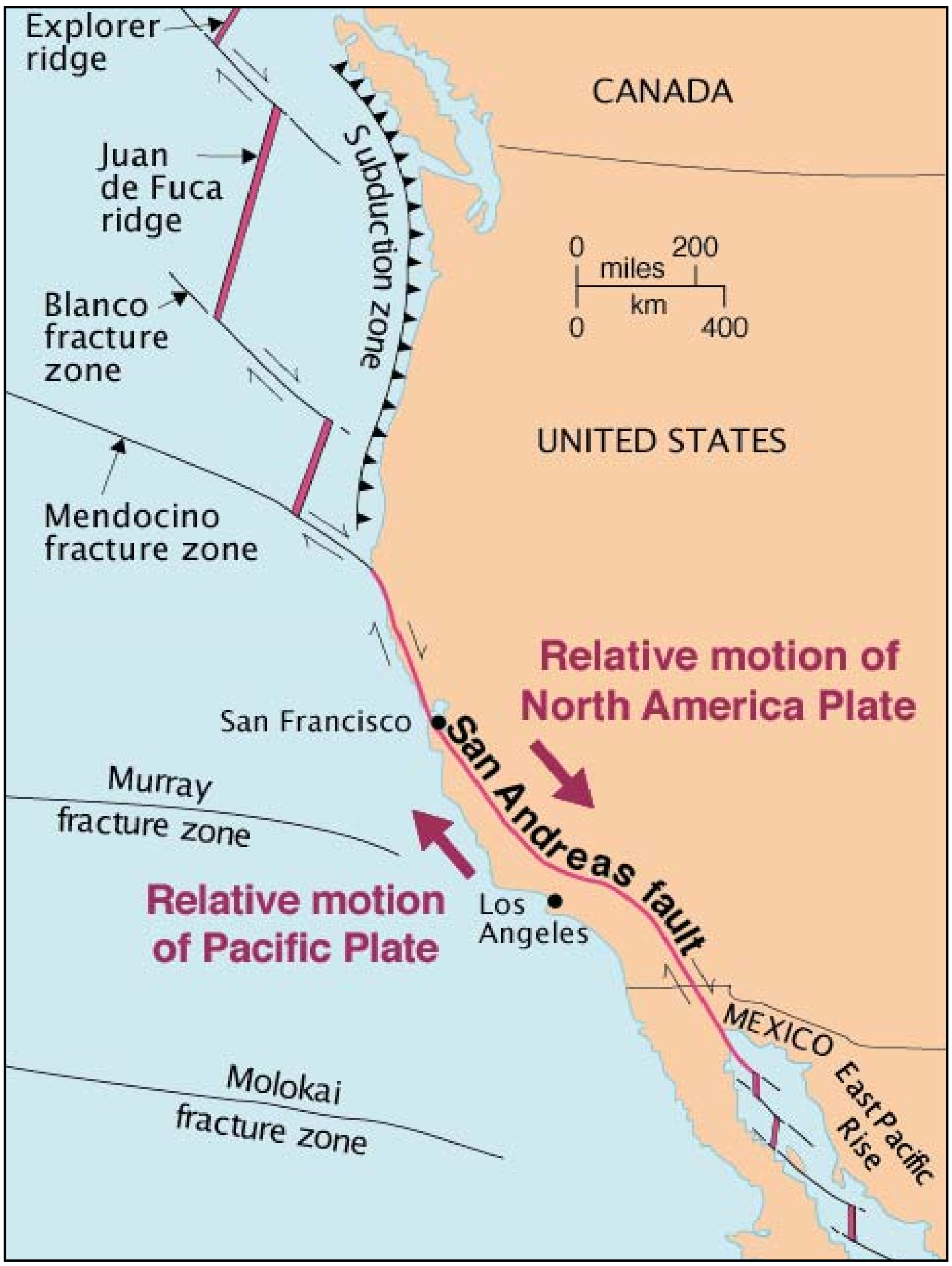


Figure 2.21: Plate boundaries of the West Coast. (See TFG website for full-color version.)

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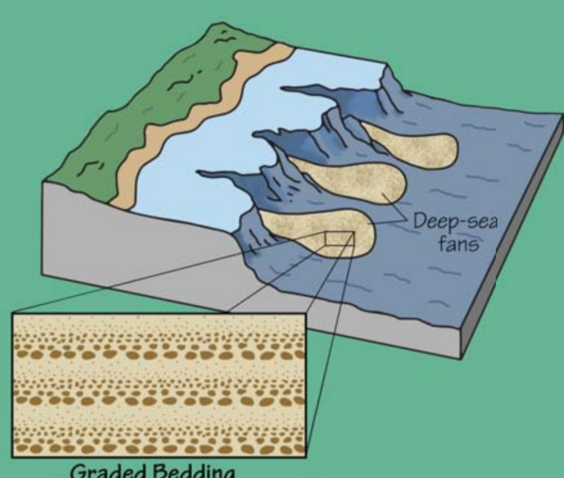
earthquake • *a sudden release of energy in the Earth's crust that creates seismic waves.*

Turbidity Currents

Turbidity currents are essentially submarine sediment avalanches. These fast-moving currents of sediment are often caused by *earthquakes* or other geological disturbances that loosen sediment on a continental shelf. The sediment rushes down the continental slope, picking up sediment and speed as it moves. The density of the sediment within the current gives it great force; turbidity currents have been reported to move at speeds of 100 kph (62 mph). These massive sediment flows have extreme erosive potential, and often carve out underwater canyons. In 1929, the Grand Banks earthquake off the coast of Newfoundland generated a turbidity current that traveled more than 600 kilometers (370 miles) and snapped twelve different transatlantic cables.

Turbidity currents deposit huge amounts of sediment during their flow; such deposits are called *turbidites*. Turbidite sediments are deposited in a graded pattern, with the largest particles at the bottom (as they are the heaviest, and detach from the flow more quickly) and smaller particles on top. Turbidites commonly form in a shape called an abyssal fan, which spreads out in a wide teardrop shape from the source. 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.



Region 5

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

pillow basalt • *basaltic lava that forms in a characteristic "pillow" shape due to its extrusion underwater.*

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

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

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

continental crust that has been moving northwest along the west side of the San Andreas Fault (*Figure 2.22*). It was once an extension of the southern Sierra Nevada, but it was captured by the Pacific plate. It can be clearly seen at Point Reyes National Park, where it is separated from the Franciscan mélange by Tomales Bay.

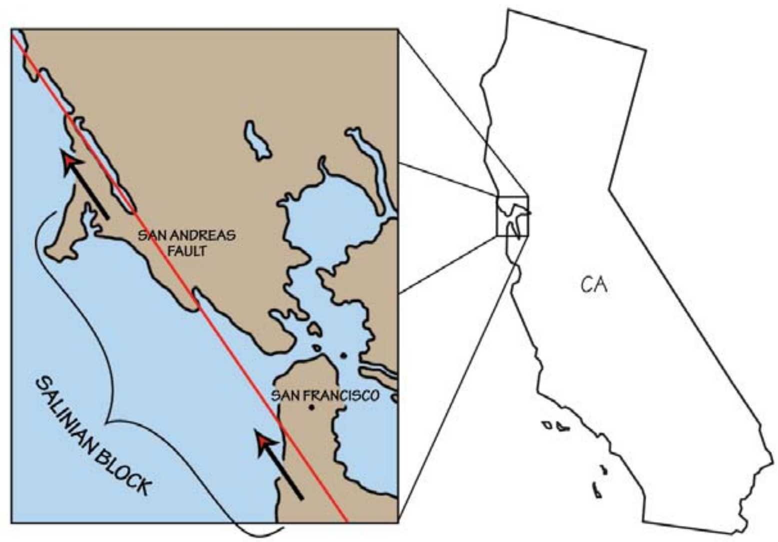


Figure 2.22: Geography of the Salinian block.

Occasionally, a subducting oceanic plate will fracture and leave behind a slice of oceanic crust on land. The resulting rock sequences, called **ophiolites** (*Figure 2.23*), are the most helpful tool we have for studying oceanic crust. The top of the crust contains deep-sea sedimentary rock, such as **chert**. Below that are **pillow basalts** that were **extruded** into the water at a mid-ocean ridge. Below the pillow basalts are intrusions of basalt known as sheeted **dikes**, formed as the mid-ocean ridge pulled apart. Below the basalt is gabbro, the plutonic version of basalt, and finally **peridotite**, the rock that composes the Earth's **mantle**. Ophiolites

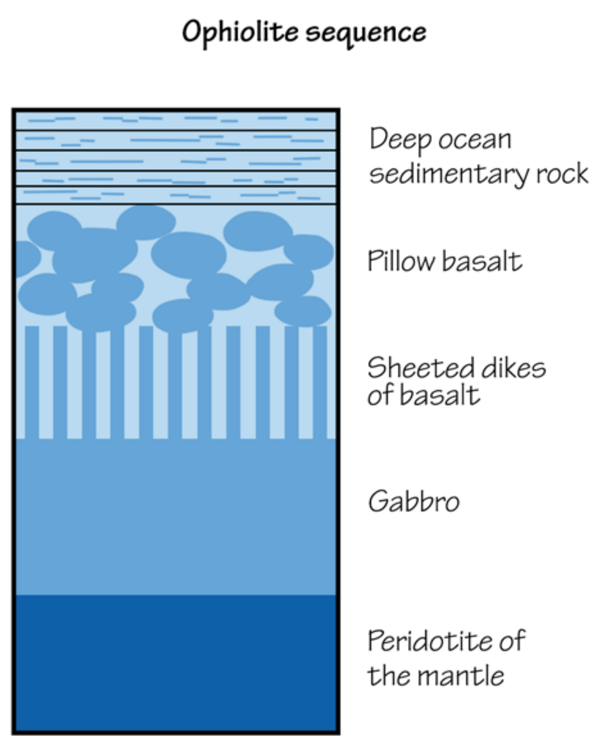


Figure 2.23: Structure of an ophiolite.

are among the only places where mantle rock can be seen on the Earth's surface. Ophiolite sequences can be found exposed at the Golden Gate National Park, Cuesta Ridge (near San Luis Obispo), and in the western Klamath Mountains.

The **Monterey Formation** is a distinctive light-colored sedimentary rock unit that formed in the Miocene seas. Its buff color comes from its high silica content. Outcrops from the Monterey Formation are visible along California's coast and peninsula, and on some of the offshore islands. It is composed primarily of shale, and it is the source rock for most of California's **oil**. Oil shale like this tends to form when deposition occurs on top of thick algal beds—the sediment layers then trap the oil that forms from the decomposing organic matter.

The Juan de Fuca plate is still subducting along Northern California, Washington, and Oregon. The Oregon Coast Range, which overlies this subduction zone, extends for 320 kilometers (200 miles) from the Washington-Oregon border south to the Coquille River (*Figure 2.24*). These mountains began to form 66 million years ago during the Cretaceous, when a series of offshore **volcanic islands** were pushed into the North American plate. The collision forced undersea basalt formations and sediment **terraces** upward, and these deposits now underlie the Southern and Central parts of the Coast Range. During the **Eocene**, the Siletz River Volcanics—basaltic pillow lavas and other lava flows that formed in submarine volcanoes present on the subducting plate—were added to the range. Lastly, basalt from the edge of the Columbia Basin basalt flow added further material to the range.

See Region 2: Rocks of the Columbia Plateau in this chapter for more information about the Columbia Basin basalt flow.

The Northern portion of the Oregon Coast Range, though it still contains the same basaltic core as the range's more southern portions, tells a slightly different geologic story. Portions of this area contain marine sedimentary rock, uplifted by the subducting Juan de Fuca plate. Sandstone, mudstone, siltstone, and shale are common rocks here, and marine **fossils** also appear in some areas. Heavy rainfall has contributed to the erosion of much of the landscape, leading to the formation of steep slopes and deep valleys.

In Washington State, the coastal region is made up of the Olympic Peninsula, a large arm of land that juts out into the Pacific Ocean. The Olympic Mountains, an extension of Oregon's Coast Range, form the Peninsula's core. These mountains formed in the same way as the Coast Range (*Figure 2.25*), and are underlain by a very similar basalt formation called the Crescent Formation. As convergence of the Juan de Fuca plate accelerated in the middle Miocene, a variety of sedimentary, metamorphic, and volcanic rocks accreting to the Olympics were chaotically jumbled to form a mélange called the **Hoh rock assemblage**. These rocks are exposed along 72 kilometers (45 miles) of Washington's Olympic Coast (*Figure 2.26*).

During the Pleistocene, continental **ice sheets** sculpted the Olympic Mountains, leading to the formation of U-shaped valleys and the deposition of many granitic glacial **erratics**.

Region 5

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

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

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

fossil • *preserved evidence of ancient life.*

Hoh rock assemblage • *a mélange formed from a variety of chaotically jumbled sedimentary, metamorphic, and volcanic rocks that accreted to the Olympic Peninsula during the Eocene.*

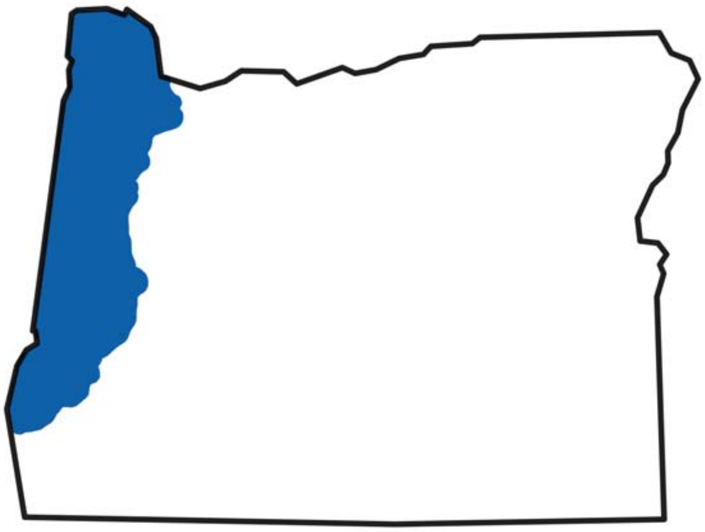


Figure 2.24: Extent of the Oregon Coast Range.

See Chapter 6: Glaciers for more information about the landforms created by glaciers in the Western States.

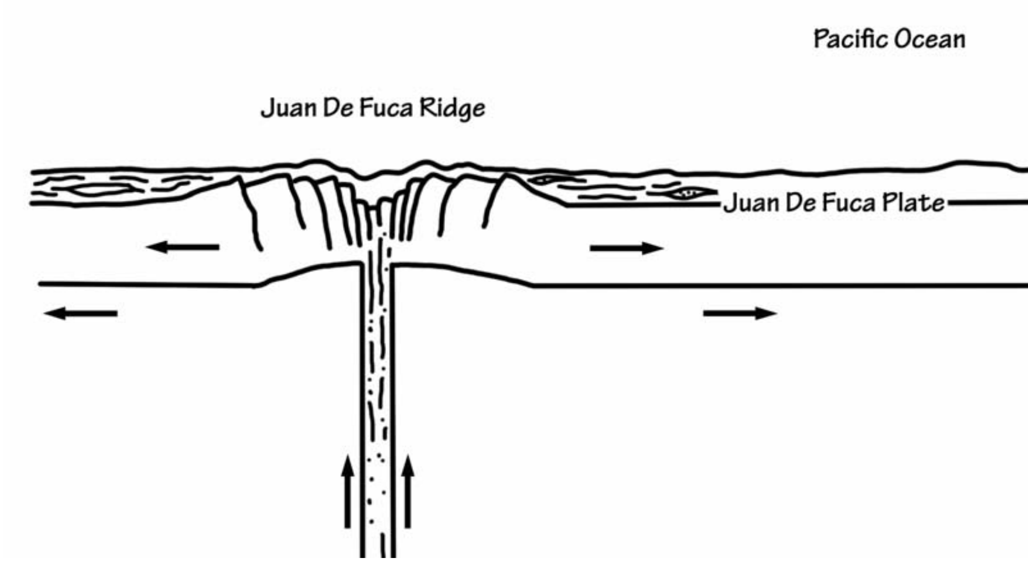
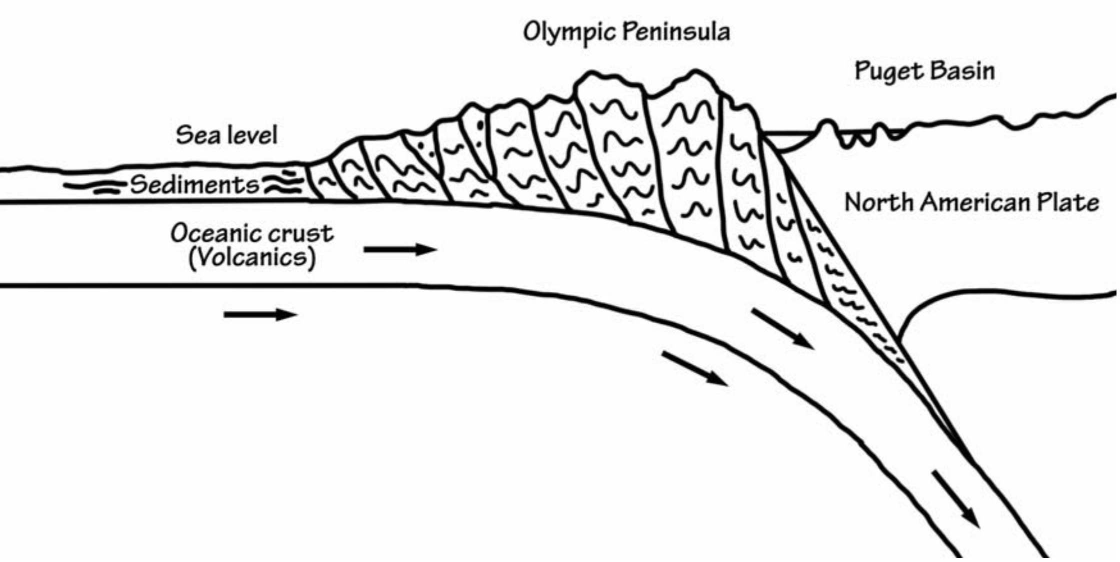


Figure 2.25: Formation of the Olympic Peninsula and Mountains.

Figure 2.26: Hoh assemblage rocks along the Olympic Coast.



Rocks of Alaska
Region 6

Alaska is a mosaic of accreted terranes, each with its own history (*Figure 2.27*). Due to the accretion of these terranes over time, Alaska today showcases a diverse array of mountain ranges and physiographical regions (*Figure 2.28*). The first rocks of Alaska were put in place when the Yukon-Tanana terrane collided with the western edge of North America 200 million years ago. These rocks are late Precambrian in age and are mostly composed of schist. The greenschist and blueschist of the southwestern Brooks Range show clear signs of having been formed at this convergent plate margin, as they contain minerals that form at high pressure but low temperature. The Brooks Range,

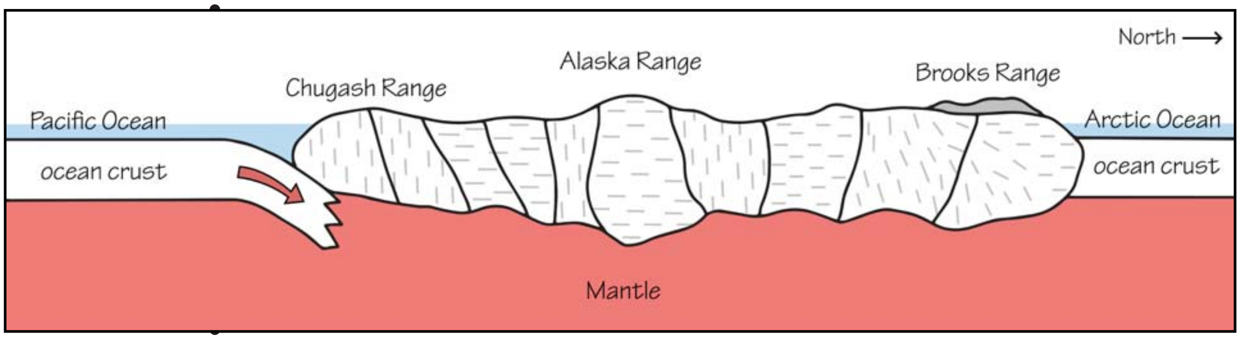


Figure 2.27: A cross-section of Central Alaska. Each section delineates a separate terrane.

Alaska's northernmost mountain range, is heavily composed of the Yukon-Tanana's ancient seabed, and contains many ancient marine fossils. Rocks on the northern side of the Alaska Range, Alaska's central mountain chain, have also been correlated with schists from the Yukon-Tanana.

Other late Precambrian and Paleozoic rocks of Alaska include gneisses of the Seward Peninsula, which extends from northwest Alaska and is a remnant of the Bering land bridge that connected Alaska to Siberia during the Pleistocene. The Seward

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.

Region 6

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

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

Peninsula is actually composed of two terranes: the Seward terrane, which is made up of Precambrian schists, granites, and marbles, and the York terrane, which consists of **Ordovician** through **Mississippian** limestone, **dolostone**, and phyllite. The sedimentary rocks of the York terrane would have originally been deposited in a shallow marine environment before their accretion onto the North American plate. During the Cretaceous, thrust faulting deformed the York terrane, allowing the formation of intrusive granites.

See Chapter 3: Fossils to learn more about Alaska's ancient marine fossils.

In the late Cambrian to early **Devonian**, undersea volcanism resulted in large quantities of igneous material being mixed with fossiliferous limestone. As these units were transported to finally dock against North America, they accreted as part of the northern Alaska Range, and metamorphism created large quantities of carbonaceous schist.

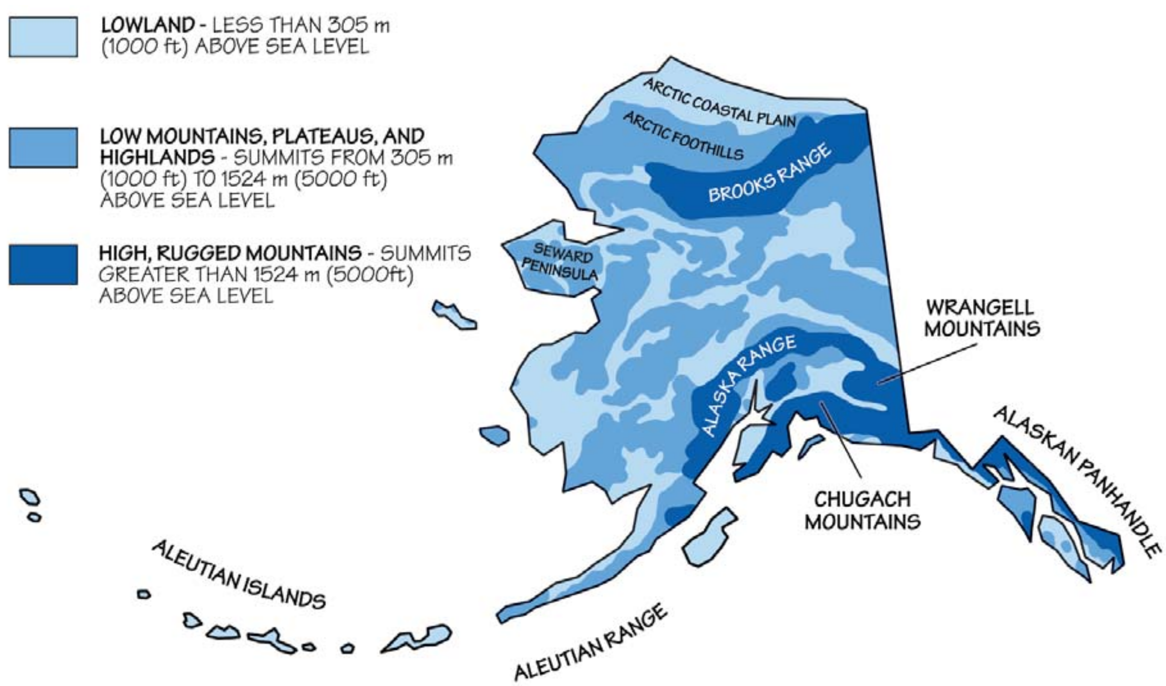


Figure 2.28: Regions and ranges of Alaska. (See TFG website for full-color version.)

The next major terrane, Stikinia, began as a volcanic island arc that formed on the **rifted** margin fragments of the Yukon-Tanana. Its formation would have been similar to the volcanic arc that makes up the islands of Japan today. As this island arc traveled towards a collision with Alaska during the Cretaceous, it scooped up marine shales, sandstones, and limestones that became jumbled up with the volcanic rhyolites, andesites, and basalts that formed the islands. This collection of varied, jumbled rocks eventually became part of the Alaska

Range. The Taku terrane and the Tracy Arm terrane were the next to crash into Alaska, adding more metamorphic rocks such as gneiss, schist, and marble.

The Wrangellia terrane, born near the equator about 300 million years ago, didn't dock with Alaska until 120 million years ago, so it contains rocks that tell a complex story of many years of volcanism, erosion, deposition, sinking, and uplift. Wrangellia's defining unit is a 2500-kilometer (1553-mile) Triassic flood basalt, which would have been extruded onto the terrane's landmass about 230 million years ago. Shallow seas later inundated the region, covering these volcanic rocks with layers of limestone and other marine sediments. Today, these flood basalts and their overlying sediments extend across the southern portion of the Alaska Range and the Wrangell Mountains. As Wrangellia moved toward North America, it also collided with a variety of other smaller terranes, compressing seafloor rocks against it and forming a complex fault system. This fault is expressed today as the Border Ranges Fault, which occurs throughout the Chugach Mountains at the southern edge of Alaska.

Each terrane was brought to Alaska on a subducting plate, and subduction is still occurring along the Aleutian Trench, resulting in the formation of the Aleutian Islands. The subduction creates stratovolcanoes and plutonic igneous intrusions (*Figure 2.29*) along the entire Aleutian Range. The stratovolcanoes produce rocks that tend to be intermediate in silica content, so andesite and dacite are common. Pyroclastic rocks from explosive events are also quite common. One spectacular example is found at Novarupta in Katmai National Park, where a volcanic eruption thirty times as large as Mt. St. Helens occurred in 1912. Geologists who investigated the aftermath of the eruption were awe-

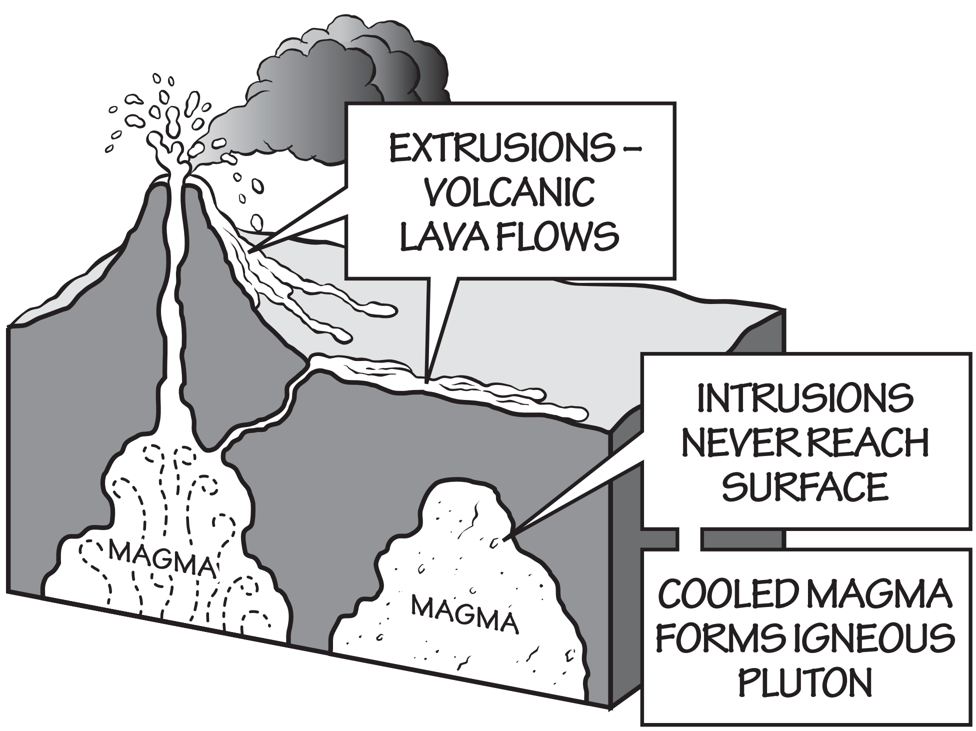


Figure 2.29: Intrusive and extrusive igneous features.

struck by the still-smoking tuff that covered the surrounding area, and named it the Valley of Ten Thousand Smokes (*Figure 2.30*).

Today, the Yakutat Block is the terrane currently accreting to Alaska, along the state's south-central coast. Its convergence with Alaska is responsible for the volcanism evident in the Wrangell Mountains today. The largest volcano in the range, Mt. Wrangell, is unusual because it formed from massive andesitic lava flows that gave it a shield shape rather than the cone shape of a typical stratovolcano. The process that allowed andesite to form a shield volcano is poorly understood, but is likely related to the volume of ejected magma. Besides these andesitic lava flows, the rocks of the Wrangell Mountains include scattered cinder cones and rhyolite domes (*Figure 2.31*).

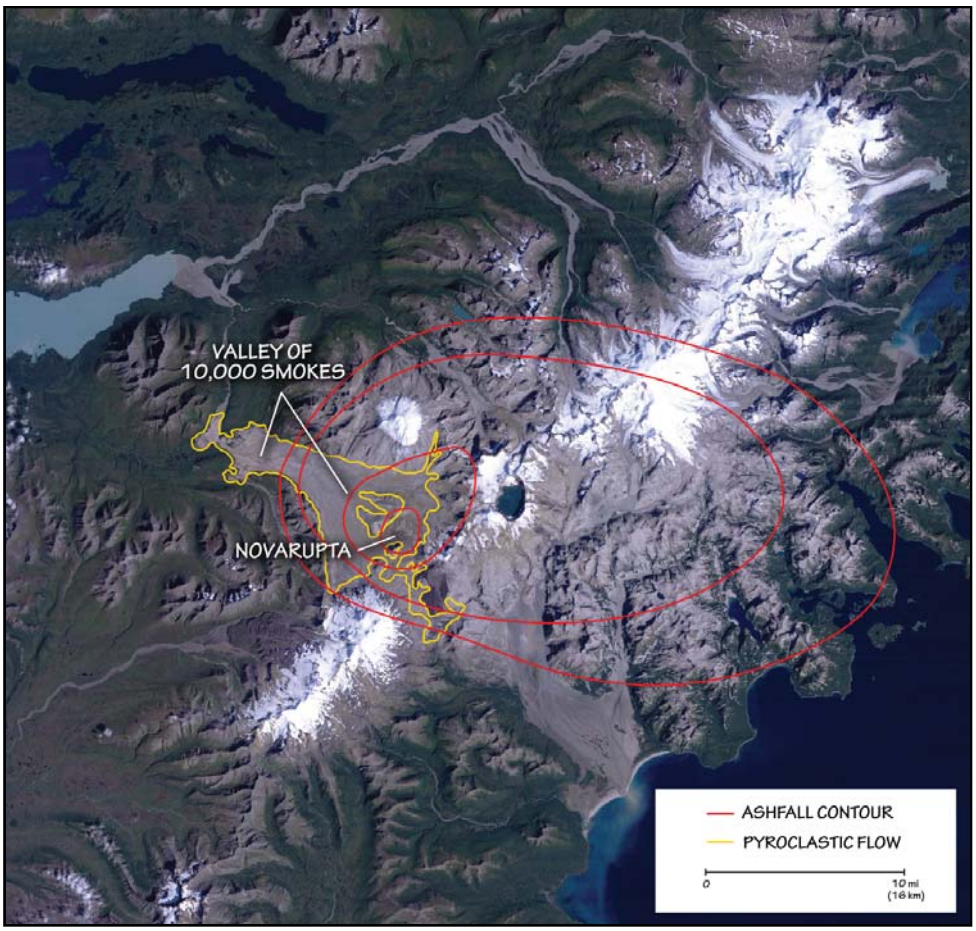


Figure 2.30: Novarupta Volcano in the Aleutian Range. (See TFG website for full-color version.)

During the late Jurassic and early Cretaceous, rotation of the North American plate caused basins to open up in the Arctic, creating shallow seas that filled with sediments eroded from the Brooks Range. Today, these sediments form the upper source rocks of the Arctic Foothills and Arctic Coastal Plain, north of

Pliocene *• a geologic time interval extending from roughly 5 to 2.5 million years ago.*

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

Figure 2.31: The Wrangell Mountains, showing (left to right) Mt. Drum, Mt. Blackburn, and Mt. Wrangell.

the Brooks Range. The shales here are rich with oil, formed as the sediments were deposited in a marine environment with high biological activity. Prudhoe Bay, at the edge of the Coastal Plain, is estimated to hold nearly 25 billion barrels of oil.

Southeastern Alaska, also known as the Alaskan Panhandle, expresses a slightly different geologic history than does the main body of the state. The core of the Coast Mountains is a granitic batholith, parts of which have been deformed by metamorphism to form schist, gneiss, and marble. The region contains a large fault system, which has increased uplift in many areas to expose more metamorphic rock. In addition, a jumble of marine sedimentary rock and conglomerates was accreted to the southeastern coastal area as terranes continued to dock and subduct.

Rocks of Hawai'i

Region 7

In Hawai'i, younger igneous rocks dominate the landscape, and basaltic lava flows are part of almost any vista. On the eight main Hawaiian Islands, the oldest exposed flows are approximately five million years old, still within the **Pliocene** epoch. The uniform lithology and young age of Hawaiian rocks are fascinating, particularly since the processes that create these rocks and shape the islands are both active and visible.

Hawaiian volcanism occurs far from any plate boundary—the Hawaiian Islands sit above a mantle **hot spot** located beneath the Pacific plate. The eruptive behavior that has created the Hawaiian volcanoes is quite different from either mid-ocean ridge or subduction zone volcanism.

Hawaiian eruptions produce high-temperature, low-viscosity, basaltic lavas. Repeated eruptions build large, gently sloping shield volcanoes, so named for their likeness to the profile of an ancient warrior's shield. The low-viscosity magma under shield volcanoes flows quickly, resulting in the typical expansive size and gentle slopes of the volcano. Shield volcanoes can erupt from a summit vent, or through vents on the volcano's flanks. Typically, a volcano will have one or more rift zones: linear arrays of vents extending away from the summit. Magma can migrate away from the summit vent through a series of **fractures** that create the rifts.

See Chapter 1: Geologic History for more information about hot spots.

__fracture__ • a physical property of minerals, formed when a mineral crystal breaks.

__cinder__ • a type of pyroclastic particle in the form of gas-rich lava droplets that cool as they fall.

Oceanic hot spot eruptions are characterized by lava fountains that feed subsequent lava flows. Lava fountains are spectacular, but on the scale of global volcanism, they are considered gentle and effusive (*Figure 2.32*).

See Chapter 1: Geologic History to learn more about stages in the formation of a hot spot shield volcano.

During the fountaining phase of an eruption, various types of pyroclastic particles form. Lava fountains produce abundant **cinders**: gas-rich lava droplets that cool as they fall. Well-formed glassy droplets of cooled lava are known as Pele's tears, after the Hawaiian goddess of fire and volcanoes (*Figure 2.33*). Larger blobs can cool into aerodynamic shapes called bombs. Molten lava can be spun into windblown

Figure 2.32: A flank eruption on Kīlauea. The vent erupts a fountain of lava that feeds a channelized lava flow. The dark color of the flow in the lower portion of the photo shows how quickly the surface of the molten lava freezes when in contact with air, while liquid lava continues to flow beneath the chilled crust.

tephra *• fragmented material produced by a volcanic eruption.*

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

threads called Pele's hair (*Figure 2.34*). Pele's tears, Pele's hair, cinders, and bombs are common **tephra** forms found near Kīlauea volcano.

Basaltic lavas have two characteristic modes of motion that produce two very different textures after the flows harden. These textures are controlled by the eruption and effusion rate of the lava, as well as by its viscosity (controlled by temperature and gas content) and strain rate (usually controlled by **topography**).

Figure 2.33: Two examples of Pele's tears, ~1 centimeter (0.39 inches) in diameter.

Figure 2.34: Windblown accumulation of Pele's hair.

Pahoehoe results from the rapid motion of highly fluid basalt. It cools into smooth glassy flows, or can form fantastic, twisted, ropey shapes (*Figure 2.35*). Pahoehoe is formed from lava that has a low viscosity and strain rate, as well as a low rate of gas effusion.

Figure 2.35: The skin on a pahoehoe flow is deformed by the motion of the underlying molten lava. The resulting texture is ropey and lumpy.

lava tube • *a natural tube formed by lava flowing beneath the hardened surface of a lava flow.*

‘A‘a flows are dense and blocky, and advance as a more massive front of hardened fragments. Cooled ‘a‘a is a jagged landscape of sharp lava rubble (*Figure 2.36*). ‘A‘a is produced by lava that has a high viscosity and strain rate, as well as high gas effusion.

Both ‘a‘a and pahoehoe have the same basic chemistry, and one type of flow can transition to the other during an eruption (*Figure 2.37*).

Highly fluid lava can move as a broad flow with many advancing pahoehoe fingers, or it may channelize in a narrow lava river. Since the ambient air temperature is hundreds of degrees lower than the temperature of the flow (1100°C [2000°F]) the flow forms a skin of cooled lava almost immediately after leaving the vent. As long as lava is supplied from the vent, however, the flow will continue to advance beneath the cooled skin. A broad, slow-moving pahoehoe flow will advance by inflating the surface from beneath until molten lava spills out below the frozen skin. Alternately, a narrow lava river creates a well-defined **lava tube** through which fast-moving lava can flow—often over

Region 7

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

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

Figure 2.36: An ʻaʻa flow showing its jagged surface and massive molten interior.

Figure 2.37: Juxtaposition of pahoehoe (left) and ʻaʻa flows (right).

distances of tens of kilometers (miles). The cooled skin is an excellent insulator for the lava flowing beneath, so basaltic lava flows can quickly advance from the volcano summit to the sea. When the eruption ceases, lava will drain out of the tube, leaving behind an empty chamber. Lava tubes are a common feature of the Hawaiian landscape, and they occur on all scales, from large tubes tens of kilometers (miles) long, to the very small, ubiquitous tubes seen in every roadcut.

Although Hawaiian volcanoes are known for their effusive eruptions, there are also occasional episodes of more violent explosive behavior. When groundwater interacts with a magma chamber, the high temperatures cause water to flash into steam, initiating an explosive eruption. In this case the energy of the eruption shatters the lava into tiny particles of **volcanic ash**. Layers of ash are widespread and are found in volcanic **stratigraphy** across the islands (*Figure 2.38*). On Hawai'i Island the distribution of Kīlauea's ash deposits clearly indicates that some eruptions were powerful enough to blast ash above the **trade wind inversion** into the west winds of the **jet stream**. Closer to the volcanic vent wall, rocks can be blasted from the caldera or vent wall itself.

Figure 2.38: Ash from an explosive eruption of Kīlauea.

Non-Igneous Rocks

Metamorphic rocks are uncommon in Hawai'i and are represented by only a few occurrences of contact metamorphism. Sedimentary rocks are more widespread. Conglomerates and **alluvial** deposits can be found in stream valleys, but the most common sedimentary rocks are marine limestone and calcareous sandstone.

Colonial coral polyps build calcareous skeletons that create Hawai'i's beautiful reef ecosystems. Because corals live close to the ocean surface, reefs are highly susceptible to changes in sea level. Both relative and absolute sea level changes can leave reefs quite literally high and dry. Wind and wave action erode the exposed reef to form large quantities of **carbonate** sand and dunes. During times of particularly high sea level, water movement pushes these dunes inland where they are lithified and preserved (*Figure 2.39*). These **aeolian** (wind-

trade wind inversion *• a reversal of the typical atmospheric situation directly above the Earth's surface, where air temperature decreases with altitude.*

jet stream *• a fast-flowing, narrow air current found in the atmosphere.*

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

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

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

formed) sandstones are most extensive on the older islands but can occur even on young Maui. The ancient dunes are highly fossiliferous and record the range and variation of Hawai‘i’s **extinct** flora and fauna.

See Chapter 3: Fossils for more information about Hawai‘i’s fossil record.

Figure 2.39: Sedimentary rocks on Kaua‘i. These lithified dunes range in age from 4000–350,000 years before present.

State Rocks, Minerals, and Gems

Alaska
State mineral: gold
Gold can be found and mined throughout Alaska, and has always been a major state industry and force for exploration.

State **gem**: nephrite jade
Large deposits of this green metamorphic stone are found throughout the Seward Peninsula. It formed during accretion of the area's terranes.

California
State mineral: gold
California's nickname is the "Golden State." Its early population expansion and modern development, including roads and infrastructure, can be traced back to the discovery of gold there in 1848 and the ensuing gold rush.

State rock: serpentine
This green metamorphic rock is found throughout California's Coast Ranges, Klamath Mountains, and Sierra Nevada foothills. It formed through the metamorphism of oceanic peridotite during subduction.

State gem: benitoite
Benitoite is a rare blue fluorescent mineral formed when serpentine undergoes metamorphism.

Hawai'i
Hawai'i has no state rock. The designated state "gem" is black coral.

Nevada
State mineral: silver
Nevada's nickname is the "Silver State," dating back to the silver rush of the mid-1800s. In some areas, silver had weathered out of desert rocks over millions of years, and could often be shoveled right off the ground. Within a few decades, the desert had been picked clean of these silver deposits.

State rock: sandstone
Sandstone is found throughout the entire state of Nevada and makes up some of its most spectacular scenery. The State Capitol Building is even built of sandstone.

State gem: black fire **opal**
These gems are found in layers of **clay** that formed when a volcanic eruption filled an ancient lake. Silica in the ashfall replaced the cells and cavities in buried wood, hardening over time into opal.

State Rocks

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

opal *• a silicate gemstone lacking a rigid crystalline structure.*

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

2 Rocks

State Rocks

geode • *a hollow, roughly spherical node of crystal that forms when minerals precipitate within hardened vesicles (gas bubbles) in volcanic rocks.*

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

Oregon

State rock: **geode**

These geodes, locally called "thunder-eggs," are found in Eocene-age rhyolite lava flows, having formed within gas pockets that served as molds.

State gem: Oregon sunstone

This type of translucent **feldspar** formed as large crystals in basaltic lava flows.

Washington

Washington has no state rock. The designated state "gem" is petrified wood.

Resources

Rock and Mineral Field Guides

Brown, V., D. Allan, & J. Stark, 1987, *Rocks and Minerals of California, 3rd revised edition*, Nautregraph Publishers, Happy Camp, CA, 200 pp.

Chesterman, C. W., 1979, *National Audubon Society Field Guide to North American Rocks and Minerals,* Knopf, New York, 850 pp.

Dixon, D., & R. L. Bernor, 1992, *The Practical Geologist: The Introductory Guide to the Basics of Geology and to Collecting and Identifying Rocks,* Simon and Schuster, New York, 160 pp.

Johnsen, O., 2002, *Minerals of the World,* Princeton University Press, Princeton, NJ, 439 pp.

Mitchell, J., 2008, *The Rockhound's Handbook, revised editioin,* Gem Guides Book Company, Baldwin Park, CA, 299 pp.

Pellant, C., 2002, *Rocks & Minerals*, Dorling Kindersley (Smithsonian Handbooks), New York, 256 pp.

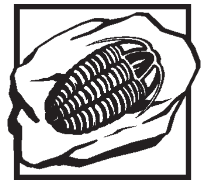
Prinz, M., G. Harlow, & J. Peters, eds., 1978, *Simon & Schuster's Guide to Rocks & Minerals,* Simon and Schuster, New York, 607 pp.

Books

Vernon, R. H., 2000, *Beneath Our Feet: The Rocks of Planet Earth,* Cambridge University Press, Cambridge, UK, 216 pp.

Websites

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



Chapter 3:
Fossils of the Western US

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

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

Fossils are also the most important tool for dating the rocks in which they are preserved. Because species only exist for a certain amount

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

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

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

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

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

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

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

CHAPTER AUTHORS

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3 Fossils

Review

amber • *a yellow or yellowish-brown hard translucent fossil resin that sometimes preserves small soft-bodied organisms inside.*

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

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.*

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

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

Lagerstätte

The "soft" tissues of an organism, such as skin, muscles, and internal organs, are typically not preserved as fossils. Exceptions to this rule occur when conditions favor rapid burial and mineralization or very slow decay. The absence of oxygen and limited disruption of the sediment by burrowing are both important for limiting decay in those deposits where soft tissues are preserved. Examples of such exceptional preservation, also called *Lagerstätte*, from the West include leaves and insects preserved in *amber*, and bones and insects preserved in asphalt at the La Brea Tar Pits. Another recently discovered example is the Indian Springs Lagerstätte exposed in the northern part of the Montezuma Range, in Esmeralda County, Nevada. This fossil assemblage includes the remains of many animals with hard (mineralized) skeletons, such as *echinoderms* and brachiopods, but many of these fossils also preserve non-mineralized parts, such as tentacles, gut tracts, and soft appendages.

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 the **Law of 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.

Fossils also have helped geologists piece together the complicated geology of North America's northwest coast. Fossils were one of the most important pieces of evidence that **terranes** had moved to assemble the edge of the continent as we now know it. For example, similar-aged but very different fossils that are now found in close geographic proximity can be explained by their host rocks having moved from their original locations. This is called **paleobiogeography**.

See Chapter 1: Geologic History to learn more about accreted terranes.

Ancient Biodiversity

Since life began on Earth more than 3.7 billion years ago, it has continuously become more abundant and complex. It wasn't until the beginning of the **Cambrian** period, around 543 million years ago, that *complex life*—living things

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.**

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.

Review

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

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

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

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

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

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

3 Fossils

Review

mass extinction • *the extinction of a large percentage of the Earth's species over a relatively short span of geologic time.*

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

passive margin • *a tectonically quiet continental edge where crustal collision or rifting is not occurring.*

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.*

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

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

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

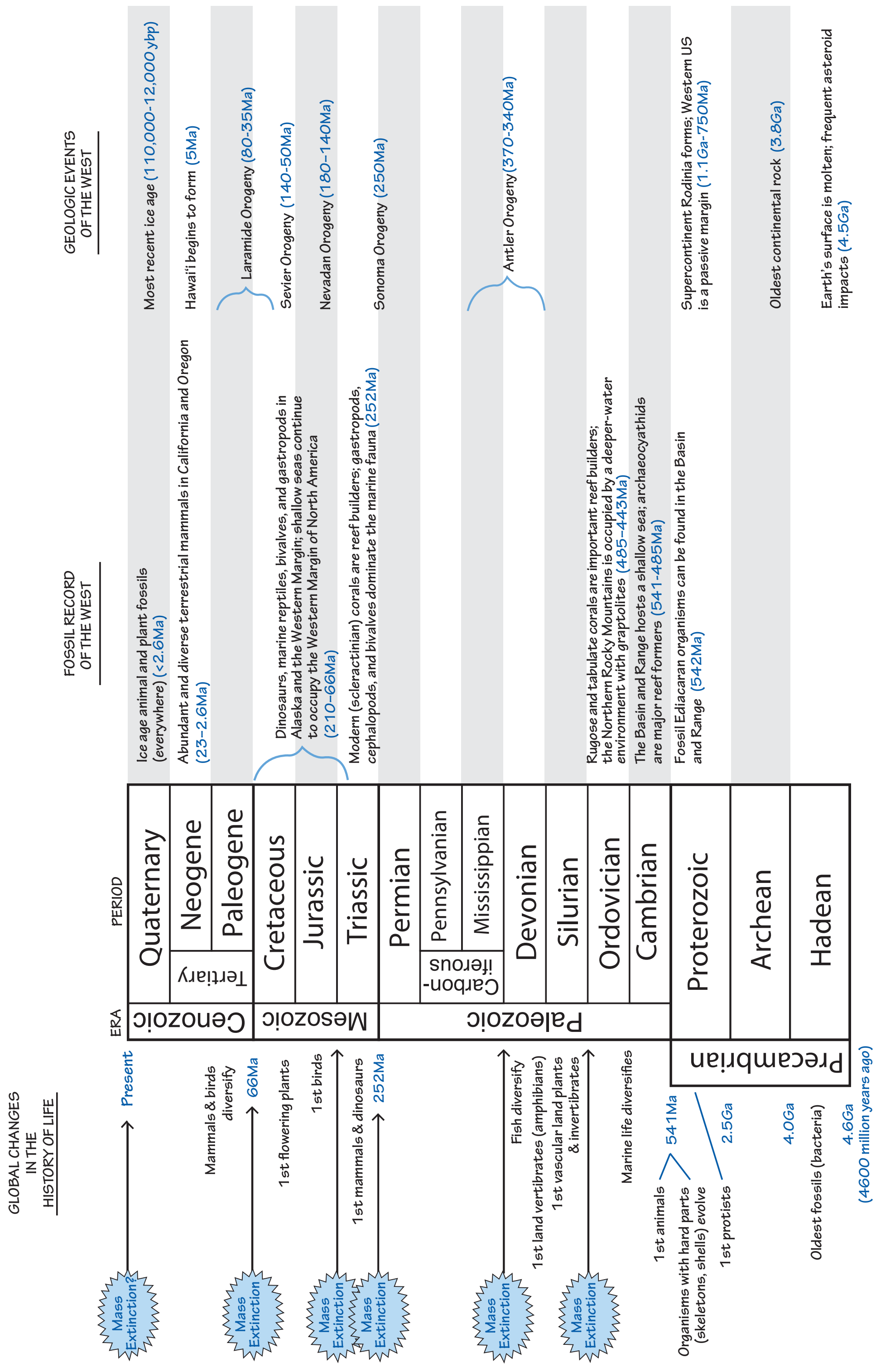


Figure 3.1. The history of life in relation to global and regional geological events and the fossil record of the Western US. (Time scale is not to scale.)

Fossils 3

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

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.

Fossils of the Western US

Western rocks preserve an excellent fossil record of the history of life (*Figure 3.1*)—so much so, in fact, that it is impossible to describe all of it here. We will therefore highlight the major types of fossils present in most of the geologic periods represented by rocks in each state. The resources at the end of the chapter should be consulted for details, especially for identifying particular fossils you might find.

Fossils of the Basin and Range

Region 1

During the early **Paleozoic**, the area that is now the Basin and Range was a **passive continental margin** with no tectonic activity, similar to the east coast of the US today. A warm shallow sea flooded what is now Nevada, and **trilobites** were abundant and diverse (*see Figure 3.21,* see box p. 101). During the Cambrian, **reefs** were built by an extinct group of **sponge**-like organisms known as **archaeocyathids** (see box p. 86). During the **Ordovician** and **Silurian**, these were replaced by reefs built by **rugose** and **tabulate corals** (*Figure 3.2,* see box p. 87) along with **brachiopods** (*Figure 3.3,* see box p. 88) and **bryozoans** (colonial **filter-feeding** animals that build **calcium carbonate** skeletons, *Figure 3.4)*. One kind of brachiopod found in **Mississippian** rocks in northern California and Oregon is among the largest brachiopods in the world: *Titanaria* (*Figure 3.5*) reached shell widths (along the hinge line) of more than 35 centimeters (14 inches). In deeper waters, planktonic **graptolites** were common.

The **Triassic** and **Jurassic** rocks of Oregon testify to major global changes in marine life, especially when compared to the Paleozoic. The once-abundant brachiopods on the seafloor are gone, replaced by faunas composed primarily of burrowing **bivalves** and **gastropods**. Tabulate and rugose corals were replaced by **scleractinian** corals, which were building reefs in this region by the mid-Triassic (*see Figure 3.2D*).

Region 1

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

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.*

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

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

3 Fossils

Region 1

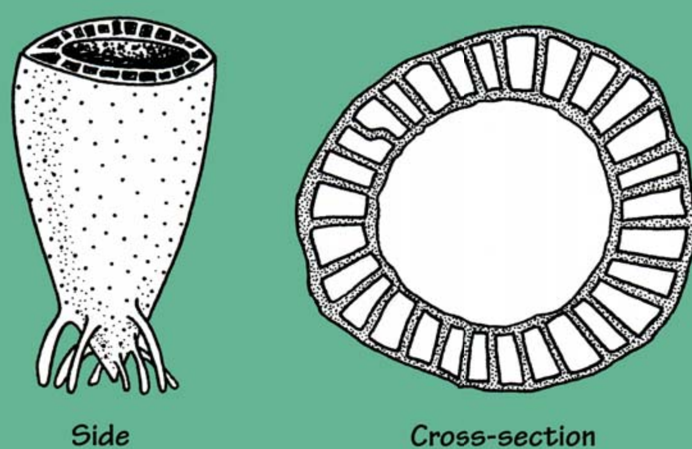
ammonoid • *a member of a group of extinct cephalopods belonging to the Phylum Mollusca, and posessing a spiraling, tightly coiled shell characterized by ridges, or septa.*

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

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

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.



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

Ammonoid cephalopods (*Figure 3.6*) also diversified during the Triassic, and their fossils can be found in Oregon, California, and Nevada. Swimming with (and probably feeding on) these ammonoids were marine reptiles called **ichthyosaurs** (*Figure 3.7,* see box p. 92). *Shonisaurus popularis* (*Figure 3.7B*) was an ichthyosaur first discovered in Berlin, Nevada in the mid-1800s. It lived around 217 million years ago, while Nevada was still covered by the ocean. In contrast to Jurassic and **Cretaceous** ichthyosaurs, *Shonisaurus* (along with other early ichthyosaurs) is thought to have lacked dorsal fins. *Shonisaurus* was over 15 meters (50 feet) long and was the largest known ichthyosaur until 2004, when an even larger species was discovered in British Columbia.

Nevada's shallow seas persisted into the Jurassic and part of the Cretaceous, and remained inhabited by ammonoids and bivalve mollusks (*Figures 3.8* and *3.13*). In the northernmost part of the Basin and Range (northern California and southern Oregon), bivalves called **rudists** (*Figure 3.9*) frequently formed

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.

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 domed 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, or scleractinians, appeared in the Triassic, and include both solitary and colonial species. Many modern scleractinian corals have photosynthetic symbiotic algae called zooxanthellae in their tissues. These algae provide nutrition to the coral polyps, helping them to grow more rapidly.

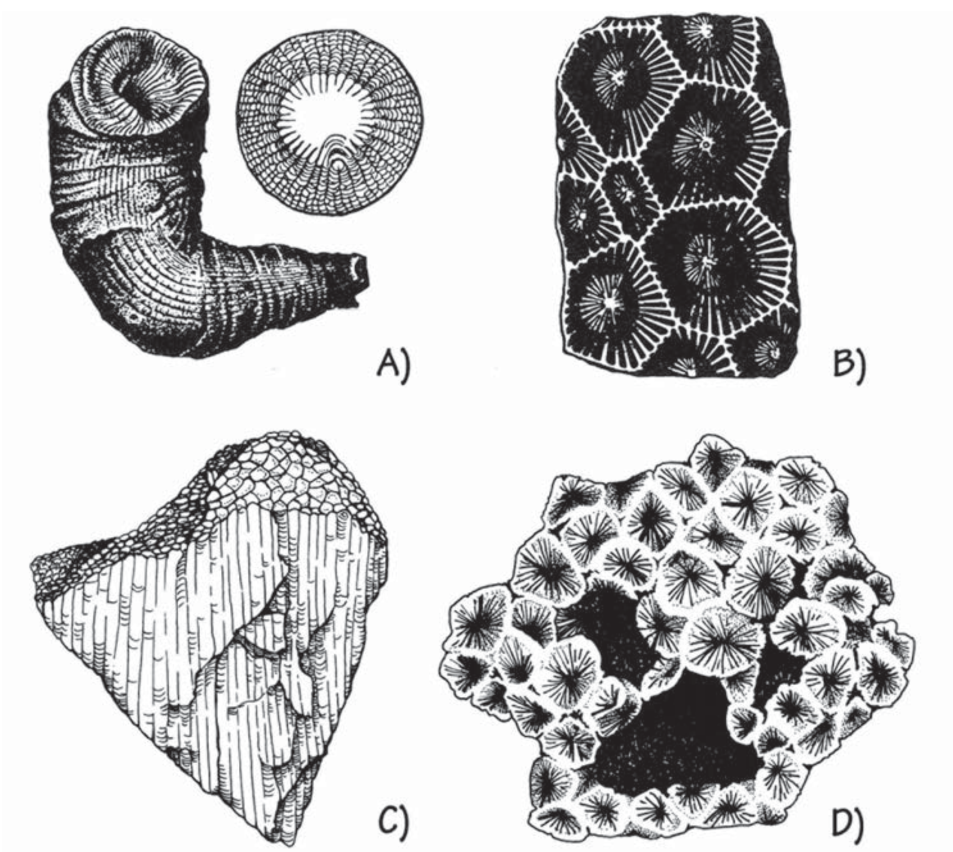


Figure 3.2: Corals. A) Solitary rugose ("horn") coral, Campophyllum, *up to 20 centimeters (8 inches) long, Devonian. B) Colonial rugose coral,* Lithostrotion, *Carboniferous. C) Tabulate coral,* Favosites, *Devonian. D) Colonial scleractinian coral,* Kompsasteria, *Triassic, Alaska.*

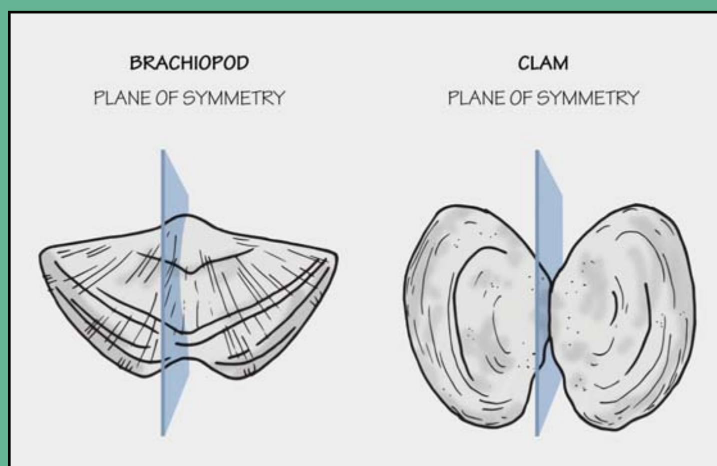
dinosaur • *a member of a group of terrestrial reptiles with a common ancestor and thus certain anatomical similarities, including long ankle bones and erect limbs.*

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

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

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), while most bivalves have a plane of symmetry between the valves.

reef-like mounds. Rudists became extinct with the **dinosaurs** and many other species at the end of the Cretaceous.

The sea retreated during the late Cretaceous, and the Basin and Range became entirely terrestrial. During the **Cenozoic** era, the region was home to diverse and abundant mammals such as camels, **mammoths**, and rhinoceroses. Freshwater lakes dotted the area and were inhabited by fish such as sticklebacks, Nevada killifish, and topminnows.

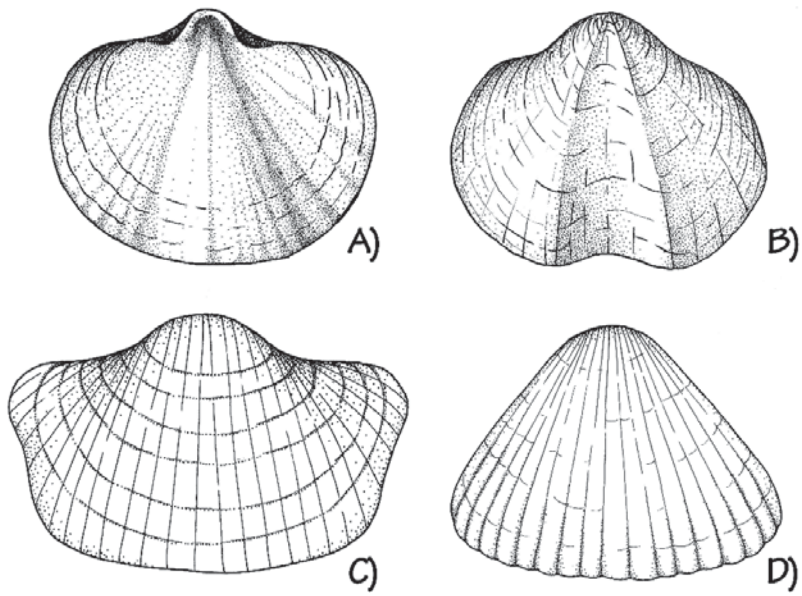


Figure 3.3: Paleozoic brachiopods. A) Strophatrypa, *Silurian of Alaska, about 1 centimeter (inches 0.4 inches). B)* Warrenella, *Devonian of Oregon, about 2 centimeters (1 inch). C)* Retzia compressa, *Carboniferous of California, about 3 centimeters (1.2 inches). D)* Kirkidium alaskense, *Silurian of southeastern Alaska, about 8 centimeters (3 inches).*

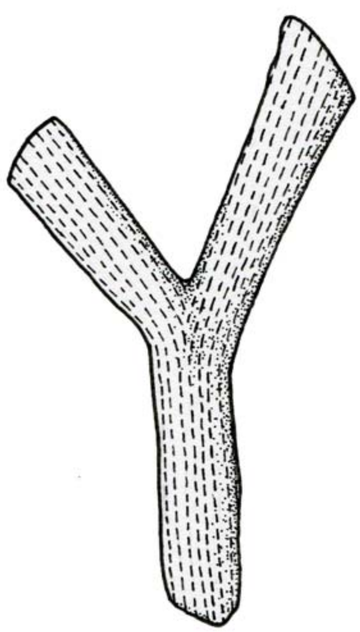
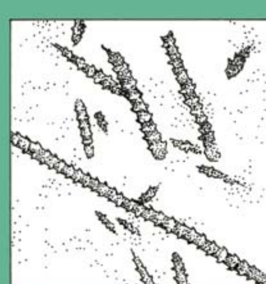


Figure 3.4: A branching bryozoan colony. Some bryozoans had skeletons resembling branching corals, but with smaller cavities for the individual organisms. About 2–5 centimeters (1–2 inches) tall.

Figure 3.5: Specimen of the giant brachiopod Titanaria, *from the Mississippian of Oregon. The specimen is slightly broken; the dotted line shows its reconstructed size and shape. This specimen, from the collections of the National Museum of Natural History, Smithsonian Institution, in Washington, DC, is one of the largest brachiopod fossils in the world.*

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.

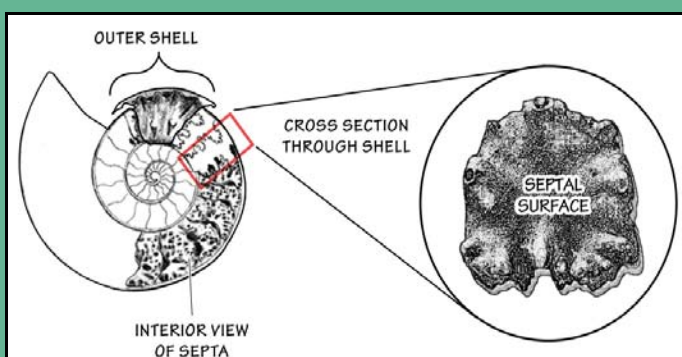


Rock with many fragments of* Climacograptus *colonies.

Restoration of what graptolite colonies may have looked like when they were alive, floating in the water.

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.

Figure 3.6: Triassic ammonite, Harpoceras, *about 15 centimeters (6 inches) in diameter.*

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

Ichthyosaurs

Ichthyosaurs are an extinct group of Mesozoic marine reptiles that evolved in the Triassic and went extinct in the late Cretaceous. They superficially resembled dolphins with long, toothed snouts, dorsal fins, and vertical tail fins. These animals were descended from land-dwelling reptiles, and evolved dorsal fins and vertical tails independently from other animal groups. These structures were not bony and are only known due to a few exceptionally preserved specimens that show outlines of the entire animal. Ichthyosaurs are known to have given live birth, and some may have been warm-blooded.

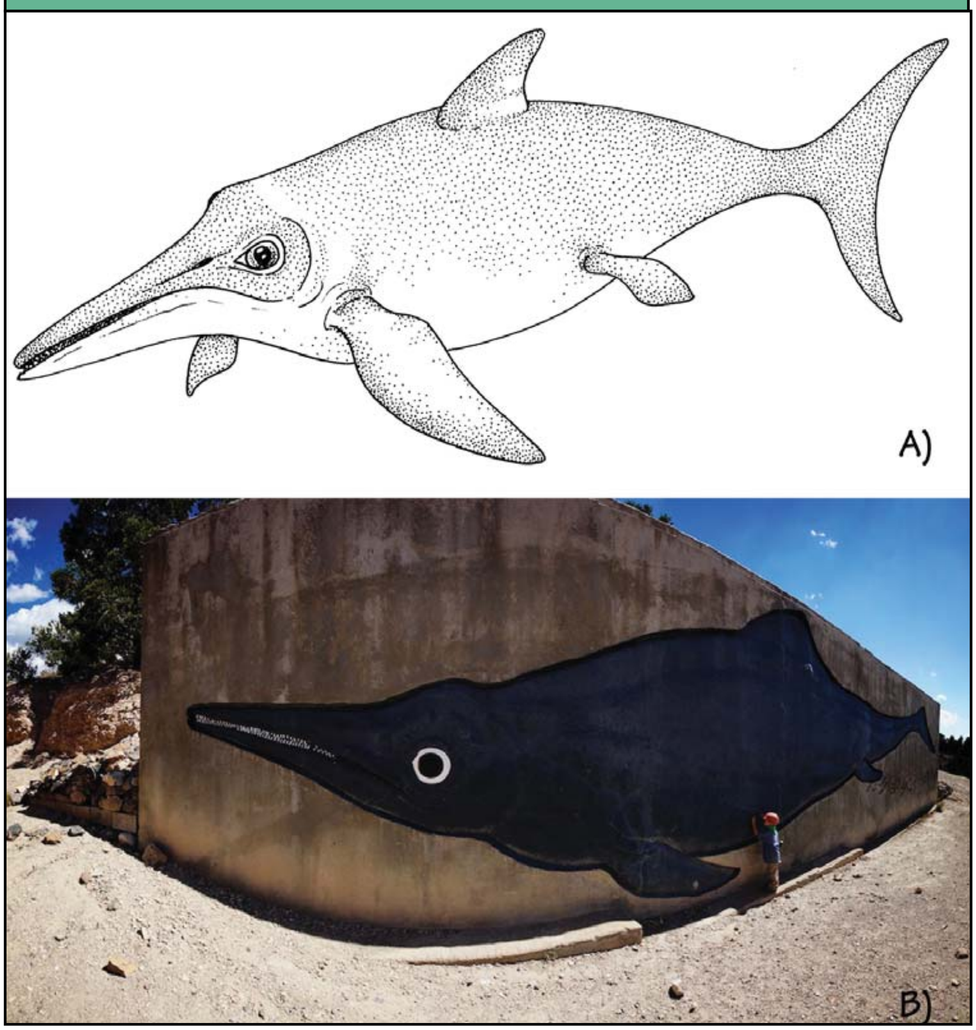


Figure 3.7: Ichthyosaurs. A) A typical ichthyosaur, as it might have looked in life. B) Shonisaurus, *the largest known ichthyosaur, from the Triassic of Nevada. Painting at Ichthyosaur State Park, Nevada.*

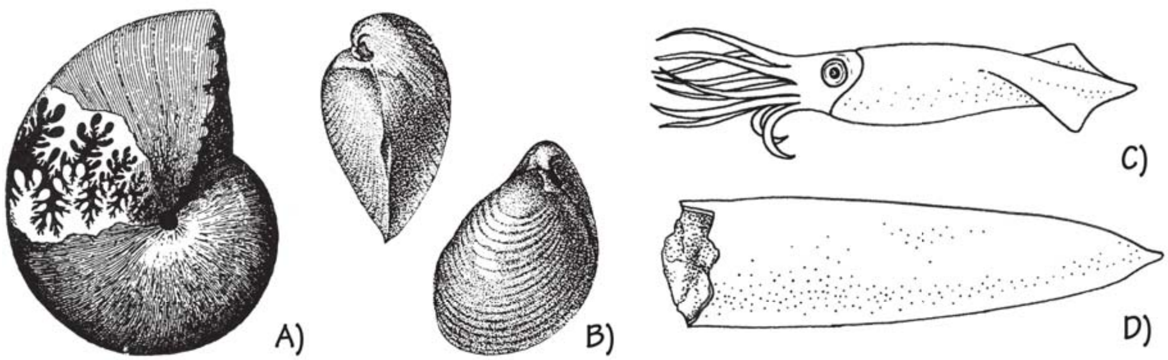


Figure 3.8: Jurassic marine mollusks. A) Ammonite, Phylloceras*, about 15 centimeters (6 inches) in diameter. B) Bivalve,* Buchia piochii*, about 5 centimeters (2 inches) in diameter. C. Reconstruction of a typical belemnite as it appeared alive. D) Belemnite internal shell; most are 5–10 centimeters (2.5–5 inches) long.*

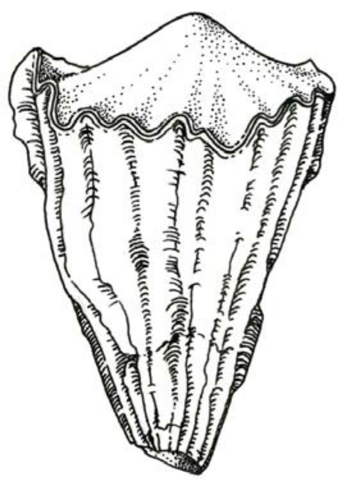


Figure 3.9: Rudists were unusual cone- or cylinder-shaped bivalves that clustered together in reef-like structures and went extinct at the end of the Mesozoic era. They ranged in size from a few centmeters to more than 50 centmeters (1.5 feet) tall.

During the last glacial period (**Pleistocene**), southern Oregon was home to many species of large and now-extinct mammals, including *Arctodus,* the giant short-faced bear, which was 1.8 meters (6 feet) tall at the shoulder with 25-centimeter-long (10-inch-long) paws (*Figure 3.10*). Alongside these massive mammals lived *Teratornis,* a giant vulture with a wingspan of up to 3.8 meters (12.5 feet)—the modern California condor, in comparison, has only a 2.7-meter (9-foot) wingspan (*Figures 3.11* and *3.12*).

3 Fossils

Region 1

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

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

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

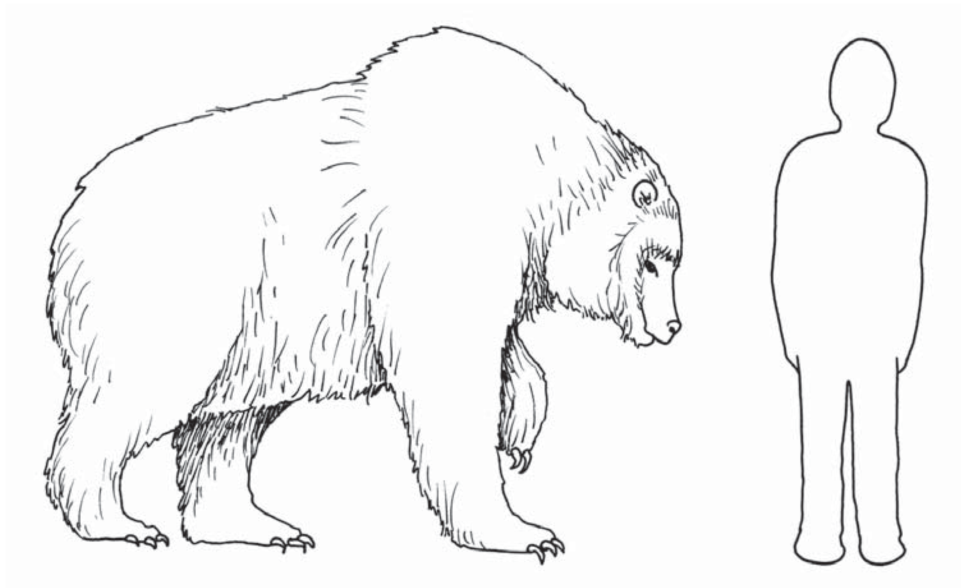


Figure 3.10: Reconstruction of the giant short-faced bear Arctodus*, compared to a six-foot human.*

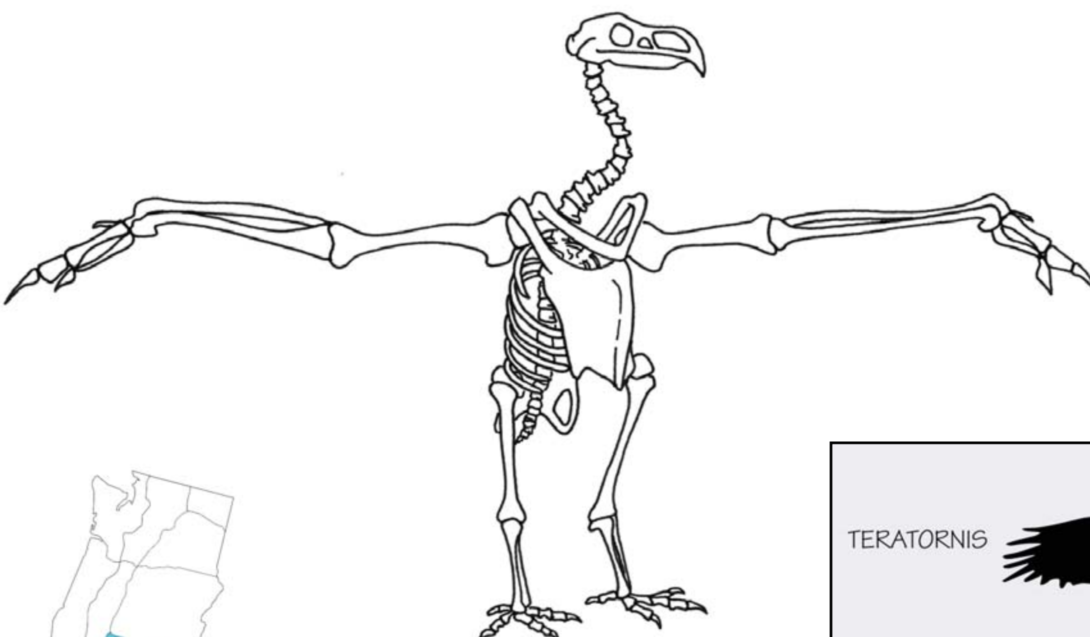


Figure 3.11: Skeleton of Teratornis*, a giant predatory/scavenging bird similar to a modern condor.*

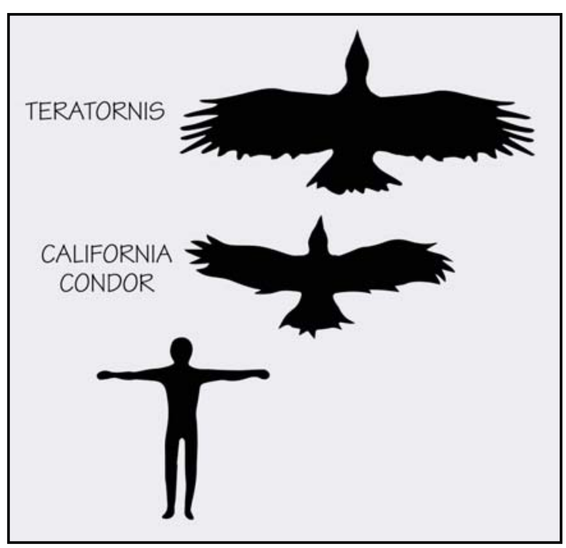


Figure 3.12: Teratornis *size comparisons.*

Fossils of the Columbia Plateau
Region 2

During the Jurassic and part of the Cretaceous, ammonoid cephalopods and bivalves were abundant and diverse in the shallow sea that covered this region (*Figure 3.13*).

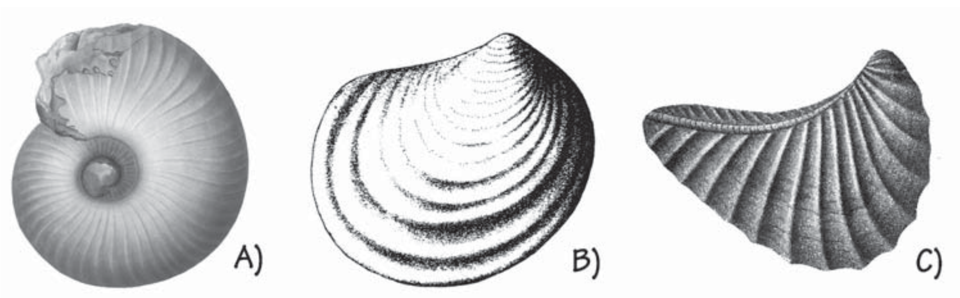


Figure 3.13: Cretaceous marine mollusks. A) Ammonite, Canadoceras newberryanum*, Cretaceous of California, about 15 centimeters (6 inches) in diameter. B) Inoceramid bivalve, Cretaceous of Oregon, about 12 centimeters (5 inches). C. Bivalve,* Trigonia*, Cretaceous of California, about 6 centimeters (2 inches).*

Several sites in Oregon and Washington preserve abundant Cenozoic terrestrial fossils, especially plants and mammals, as a result of widespread **volcanic** activity in the area. During the **Neogene**, the Columbia Plateau was covered in large volcanic outflows of flood **basalt**. These outflows are associated with the same **hot spot** that now heats Yellowstone National Park. Some of these lava flows overran forests, leaving behind empty molds of **trees**. At some localities (such as Ginkgo Petrified Forest State Park in Washington) petrified (permineralized) wood has been preserved either by burial within lake sediments or in volcanic mudflows (*Figure 3.14*). Tree species thus preserved include swamp cypresses, hemlock, spruce, oak, and **ginkgo**.

See Chapter 2: Rocks to learn more about the Columbia flood basalts.

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

The **Eocene** Clarno Formation, exposed at several sites in central Oregon, consists of a series of **volcanic ash** deposits, which quickly buried plants and animals and protected them from decomposition. The resulting spectacular fossils include hundreds of kinds

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

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.*

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

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

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 3.14: A petrified log at the Ginkgo Petrified Forest State Park, central Washington. About 0.6 meters (2 feet) in diameter.

of leaves and seeds, as well as insects, mammals, and other animals. The famous Clarno "nut beds" exposed in Wheeler County in north-central Oregon have yielded more than 170 species of fossil seeds (*Figure 3.15*). Clarno fossil leaves include palms, bananas, and many other flowering tree species (*Figure 3.16*). These fossils indicate that between 50 and 44 million years ago, the **climate** of what is now the Pacific Northwest was warm and humid.

Figure 3.15: Fossil seeds from the Clarno "nut beds": A) Walnut (Juglans)*, about 2 centimeters (0.8 inches). B) Oak acorn* (Quercus)*, about 2.5 centimeters (1 inch).*

The Oligocene John Day Formation is another series of volcanic ash layers rich in fossil plants and animals, which formed between 35 and 25 million years ago. The climate was cooler, but species diversity is still high. Fossils found in the John Day include more than 60 species of plants—including the "dawn

Region 2

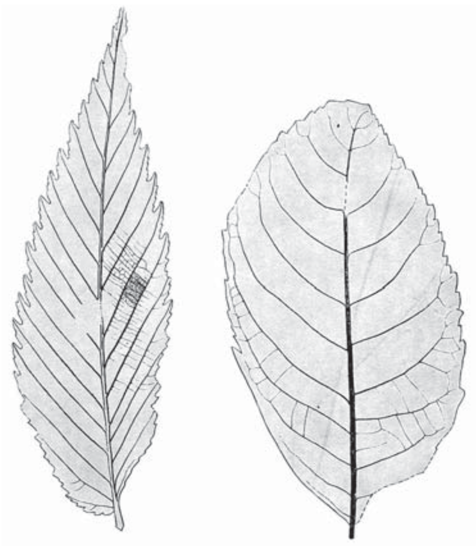


Figure 3.16: Fossil leaves of broadleaf (flowering) trees, from the Clarno Formation. Leaves are about 5 centimeters (2 inches) long.

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

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

redwood" *Metasequoia* (*Figure 3.17*), a relative of sequoias that was believed to have gone extinct in the **Miocene**, until living specimens were discovered in China. *Metasequoia* differs from *Sequoia* (the giant redwood) in that it is deciduous. Living *Metasequoia* leaves are identical to late Cretaceous fossils, indicating that this species has retained much the same form for over 65 million years. The John Day Formation also contains more than 100 species of mammals, including **oreodonts**, saber-toothed cats, horses, camels, and rodents (*Figure 3.18*).

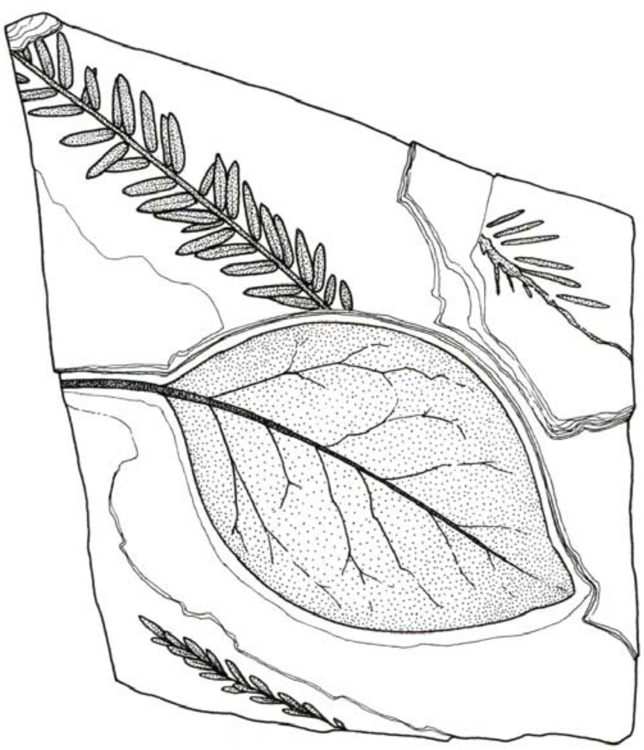


Figure 3.17: The "dawn redwood," Metasequoia *(top) with an unidentified broadleaf angiosperm. Slab is about 5 centimeters (2 inches) wide.*

Region 2

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

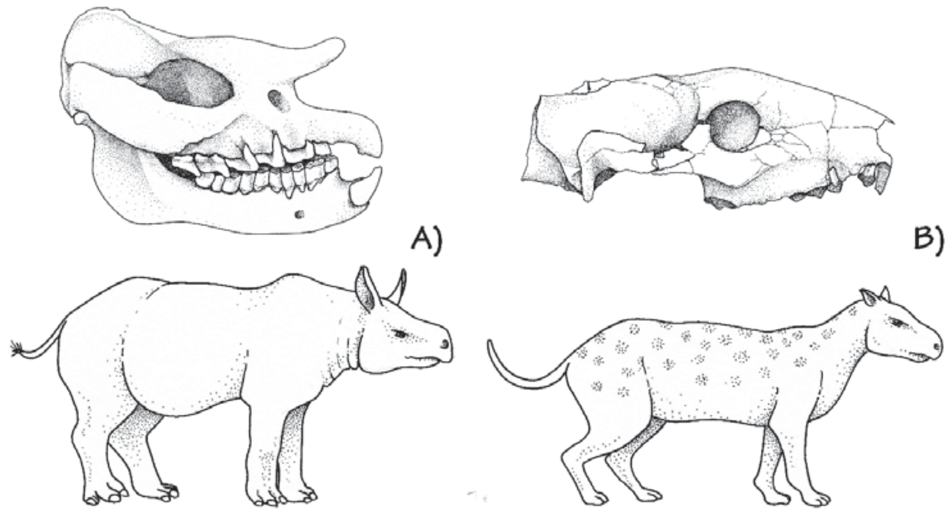


Figure 3.18: Mammal fossils from the John Day beds of Oregon. A) A hornless rhinoceros, Teletoceras*; skull is roughly 20 centimeters (10 inches) long. B) A small sheep-like herbivorous mammal called an oreodont,* Eporedon*; skull is about 12 centimeters (5 inches) long.*

Following the eruption of the Columbia River Basalt flows, between 17 and 12 million years ago, further ashfalls from eruptions in the Cascades formed the Mascall Formation, which includes another diverse assemblage of mammals (including horses, camels, rhinoceroses, bears, pronghorn, deer, weasels, raccoons, and cats). The Mascall's plant fossils, including oak, sycamore, maple, ginkgo, and elms, reflect the region's cooling climate during this time period.

The flood basalts also contain one of the world's most unusual fossils—the "Blue Lake Rhino," in Grant County, Washington (*Figure 3.19*). It is an external mold of a rhinoceros, which lived around 14.5 million years ago. It apparently formed when lava flowed into the water, forming pillows. These were still hot enough to be soft but not hot enough to completely burn away the body.

The Clarno, John Day, and Mascall formations are collectively known as the John Day Fossil Beds. They span over 40 million years and can be best seen in and around John Day Fossil Beds National Monument in Wheeler and Grant Counties in north-central Oregon.

Large mammals, including woolly mammoths and camels dating from the **Quaternary**, have been found in a variety of locations representing ancient riverbanks and lakes. The oldest known **mastodon** (another relative of modern elephants) in North America comes from the Ringold Formation at White Bluffs in south-central Washington (*Figure 3.20*).

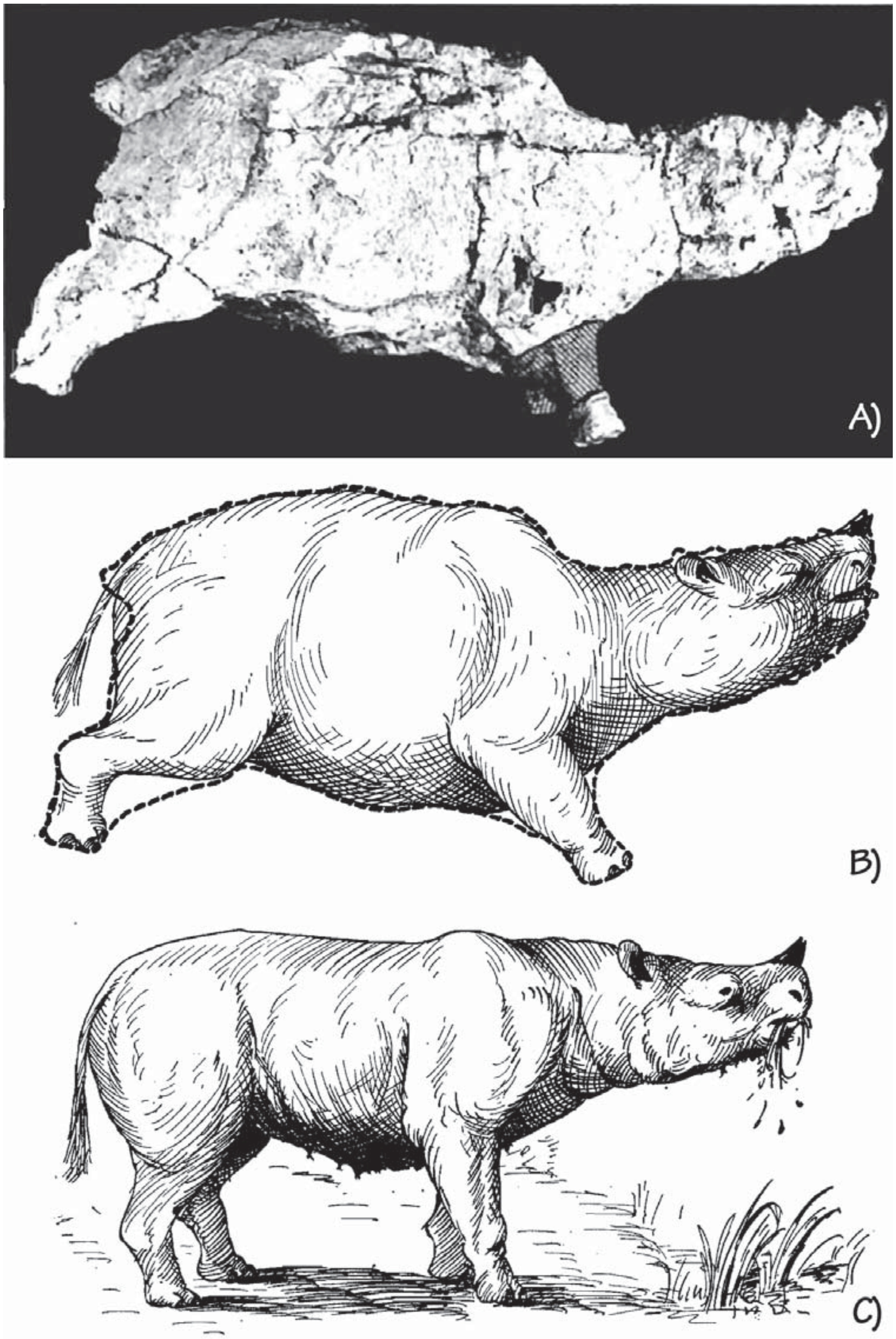
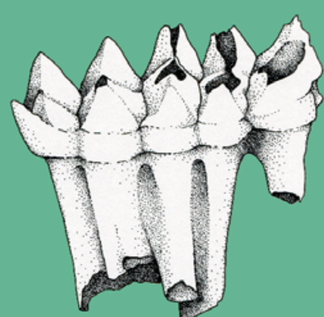


Figure 3.19: The "Blue Lake Rhino," probably Diceratherium. *A) External cast made by applying plaster-soaked burlap to the sides of the hollow natural mold of the body, and then removing it in sections. Total length about 2.4 meters (7 feet). B) What the carcass may have looked like before it was covered with lava. C) Reconstruction of the living animal.*

Mastodons and Mammoths

People frequently confuse these two kinds of ancient elephants (or, more technically, proboscideans). Both were common during the Pleistocene, but they had different ecological niches and are usually found separately. Mammoths are from the same line of proboscideans that gave rise to African and Asian elephants; mastodons are from a separate line of proboscideans that branched off from the modern elephant line in the Miocene. Mastodons have a shorter, stockier build and longer body; mammoths are taller and thinner, with a rather high "domed" skull. In skeletal details, the quickest way to tell the difference is with the teeth: mastodons have teeth with conical ridges, a bit like the bottom of an egg carton; mammoths, in contrast, have teeth with numerous parallel rows of ridges. The teeth are indicative of the two species' ecological differences. Mastodons preferred to bite off soft twigs and leaves, 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 softer vegetation. About 25 centimeters (almost 1 foot) long.

Regions 2–3

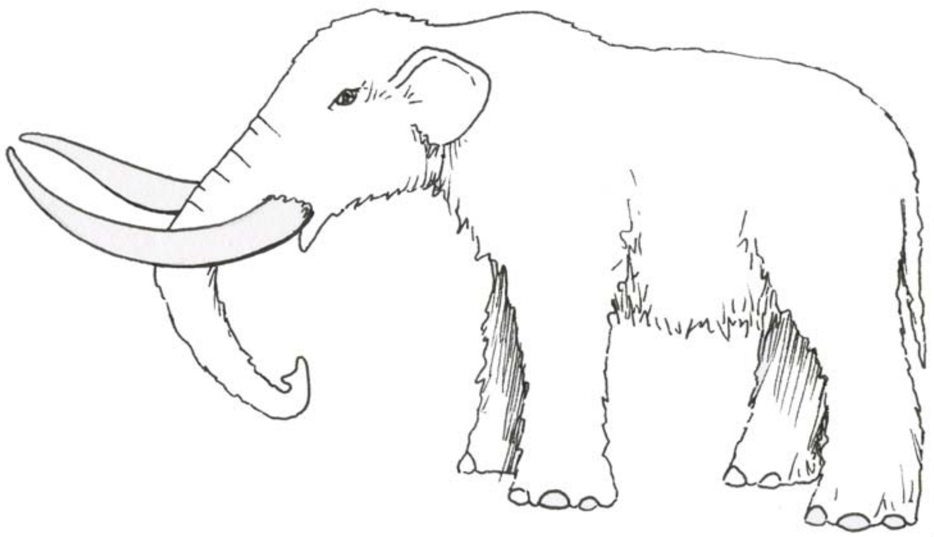


Figure 3.20: A Pleistocene mastodon, *Mammut americanum.*

slate • a fine-grained, foliated metamorphic rock derived from a shale composed of volcanic ash or clay.

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

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

Fossils of the Northern Rocky Mountains
Region 3

The region that is now northeastern Washington State has few unmetamorphosed sedimentary deposits. Stevens and Pend Oreille Counties in Washington contain some Cambrian rocks that hold trilobites (*Figure 3.21*) and brachiopods. On rare occasions, these rocks also yield sponges. There are also Ordovician **slates** containing fossil graptolites and **conodonts**, indicating that a deep-water marine community was present during at least part of this time.

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 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.

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

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

Figure 3.21: Cambrian trilobite Olenellus. *These and similar forms occur in Cambrian rocks in California and Nevada. They are typically 5–10 centimeters (3–6 inches) long.*

Fossils of the Cascade-Sierra Mountains
Region 4

Permian-age rocks in the northern Cascades contain gastropods and corals, along with fusulinid **foraminifera** shells (*Figure 3.22*). Fusulinids are the rice-sized shells of single-celled, amoeba-like organisms that lived in huge numbers on the sea floor during the late Paleozoic.

Late Triassic rocks found in the Cascades and Sierra Nevada contain abundant ammonoids and nautiloids, as well as brachiopods and oysters. Jurassic rocks exposed in Stanislaus and San Joaquin Counties in central California indicate

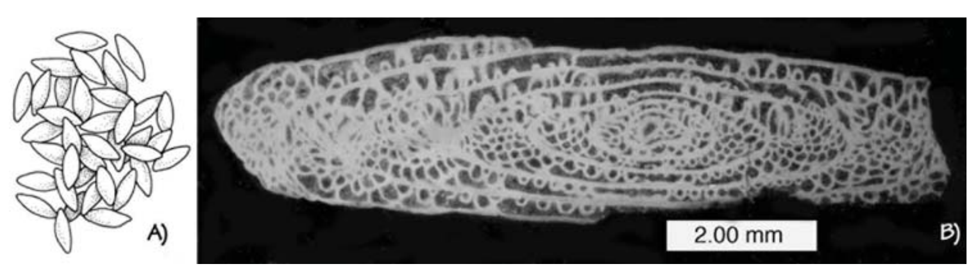


Figure 3.22: One-celled fusulinid shells from the Permian. A) A cluster of shells, the size and shape of large rice grains. B) Photograph of a cross section through a single fusulinid, as seen through a microscope.

Region 4

a coastal marine environment, with marine fossils including sea urchins, ammonoids, and bivalves. Terrestrial fossils are primarily plants such as **cycads** and ginkgos.

Most Neogene fossils from the Cascades represent terrestrial forest and grassland communities. Fossil plants include petrified wood from willow, yew, swamp cypresses (*Figure 3.23*), and *Metasequoia* (*see Figure 3.17*). Fossil vertebrates are less common, but include rabbits, beavers, camels, and the extinct horses *Parahippus, Archaeohippus,* and *Merychippus* (*Figure 3.24*). *Merychippus* was about 90 centimeters (3 feet) tall and had three toes, as opposed to the single toe found in modern horses. It is also the first horse known to have primarily grazed on grasses, rather than to have browsed on shrubs, as earlier horses did.

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.*

Figure 3.23: Cross section of the permineralized trunk of a species of cypress (Taxodium) *from the Miocene of Washington. About 0.3 meters (1 foot) in diameter.*

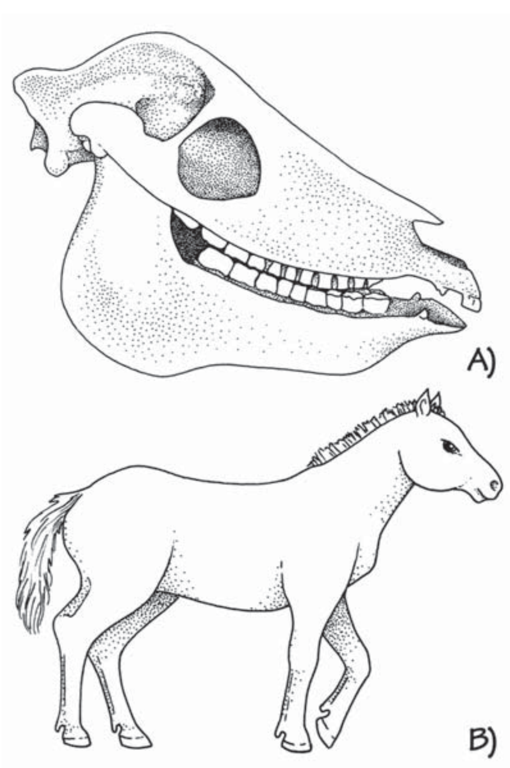


Figure 3.24: A primitive horse, Merychippus. *A) Skull, about 40 centimeters (16 inches) long. B) Reconstruction.*

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.

plesiosaur • a member of 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.

Fossils of the Pacific Border
Region 5

The Pacific Border includes terranes and former island arcs that **accreted** onto the West Coast, along with sediments deposited after this merger. Nearly every newly-exposed hillside or roadcut in this region exposes fossiliferous sediment, even in developed areas.

Fossil-bearing rocks of both Jurassic and Cretaceous age can be found in this region in northwestern California and southwestern Oregon. Jurassic marine fossils include abundant clams such as *Buchia* (*see Figure 3.8B*) and ammonoids (*see Figure 3.8A*). During the Cretaceous, sea levels were higher, and the Pacific shoreline was much further inland. The shore was lined with palms, and the waters were filled with bivalves such as *Inoceramus* (*see Figure 3.13B*) and *Trigonia* (*see Figure 3.14C*). Recognizable relatives of many extant bivalves, such as oysters, also became common during the Cretaceous. Ammonoid cephalopods, including the straight-shelled *Baculites* (*Figure 3.25*), were extremely diverse and can be found in many Cretaceous rocks. Marine reptiles such as ichthyosaurs, **plesiosaurs**, and **mosasaurs** are also found through much of coastal California.

Although there were presumably many dinosaur species on land, only a few dinosaur fossils have been found in this region. These include the bones of hadrosaurs and the armor-plated ankylosaur *Aletopelta* (*Figure 3.26*). One specimen of *Aletopelta* found in California evidently floated out to sea, where its armor plates and spines were encrusted by bivalves!

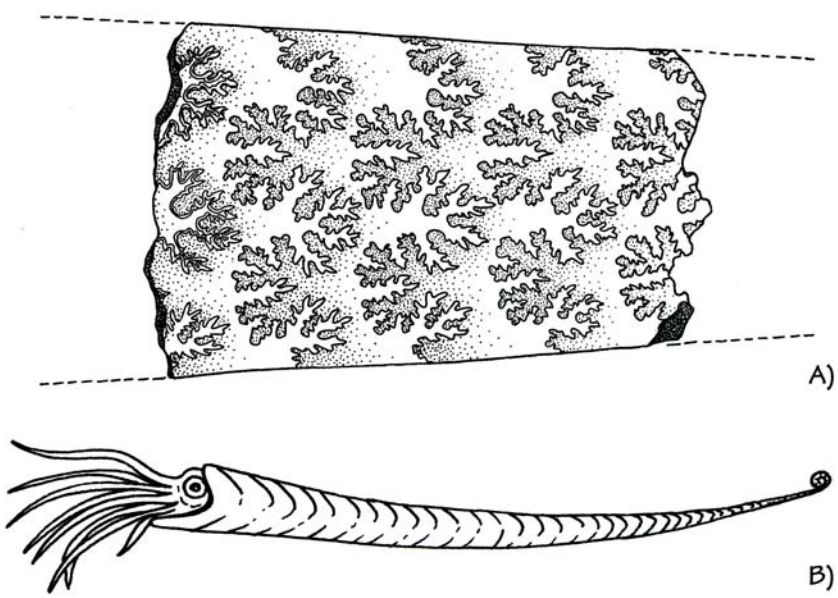


Figure 3.25: A) Broken specimen of Baculites, *a straight-shelled ammonite from the Cretaceous, showing internal suture lines. Usually around 3-4 centimeters (2 inches) in diameter. B) Reconstruction.*

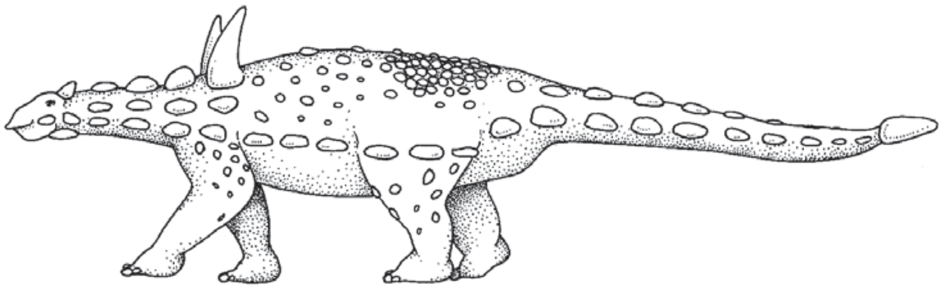


Figure 3.26: Reconstruction of the Cretaceous ankylosaur Aletopelta *from California, about 6 meters (20 feet) long.*

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

The **Paleogene** marine fossils of the Pacific Border strongly resemble the hard-shelled organisms living in the Pacific today, although some may seem geographically out of place (an important piece of evidence for environmental change through geological time). Gastropods and bivalves are the most

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. 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 the modern oceans.

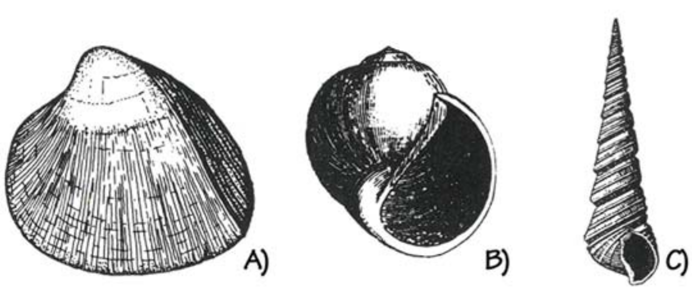


Figure 3.27: Eocene marine mollusks from Washington, Oregon, and California. A) Bivalve, Nemocardium, *about 3 centimeters (1.3 inches). B) Gastropod,* Natica, *about 2 centimeters (1 inch). C) Gastropod,* Turritella, *about 3 centimeters (1.3 inches).*

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.*

Gastropods

Commonly known as snails, gastropods are among the most diverse marine organisms in the ocean today. Modern gastropod mollusks encompass terrestrial, fresh-water, and marine species, and include varieties with and without shells (e.g., slugs). Only insects have more named species. The soft parts of gastropods are similar to those of bivalves, but typically have coiled shells. Gastropods are present in Paleozoic and Mesozoic rocks but are more common in Cenozoic rocks.

common marine fossils of the Paleogene and include clams, oysters, whelks (Buccinidae), moon snails (Naticidae), and tower snails (Turritellidae) (*Figure 3.27*). Crabs are sometimes common, although it is rare to find fossils of whole individuals, as these organisms typically break apart after death. However, some locations preserve crabs (and other fossils) within **concretions** (*Figure 3.28*). Concretions are hard, layered **nodules**, often with a different chemical makeup from the surrounding rock. They form when minerals precipitate (crystalize) around a nucleus within the sediment. While concretions are not fossils themselves, they may contain fossils—even trace fossils, as many organisms line their burrows with mucus, and the decay of that mucus may begin the formation of a concretion.

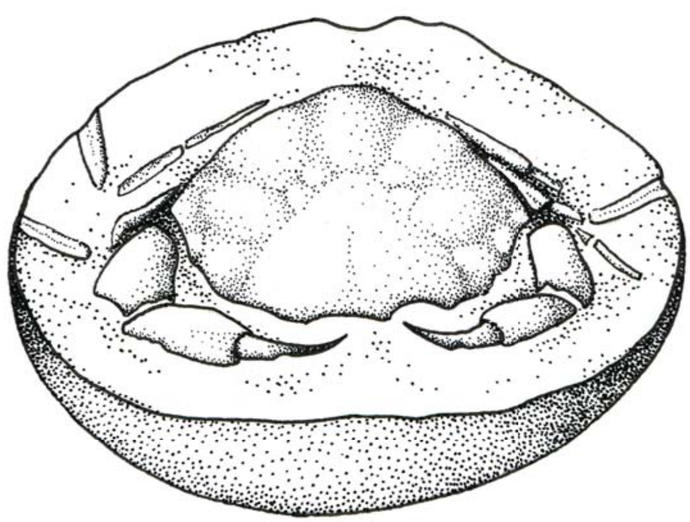


Figure 3.28: The crab Zanthopsis vulgaris*, preserved in a concretion from Oligocene strata in Vernonia, Oregon. Specimen is about 10 centimeters (4 inches) wide.*

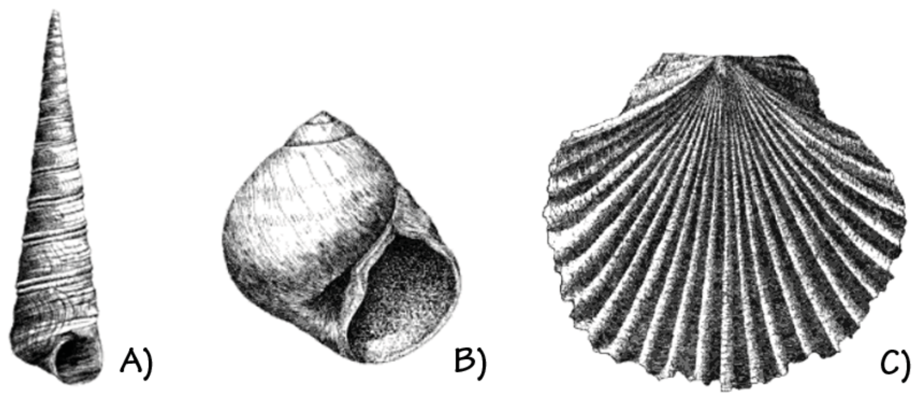


Figure 3.29: Neogene (Miocene–Pliocene) fossil mollusks of the coast of Oregon and California. A) Turritella*, about 3 centimeters (1.3 inches). B)* Polinices*, about 2 centimeters (1 inch). C)* Flabellipecten*, about 4 centimeters (1.5 inches).*

Region 5

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

regression *• a drop in sea level.*

asphalt *• a black, sticky, semi-solid and viscous form of petroleum.*

The general character of fossils from the Neogene is similar to that of the Paleogene, with gastropods such as moon snails, whelks, and tower snails remaining important components of the marine fauna (*Figure 3.29*). Mussels, clams, scallops, and oysters are all common, and can often be found in the rocks exposed at beach cliffs along much of the Oregon and California coasts.

Prior to 100,000 years ago, much more of the coast was submerged, and the region was ultimately exposed when the expansion of **glaciers** caused a **regression** in sea level. The coasts of California, Oregon, and Washington and the central valley of California contain numerous Pleistocene-age fossil deposits. Bivalves and gastropods are the most common marine invertebrate fossils from this time, particularly scallops (*Pecten*) and oysters (*Ostrea*), but also clams such as *Saxidomus*, *Mya,* and *Clinocardium* and snails such as *Polinices, Neptunea, Turricula,* and *Cancellaria*.

During the Pleistocene, large terrestrial mammals were common, including mammoths, woolly rhinos, horses, camels, bison, saber-toothed cats, and dire wolves. The famous La Brea Tar Pits in downtown Los Angeles provide a spectacular window into the region's Pleistocene mammal communities. The tar pits formed around 40,000 years ago, when natural **asphalt** deposits began to seep up from cracks in the ground to form pools. As this asphalt seeped from the ground, it became covered with leaves and dust. Animals that wandered in became trapped, as did predators that arrived to eat the mired animals (*Figures 3.30, 3.31*). The oldest remains from La Brea have been dated to 38,000 years old, and the tar pits still continue to trap unsuspecting animals today.

As bones sink into the asphalt, it stains them dark brown or black, leading to the unique appearance of the fossils found here (*Figure 3.32*). Fossils of more than 600 species of animals and plants have been excavated from the asphalt here (*Figure 3.33*)—in addition to large mammals and birds, the tar pits have preserved a remarkable array of microfossils ranging from insects and leaves to pollen grains, seeds, and ancient dust.

Figure 3.30: A life-size model of a Columbian mammoth (Mammuthus columbi) *shown stuck in the tar outside the Page Museum at the La Brea Tar Pits in downtown Los Angeles. Columbian mammoths were close relatives of woolly mammoths, and became extinct about 11,000 years ago. They ranged from the southern US to Nicaragua and Honduras, but not as far north as the woolly mammoth.*

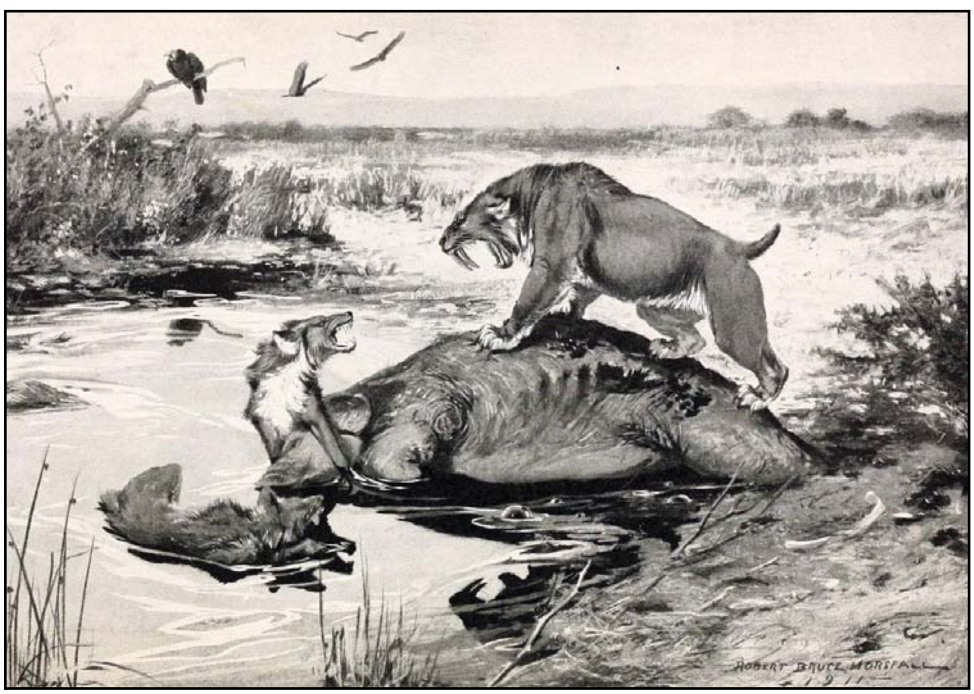


Figure 3.31: A 1911 illustration of several mammal species becoming mired in the tar pit—Smilodon fatalis *and* Canis dirus *fight over a* Mammuthus *corpse.*

Figure 3.32: Skeleton of the most common large mammal at the site, the dire wolf, Canis dirus.

Figure 3.33: Ongoing excavation of the asphalt deposit continues to uncover new fossils.

Region 5

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

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

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).*

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

Smilodon fatalis, the saber-toothed cat, is among the most famous species represented in the La Brea Tar Pits, and is well known for its prominently elongated canine teeth (*Figure 3.34*). While these animals are sometimes referred to as "saber-toothed tigers," they are not actually close relatives of tigers or any other living feline group. Elongated canines actually evolved separately in a number of cat-like lineages, including some groups more closely related to living marsupials than living cats. *Smilodon* belongs to the group known as "dirk-toothed" cats, which possess teeth with fine serrations. The elongated canines of *Smilodon* were also fairly thin and would have broken if they bit into bone, so these teeth would likely have been used to kill prey that was already subdued. The cats' most common prey were likely bison and camels, and dire wolves were probably their direct competitors. *Smilodon* became extinct during the Quaternary extinction around 10,000 years ago, along with many of the large mammals it utilized for food. These extinctions have been related to both **climate change** and hunting by humans, although the relative importance of each of these factors is still debated.

Figure 3.34: The skull of Smilodon fatalis.

Fossils of Alaska
Region 6

Although most of Alaska had not been assembled before the **Mesozoic**, the state does contain fossil-bearing rocks from the **Precambrian** through the Quaternary. The weakly metamorphosed Precambrian rocks in eastern Alaska contain **stromatolites** (*Figure 3.35*)—layered, mound-shaped fossils built by **cyanobacteria**.

See Chapter 2: Rocks for more information about stromatolites.

Figure 3.35: Stromatolite of the Baicalia *type showing curved laminations, found in late Proterozoic (800–1000-million-year-old) rocks in east-central Alaska. About 15 centimeters (6 inches) long.*

Carboniferous rocks found in parts of northern Alaska, including the Brooks Range, Point Hope, and Gates of the Arctic National Park, contain corals, brachiopods, gastropods, and **crinoids** (*Figure 3.36*).

Jurassic marine rocks in Alaska—found around Iliamna Lake in southern Alaska, and across the Brooks Range on the North Slope—contain abundant ammonites and bivalves (*Figure 3.37*).

Shallow marine rocks from the Cretaceous are well represented on Alaska's Northern Coastal Plain, around Norton Sound, the Kuskokwim Mountains, the Kenai Peninsula, and Kodiak Island. The Brooks Range and other mountains arose during the Cretaceous, which led to extensive erosion and deposition of sediment in shallow marine environments and coastal swamps. Alaska's Cretaceous marine fossils are dominated by modern groups such as bivalves and gastropods; bivalves, such as *Inoceramus* (*see Figure 3.13B*) are well represented in these rocks.

Although Alaska reached its present latitude during the Cretaceous, the world as a whole was much warmer, and fossils of dinosaurs, crocodilians, palms, and other temperate to tropical species are common in Alaskan rocks. Some Cretaceous dinosaurs found near the Colville River on the North Slope are spectacularly well preserved, containing more than half of their original bone material. Alaskan dinosaurs included herbivorous ceratopsians similar to *Triceratops*, such as *Pachyrhinosaurus* (*Figure 3.38*); *Alaskacephale,* a

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

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

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

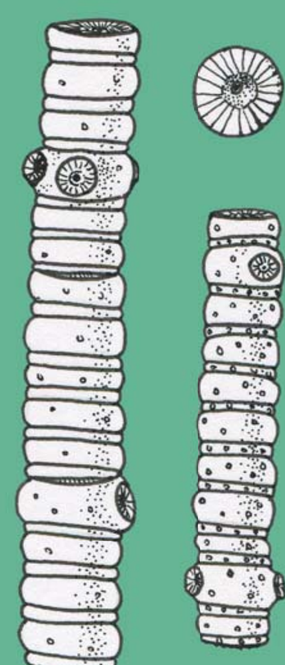
3 Fossils

Region 6

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.

Figure 3.36: Polished slab of limestone made up almost completely of crinoid bits and pieces, seen under a microscope.

pachycephalosaur (dome-headed dinosaurs similar to *Pachycephalosaurus*); and ankylosaurs, such as *Edmontonia*, the first dinosaur discovered in Alaska. Alaska even has its own native tyrannosaur, *Nanuqsaurus* (*Figure 3.39*), which was about half the length of *Tyrannosaurus rex.* Other carnivores included *Albertosaurus* and possibly *Gorgosaurus*. Plant fossils include *Parataxodium*, a relative of the bald cypress, as well as cycads, pines, and palms (*Figure 3.40*).

In Alaska's Neogene rocks, which occur mostly along the southern coast and onto the peninsula, gastropods and bivalves are the most common marine fossils. Land plants preserved in these rocks include *Metasequoia*, willows, poplars, alders, oaks, and elms.

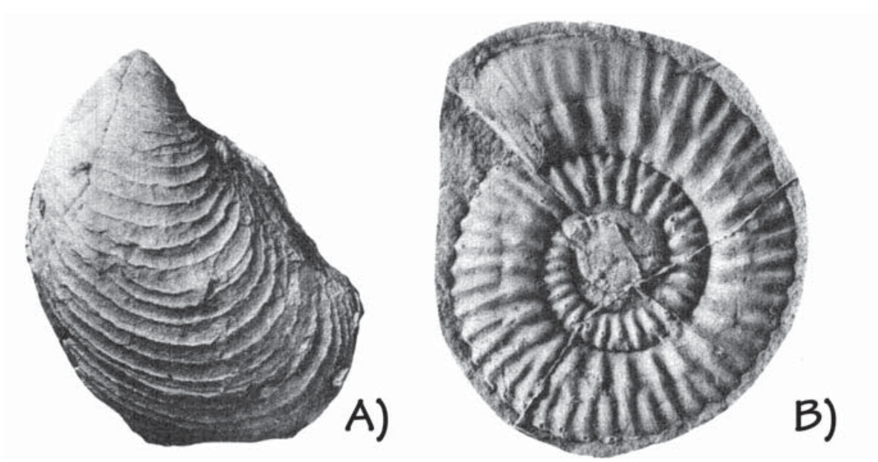


Figure 3.37: Jurassic mollusks from northern Alaska. A) Bivalve, Aucella rugosa*, about 3 centimeters (1 inch). B) Ammonite,* Reineckeia *sp., around 3 centimeters (1 inch).*

Figure 3.38: Pachyrhinosaurus perotorum*; about 8 meters (26 feet) long from head to tail.*

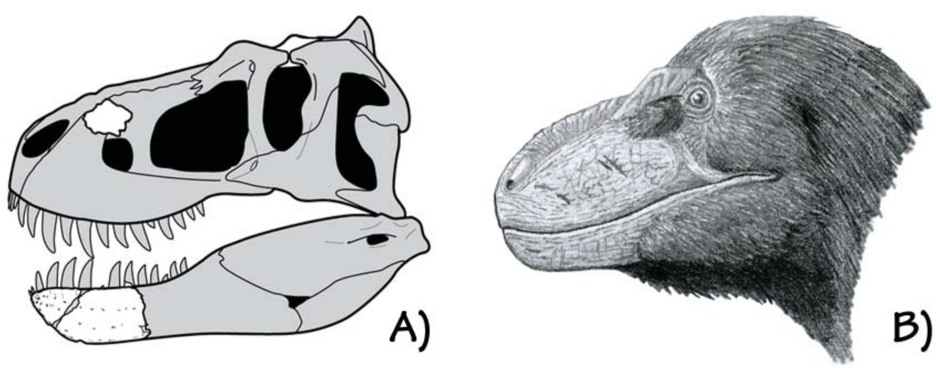


Figure 3.39: Nanuqsaurus *is a small species of Cretaceous carnivorous dinosaur from Alaska, known only from an incomplete skull. A) Drawing of the skull, with white shading showing the known fossils. B) Reconstruction of the head.*

Region 6

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.*

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.*

Holocene • *the most recent portion of the Quaternary, beginning about 11,700 years ago and continuing to the present.*

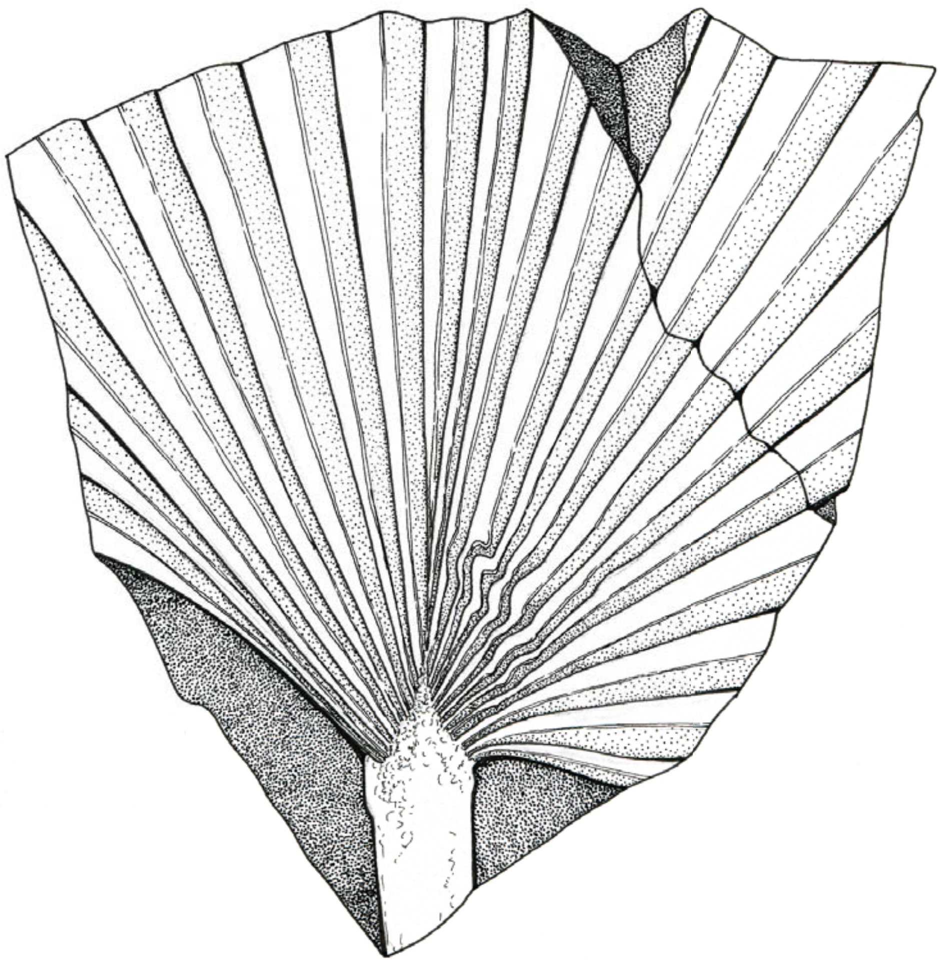


Figure 3.40: A palm fossil, common in the Mesozoic and today known primarily in warm climates. About 0.7 meters (2 feet) wide.

Much of Alaska was covered in ice during the Pleistocene **ice age**, but some refuges did exist where terrestrial animals were able to persist. Beringia, the land bridge that allowed humans and other animals to pass into North America from Asia, was likely one of these refugia. Numerous mammal fossils can be found throughout the state—the area around Fairbanks has many Quaternary deposits that yield mammoth, mastodon, bison, and elk bones.

Alaska is famously home to a number of Quaternary fossils, such as woolly mammoths, that are preserved in **permafrost**. The woolly mammoth was a Pleistocene and early **Holocene** elephant that coexisted with humans (*Figure 3.41*). Frozen carcasses preserving hair, skin, and even stomach contents have been found in Alaska, as well as in Siberia. The woolly mammoth was similar to extant elephants in size but had a heavy coat of fur, small ears, and a short tail to minimize heat loss. Mammoths primarily ate grasses and sedges and had flat

lava tube *• a natural tube formed by lava flowing beneath the hardened surface of a lava flow.*

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

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

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

teeth similar to those of modern elephants (in contrast to the pointed teeth of mastodons, which browsed trees as well; see box p. 100). Woolly mammoths survived on Wrangel Island (Russia) until 4000 years ago but became extinct in North America, along with many other megafauna, during the Quaternary extinction event as a result of climate change and exploitation by human hunters (the relative contribution of each of these factors is still disputed).

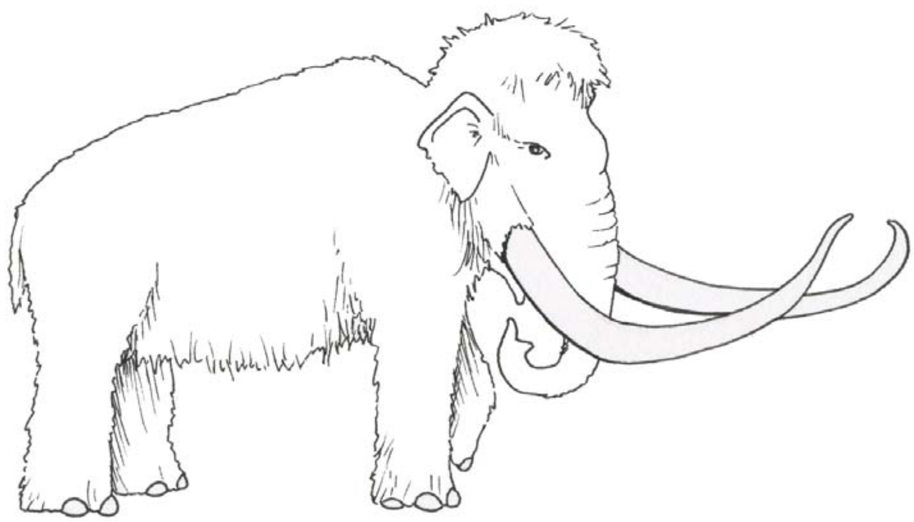


Figure 3.41: The woolly mammoth, Mammuthus primigenius, *was present in North America, Europe, and Asia during the Pleistocene.*

Fossils of Hawai‘i
Region 7

Most fossils occur in sedimentary rocks, but almost all of Hawai‘i consists of igneous rock. Nevertheless, Hawai‘i does have a fossil record, and most of these fossils are found in three unusual geological settings:

- Inside **lava tubes** or caves.
- In **limestones** formed by the coral reefs surrounding the islands, which, when exposed to the air (when sea level falls or the island is **uplifted**) can become **karst.**
- As charcoalized imprints of trees in or between lava flows.

Region 7

Many of the organic remains described from Hawai‘i can be called “subfossils,” meaning that they are less than 10,000 years old (the standard—though arbitrary—age definition for fossils). In practice, such materials are treated like “true” fossils and provide the same kind of information.

The fossil record of the Hawaiian Islands preserves a 400,000-year history of island biodiversity. Fossils of plants, birds, fish, terrestrial and marine invertebrates, and a lone native terrestrial mammal paint a picture of surprisingly diverse Hawaiian ecosystems prior to the arrival of the first humans. As the most isolated archipelago in the world, the Hawaiian Islands were colonized by a relatively small number of species that could successfully disperse across the ocean by flying, floating, or being blown by **wind**. Most seed arrivals came with migratory birds, either in their stomachs, or stuck to their feathers or skin. A smaller number of organisms drifted on air or on floating plant matter in ocean currents. Those that survived the voyage and were able to reproduce in their new environment were also able to move into new ecological niches because competitors for those resources were few. This gave rise to an **adaptive radiation** of species: the creation of multiple new species from a colonizing ancestor.

The long distance and duration of the trip to Hawai‘i favored certain types of organisms and selected strongly against others. Thus there are no native Hawaiian terrestrial reptiles and amphibians, and only one terrestrial mammal, the Hawaiian hoary bat. In contrast, there are many native species of terrestrial birds, invertebrates, and plants. Even in the marine realm, the abundance

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

adaptive radiation • *process in which many new species evolve, adapting to vacant ecological niches in a relatively short interval of geological time.*

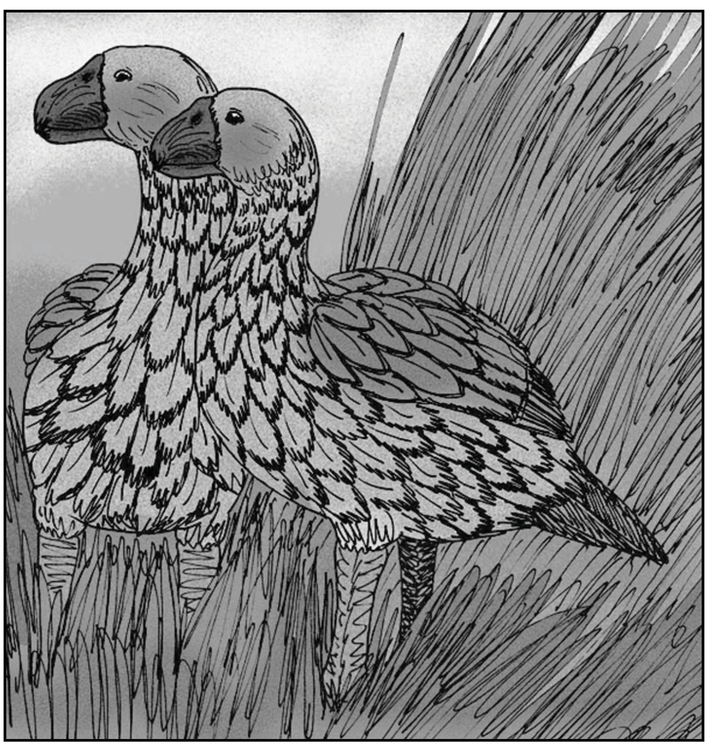


Figure 3.42: An extinct Hawaiian duck known as the turtle-jawed moa-nalo (Chelychelychen quassus). *This flightless bird became extinct prior to European contact with Hawai‘i. DNA analysis places its arrival on the islands at 3.6 million years ago.*

of species is skewed toward those that could travel across the open ocean, and a similar adaptive radiation occurred following the arrival of early near-shore reef species. These factors—long distance travel and subsequent species radiation—give Hawai‘i a very unusual and highly **endemic** group of organisms.

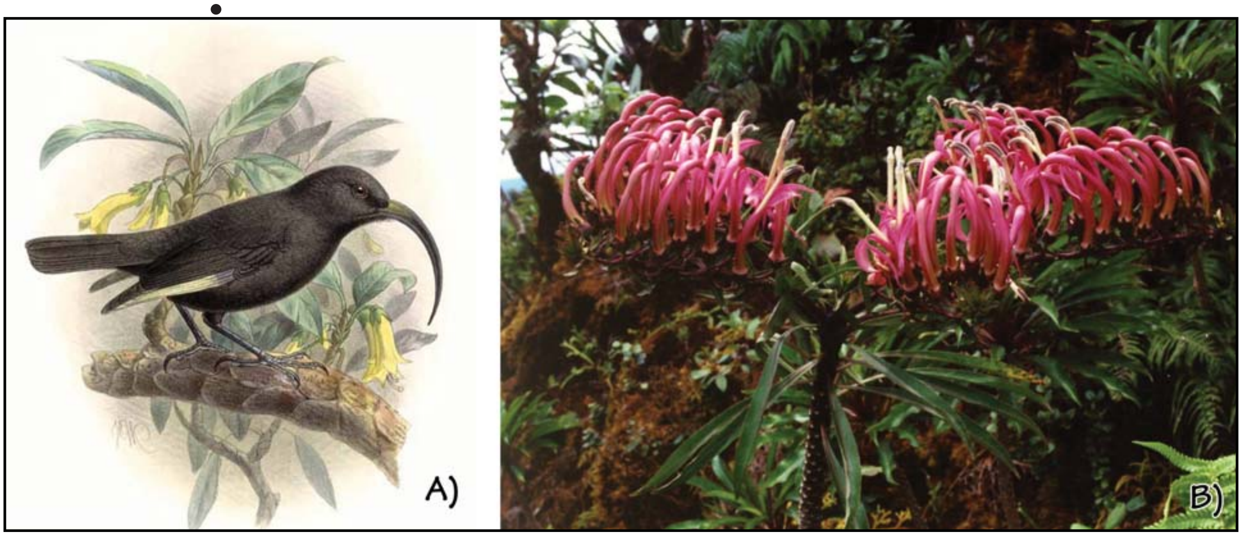


Figure 3.43: The Hawaiian Islands exhibit numerous examples of coevolution between bird and plant species. A) Extinct black mamo (Drepanis funerea)*, and B) modern* Trematolobelia *plant on O‘ahu.*

Before the introduction of continental species by humans, Hawaiian terrestrial ecosystems lacked grazing mammals and were characterized by large—often flightless—grazing ducks and geese (*Figure 3.42*). The top predators were raptors, and plants lost the chemical defenses needed to guard against large herds of grazing mammals. Carnivorous caterpillars and plants can still be found in Hawaiian forests. Without diverse insect pollinators, nectar-sipping birds co-evolved curved bills to match long curved flowers like that of the *Trematolobelia* plant (*Figure 3.43*).

The oldest terrestrial fossils in Hawai‘i are found in lake sediments at the bottom of Ulupau crater on O‘ahu. This fossil occurrence is an unusual one for Hawai‘i, and does not fall into one of the three more common modes of preservation described above. The island does not have many lakes, as its base is made up of porous lava. Eleven species of extinct birds have been identified there, dating to 400,000 years ago.

The richest fossil site in the islands is Makauwahi Cave on Kaua‘i. Makauwahi is a karstic cave system in limestone containing a sinkhole lake, in which sediments accumulated over the last 10,000 years, providing excellent preservation. The hundreds of fossil organisms identified at Makauwahi include more than 40 species of birds (half of which are now extinct), 15 or more species of native land snails (*Figure 3.44*), all now extinct, and scores of endemic plants. In

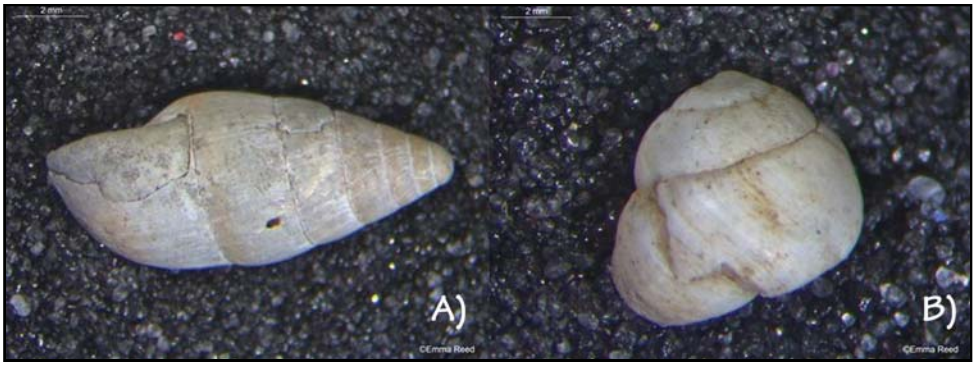


Figure 3.44: Extinct Hawaiian land snails. A) Leptachatina *sp., roughly 12 millimeters (0.5 inches) long. B)* Orobophana juddii, *roughly 6 millimeters across (0.2 inches).*

addition to extinct species, many species of living plants and animals found in the fossil record no longer grow at low elevation, rather, they are found only in high-elevation refuges in remote parts of the islands.

Radiocarbon dating of specimens at Makauwahi Cave documents the arrival of humans—and the continental species they introduced—and the relationship between these new arrivals and the native organisms. Prehistoric native species began to disappear as the first human colonists arrived; lowland birds, along with large flightless geese and ducks, were among the earliest extinctions. These species disappear from sedimentary layers shortly after the appearance of human-introduced rat fossils and other evidence of human habitation. More than half of Kaua‘i’s 140 historically described native bird species are now extinct. One of the most curious is the Kaua‘i mole duck, a bird with unusually small eyes but very large nerve passages to its bill, leading paleontologists to believe that it was nearly blind and may have inhabited caves, or was perhaps a nocturnal feeder.

What makes Hawai‘i’s extinct fossil species so surprising and important is the recency of many of the extinctions. Hawaiian fossil assemblages describe the unusual suite of organisms that once inhabited Hawai‘i, and help us better understand precisely when and how these species became extinct. Hawai‘i’s highly diverse prehuman landscape has been completely transformed, with the decline or extirpation of most native species and their replacement with a small number of introduced species. These human-caused extinctions began about 1000 years ago, accelerated 200 years ago, and the extinction rate continues to increase even today.

Trace fossils in Hawai‘i are most often represented by the trunks and branches of trees that have been consumed by molten lava. When lava flows through a forested area, the molten liquid chills and solidifies almost instantly when it comes in contact with large vegetation. The lava is still quite hot—enough to ignite and burn the trees, leaving behind a mold of the former tree trunk. Lava flows commonly deflate and subside after solidification, and tree molds can protrude above the frozen surface of the flow, leaving behind “lava trees” (*Figure 3.45*).

endemic *• native to a particular geographic area or range.*

radiocarbon dating *• a method of determining the age of a biological object by measuring the ratio of carbon isotopes ^{14}C and ^{12}C.*

Fossils

Figure 3.45: Lava molds of tree trunks at Lava Tree State Monument, Hawai'i.

Marine fossils in Hawai'i are not widespread, but can be very abundant where they do occur, along the coasts of Kaua'i, Oahu, Molokai, Lanai, and Maui. All are found in limestones formed by uplifted Pleistocene or Holocene coral reefs, and can be studied either from coastal outcrops or from cores taken by ship. More than 150 species of mollusks (bivalves and gastropods) have been reported in these reef limestones, together with numerous fossil corals.

State Fossils

Alaska
Mammuthus primigenius (woolly mammoth) (*Figure 3.20*)

California
Smilodon fatalis (saber-toothed cat) (*Figure 3.34*)

Hawai'i
Hawai'i has no state fossil.

Nevada
Shonisaurus popularis (Triassic ichthyosaur) *(Figure 3.7)*

Oregon
Metasequoia glyptostroboides (dawn redwood) (*Figure 3.17*)

Washington
Mammuthus columbi (Columian mammoth) (*Figure 3.30*)

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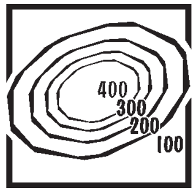

Chapter 4: Topography of the Western US

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 happen on an enormous range of timescales. For example, a flash flood can erode away tons of rock in a matter of hours, yet which rock is broken down and which remains can depend on how it was formed hundreds of millions of years ago. In the West, 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** and its associated folding, **faulting**, and **uplift**.

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

The pounding action of ocean waves on a coastline contributes to the erosion of coastal rocks and sediments. Ice also plays a major role in the weathering and erosion of the West's landscape due to frequent episodes of freezing and thawing that occur at high elevations and high latitudes. On a small scale, as water trapped in **fractures** within the rock freezes and thaws, the fractures widen farther and farther (*Figure 4.1*). This alone can induce significant breakdown of large rock bodies. On a larger scale, ice in the form of alpine **glaciers** or continental **ice sheets** can reshape the surface of a continent through mechanical weathering.

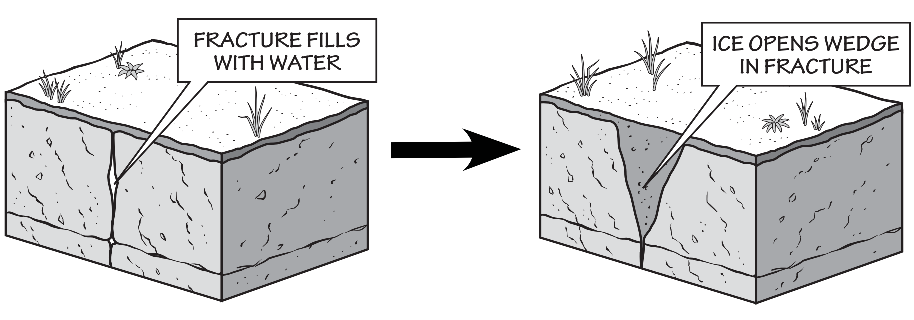

Figure 4.1: Physical weathering from a freeze-thaw cycle.

erosion • *the transport of weathered materials.*

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

plate tectonics • *the way 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.*

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4 Topography

Review

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

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

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

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

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

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

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

Working in conjunction with mechanical weathering, chemical weathering also helps to break down rocks. Some **minerals** contained in **igneous** and **metamorphic rocks** that are formed at high temperatures and pressures (far below the surface of the Earth) become unstable when they are exposed at the surface, where the temperature and pressure are considerably lower, especially when placed in contact with water. Unstable minerals transition into more stable minerals, resulting in the breakup of rock. Weak acids, such as carbonic acid found in rainwater, promote the disintegration of certain types of rocks. **Limestone** and **marble** may be 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.

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

The specific rock type found at the surface has an important influence on the topography of a region. Certain rocks are able to resist weathering and erosion more easily than are others; resistant rocks that overlie weaker layers act as caps and form ridges. The inland ocean basins of California's **Jurassic** and **Cretaceous** mountain-building events collected and preserved sediments that eventually became sedimentary rocks. Sedimentary rocks weather and erode differently than do the crystalline, and generally harder, igneous and metamorphic rocks that are more common in the Sierra Nevada. **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. Landscapes of unconsolidated sediments, like beaches and **alluvial** fans, are the least resistant to erosion. The limited degree of cement, compaction, and interlocking crystals found in alluvial fan sediments makes it difficult for these types of sediments to stand up to the effects of wind and water, which is why they tend to persist only in arid regions.

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

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. Movement of tectonic **plates** creates stress and tension within the **crust**, especially at plate boundaries, which often deform the flat layers by folding, faulting, intruding, or overturning them. These terms are collectively used to describe rock structure, and they can also be used to determine which forces have affected rocks in the past. The folding of horizontal rock beds followed by erosion and uplift exposes layers of rock to the surface. Faulting likewise exposes layers at the surface to erosion, due to the movement and tilting of blocks of crust along the fault plane. Tilted rocks expose underlying layers. Resistant layers stick out and remain as ridges, while surrounding layers of less resistant rock erode away.

Ice sheets of the **last glacial maximum**, as well as extensive mountain glaciers, covered part of the West and had a dramatic effect on the area's topography.

Glaciers carved away at the land's surface as they made their way primarily southward, creating a number of U-shaped valleys such as Yosemite and depositional features such as **moraines**. Mountains were sculpted, leaving high peaks and bowl-like **cirques**. As the ice sheet and glaciers melted, other characteristic glacial features were left behind as evidence of the glaciers' former presence, including glacial lakes and polished rock.

See Chapter 6: Glaciers for more about how glaciers influenced Western topography.

Just as we are able to make sense of the type of rocks in an area by knowing the geologic history of the West, we are able to make sense of its topography (*Figure 4.2*) based on the rocks and structures resulting from past geologic events.

Topography of the Basin and Range
Region 1

The Basin and Range possesses perhaps the most unique topography of the Western United States. It covers a large area of the US, extending to the Rocky Mountain, Southwestern, and South Central states. Basin and Range topography is characterized by alternating valleys and mountainous areas, oriented in a north-south, linear direction. The entire region, including all of Nevada, southeastern California, and southeastern Oregon, consists of high mountain ranges (mostly running north-south) alternating with low valleys.

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**—the mountain-building event that created the Rockies—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 4.3*). Such landscapes frequently occur in areas where crustal extension occurs, and the Basin and Range is often cited as a classic example thereof.

Region 1

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

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

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

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

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

4 Topography

Region 1

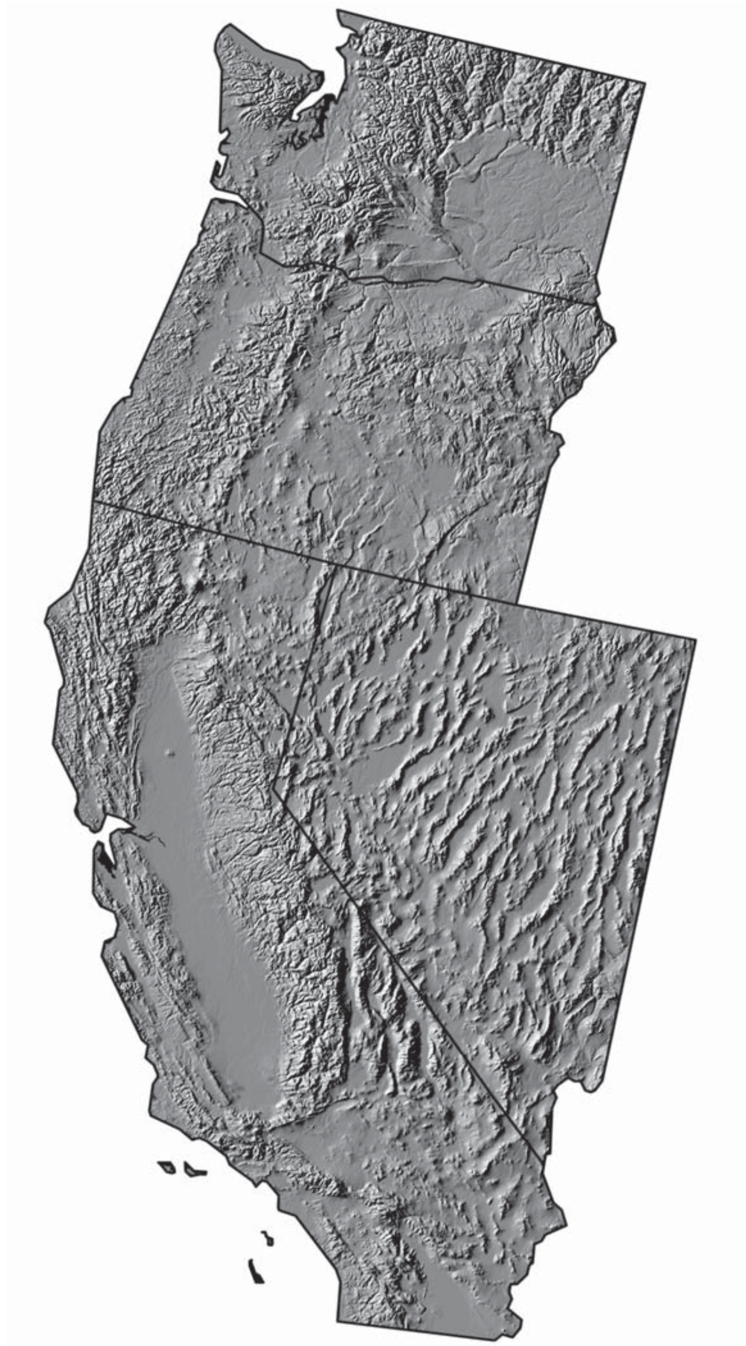
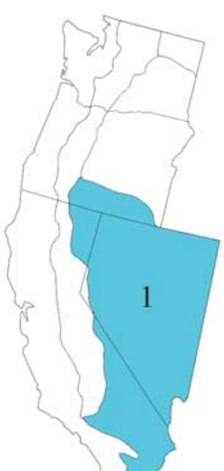


Figure 4.2: Digital shaded relief map of the contiguous Western States.

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 Basin and Range region is 30–35 kilometers (19–22 miles), compared with a worldwide average of around 40 kilometers (25 miles).



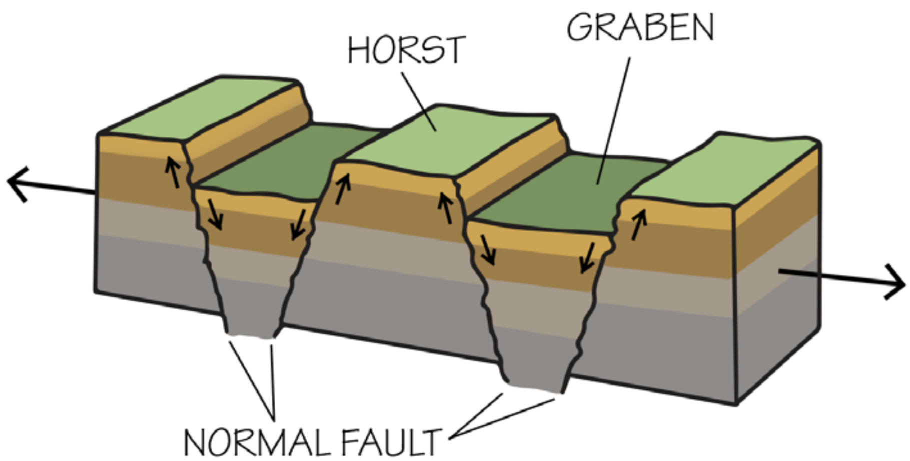


Figure 4.3: A horst and graben landscape occurs when the crust stretches, creating blocks of lithosphere that are uplifted at angled fault lines.

The Basin and Range's arid **climate** contributes to its topography. Erosion is slow, and mechanical weathering is the dominant erosional process, partly because plants, which play a role in chemical weathering, are very sparse. The rugged mountains are fringed by large features called alluvial fans (*Figure 4.4*). These features form when **gravel** and **sand**—and sometimes boulders—are washed out of the mountains by flash floods. The sediment is made up of large, heavy grains, and precipitates out of the water at canyon mouths, where streams lose power as they leave their channels to enter the valleys (*Figure 4.5*).

Plants can contribute to chemical weathering by releasing organic acids from their roots. These acids help dissolve minerals in the rock, providing nutrients to the plant.

If mountain ranges are close together, alluvial fans from opposite sides of the valley will meet in the middle, but where the ranges are farther apart, valley floors will be flat and are often occupied by either **playas** or dune fields.

Region 1

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

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

playa lake *• ephemeral or dry lakebed that occasionally contains only a thin layer of quickly evaporating water.*

4 Topography

Region 1

microcontinent • *a piece of continental crust, usually rifted away from a larger continent.*

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

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

Figure 4.4: Alluvial fans in Death Valley, California.

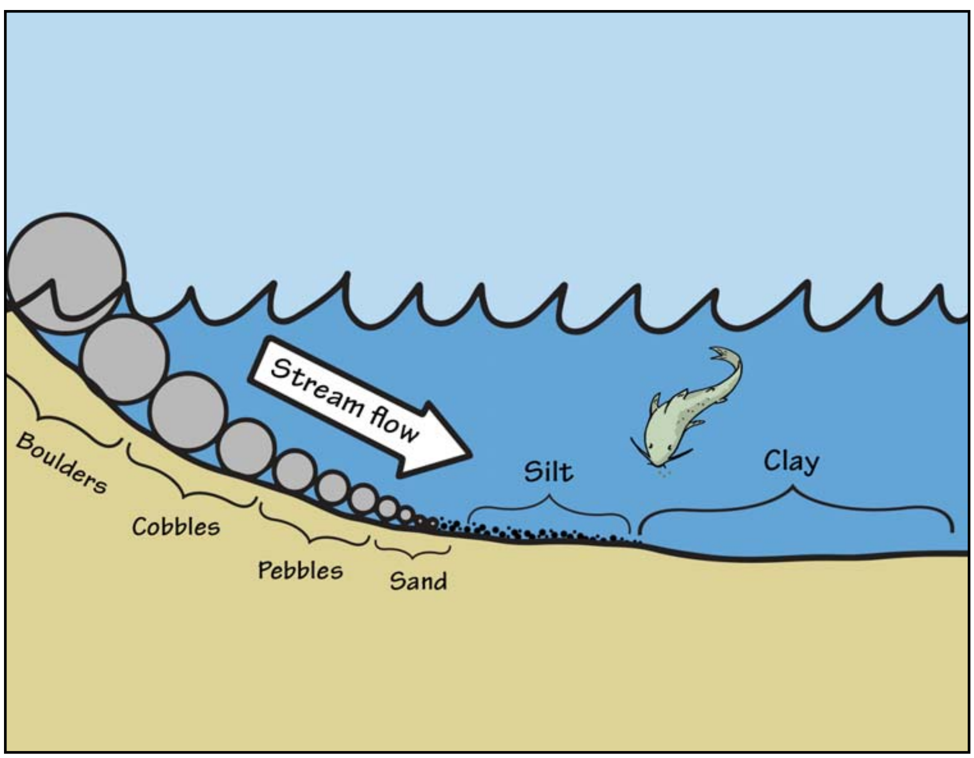


Figure 4.5: Moving water deposits sediments in what is known as a horizontally sorted pattern. As the water slows down (i.e., loses energy), it deposits the larger particles first.

Topography of the Columbia Plateau
Region 2

Region 2

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.*

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

The interior areas of eastern Washington and central and northeastern Oregon are divided into three major areas: the Blue Mountains, the High Lava Plains, and the Columbia Basin (*Figure 4.6*)

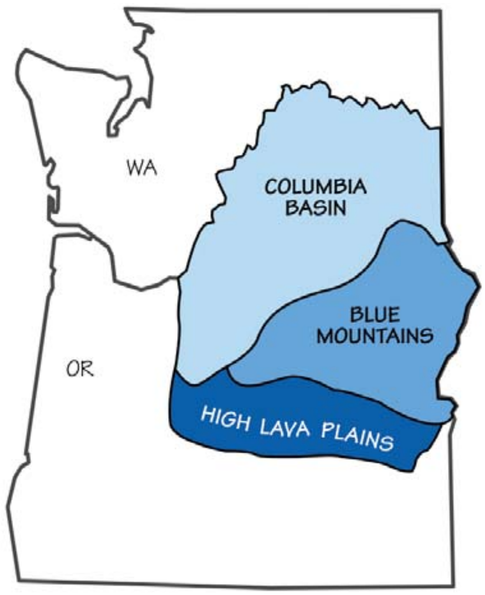


Figure 4.6: The three major divisions of the Columbia Plateau.

The Blue Mountains include the Wallowas, which reach a height of 2999 meters (9838 feet). This area is formed of ancient **microcontinents**, small pieces of continental crust that collided with North America in the Jurassic.

The High Lava Plains are the result of extensive **volcanism** during the **Neogene**. Newberry Volcano, just south of Bend, Oregon, is the westernmost point of eruption for a **hot spot** that is now responsible for the spectacular volcanic features found in Yellowstone. This hot spot, which has existed for over 16 million years, left its trail across southeastern Oregon and southern Idaho.

See Chapter 1: Geologic History to learn more about hot spot volcanism.

The Columbia Plateau, 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, flowing westward. The basalt was so voluminous and fluid that it completely filled the preexisting topography (remnants of which can be seen in hills such as Steptoe Butte [*Figure 4.7*] and Kamiak Butte in easternmost

__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.

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

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

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

Washington), forming a broad, flat plain that tilts downward to the west. The lava flowed all the way to the Cascades, and even to the ocean, along what is now the Columbia River drainage. In western parts of the plateau, the basalt has been gently folded and faulted by mountain building associated with the uplift of the Cascade Mountains.

Figure 4.7: Steptoe Butte, a 400-million-year-old quartzite mound protruding from the Columbia Plateau and Palouse Hills in Whitman County, Washington. Elevation: 1101 m (3612 feet).

The youngest topographic features in the Northern Interior of Washington formed during the most recent **ice age** when glacial outwash and **loess** was deposited and later cut by the Missoula Floods, which also carved the Grand Coulee (an ancient river bed) and many of the lakes and channels of the central part of the state. In the Palouse area of Washington and Oregon, glacial outwash formed a series of steeply-sloped **silt** dunes, which are agriculturally important today due to their highly fertile **soil** (*Figure 4.8*).

The Missoula Floods swept periodically across eastern Washington at the end of the last ice age. The floods were a result of a rupture in the ice dam that contained Glacial Lake Missoula, a massive glacial lake originally holding 2100 cubic kilometers (500 cubic miles) of water.

Figure 4.8: The Palouse Hills in southeastern Washington are an important agricultural area.

Topography of the Northern Rocky Mountains
Region 3

Extreme northeastern Washington has a history that is quite different from that of the other regions to the south and west. Although the rocks here contain both metamorphic and sedimentary structures, they share a similar degree of hardness. This means the region has been resistant to erosion, and, even though they are very old, these rocks remain exposed. Since this region was covered with ice during the last ice age, the mountains have been rounded by glaciation (*Figure 4.9*). Deep valleys were carved by glaciers flowing from the ice sheet.

Figure 4.9: Rounded topography of the Okanogan Highlands, Washington. This type of topography occurs on all scales, from these hill-sized outcrops to the region's mountains.

Region 4

granodiorite *• a coarse-grained plutonic rock rich in the elements sodium and calcium, and in the minerals potassium, feldspar, and quartz.*

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.*

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

Topography of the Cascade-Sierra Mountains
Region 4

The highest mountains in the western continental US are uniformly about 177 kilometers (110 miles) west of the Pacific coastline but are actually made up of two different mountain ranges, the Sierra Nevada and the Cascades, with the Klamath Mountains of northwestern California sandwiched in between.

The Sierra Nevada are composed almost entirely of **granodiorite** and highly metamorphosed sedimentary and volcanic rocks. This granodiorite makes up the Sierra Nevada **batholith**, which is one of the largest in the US; it is composed of a series of **plutons**, large bodies of molten rock that intruded the crust and cooled, only to be revealed by erosion millions of years later (*Figure 4.10*). Because plutons are extremely resistant to weathering and the mountains in this region are so young, the Sierra Nevada are home to some of the highest peaks in the United States. In fact, Mt. Whitney, at 4421 meters (14,505 feet), is the highest mountain in the continental US and has the most extreme **relief**. The town of Lone Pine, less than 21 kilometers (13 miles) away, lies at 987 meters (3237 feet), a drop of more than 163 meters per kilometer (866 feet per mile)!

See Chapter 2: Rocks to learn more about the Sierra Nevada.

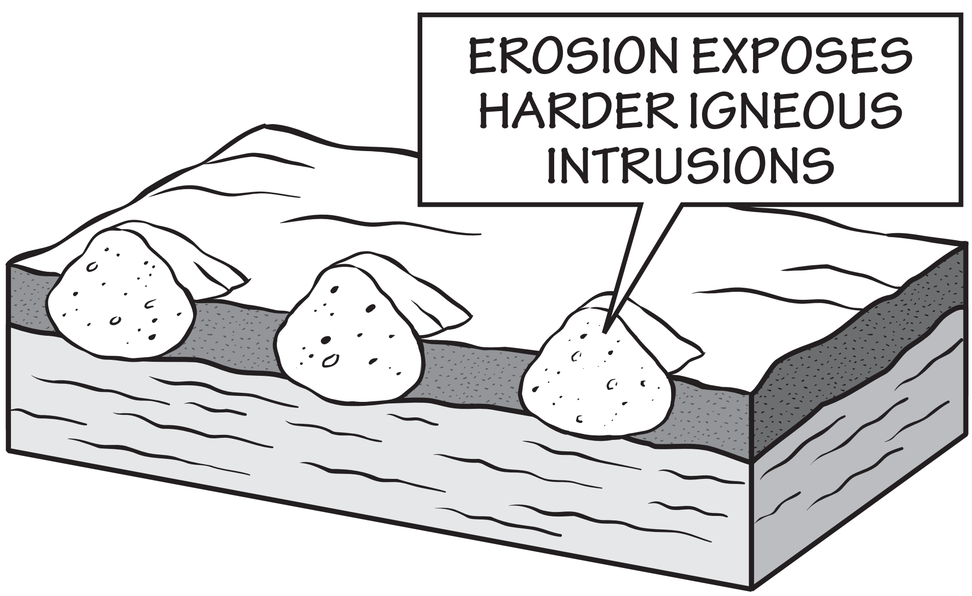


Figure 4.10: Igneous intrusions (plutons) are exposed after millions of years of erosion.

Topography

4

Region 4

The Sierra Nevada were originally thought to have been uplifted to their current height around 10 million years ago, but more recent work has provided evidence that the initial uplift occurred much earlier, as early as the Late Cretaceous, and that the Sierra Nevada may at one time have been even higher than they are today. New evidence also shows they are still rising.

The Sierra Nevada are unusual in that they are bounded on the east by an extensive fault system along which most of the uplift has occurred. This means that they are very steep on the eastern side but slope gently to the Central Valley on the western side. Because of the rain shadow effect (*Figure 4.11*), the climate on the mountains' eastern side is very dry and weathering there is predominantly mechanical, while the western side is wetter and chemical weathering is more prevalent. This weathering concentrated the **placer gold deposits** that were the object of California's mid-1800s gold rush. Gold is completely stable, so when the rock containing it weathered away, the gold remained behind, concentrated in the bottoms of streams.

See Chapter 5: Mineral Resources for more information about gold in the West.

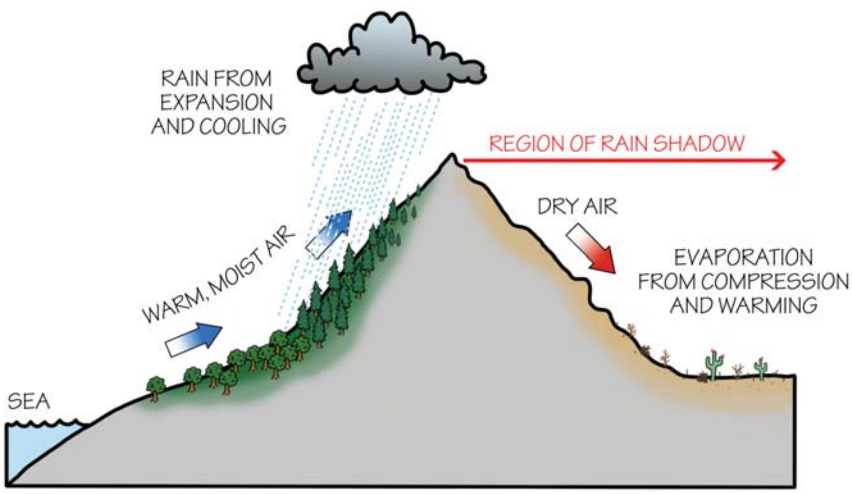


Figure 4.11: The rain shadow effect occurs when moisture-laden air rises up the windward side of a mountain, only to release this moisture as precipitation due to cooling and condensation. Once the air reaches the leeward side, it warms and expands, promoting evaporation (and a lack of precipitation).

The Klamath Mountains are one of the many **terranes** that make up large parts of the West, including much of Alaska and Oregon. The Klamath microcontinent collided with North America in the Jurassic, causing these mountains to rise. In addition, plutonic **intrusions** made the mountains relatively resistant to the weathering caused by the region's heavy winter rains.

The Cascade Mountains have largely been shaped by plate tectonics in the Pacific Ocean. Early in the Paleogene, the Cascades portion of Washington

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.*

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

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

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

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

convergent boundary *• an active plate boundary where two tectonic plates are colliding with one another.*

accretionary prism *• a pile of sediments and ocean crust, scraped off a descending plate during subduction, and piled onto the overlying continental crust.*

transform boundary *• an active plate boundary in which the crustal plates move sideways past one another.*

began as a series of basins and uplifts that formed when several smaller plates, along with their boundaries, were successively **subducted** under North America. Beginning around 37 million years ago, this subduction also created the first volcanoes that pierced the area. The remains of these extinct volcanoes define the landscape—the area that surrounds Mt. Rainier (and extends to the south) contains remnants of the ancient volcanoes themselves, while to the north only their plutonic cores remain.

The topography of the modern Cascades was created during the last seven million years. After a lull in volcanic activity, plate motion shifted, and new subduction created the modern volcanic arc and also uplifted the entire region. The greatest uplift took place in the north.

Topography of the Pacific Border

Region 5

The Pacific Border can be divided into two major areas based entirely on dominant plate tectonic forces. A transform (sideways-moving) boundary between the Pacific plate and North America extends through California. Meanwhile, a **convergent boundary** subducts off the coast of Washington and Oregon, between North America and the remnants of the ancient oceanic Farallon plate. These two areas are separated by the great Mendocino fracture zone off the coast of northernmost California.

Before the formation of the San Andreas Fault system, the area south of the Mendocino fracture zone was a subduction zone. The features of subduction zones can vary, depending on how fast the plates are moving and the angle at which the subducting oceanic crust is traveling. Where the descending plate subducts at a relatively shallow angle, a forearc basin may form oceanward of the volcanic arc (*Figure 4.12*). The Central Valley of California is the forearc basin associated with the volcanic arc that became the Sierra Nevada, and it formed partly due to the weight of the growing mountains on the crust. West of this basin, a pile of sediments and even ocean crust, known as an **accretionary prism** (*Figure 4.12*), was scraped off the subducting oceanic plate and piled higher and higher onto the overlying continental crust. The Coast Ranges of California formed in this way.

About 30 million years ago, a mid-ocean ridge called the East Pacific Rise collided with and subducted beneath North America. As this ridge subducted, the plate boundary adjacent to California gradually changed, becoming the **transform boundary** that formed the San Andreas Fault system. At this time, the accretionary prism that formed the Coast Ranges stopped growing. Since the fault is not a straight line but rather a system of faults, a lot of tectonic jostling, pushing, and pulling occurs in this part of California. Movement along these faults is responsible for the formation of hills and valleys, and sometimes of broad basins such as the western part of the Mojave Desert. The Transverse Ranges, Tehachapi Mountains, and southern Coast Ranges all owe much of their topography to movement along the San Andreas Fault system. In fact,

Region 5

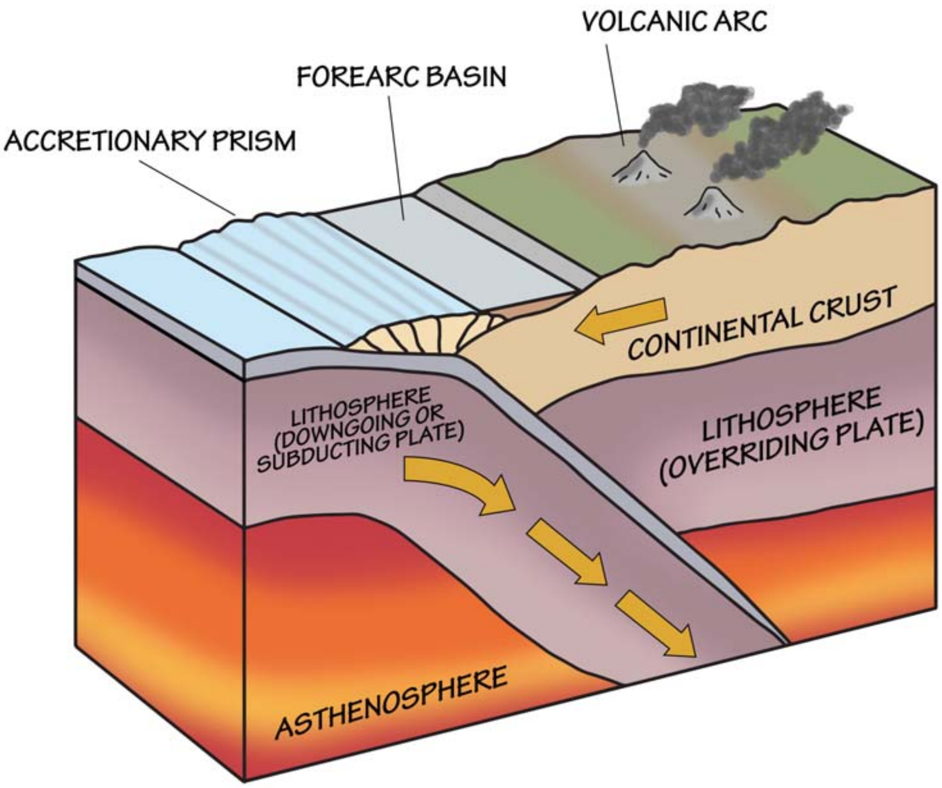


Figure 4.12: Some of the features associated with subduction zones.

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

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

terrace • *a flat or gently sloped embankment or ridge occurring on a hillside, and often along the margin of (or slightly above) a body of water, representing a previous water level.*

the Transverse Ranges have been rotated as much as 110 degrees from their original position! The southern end of the fault system lies just north of the Gulf of California, where it terminates in a **rift** zone. The rifting is responsible for the formation of the Imperial Valley, one of the lowest spots in North America. Despite the overall translational motion of the San Andreas Fault system, there is a small **compressional** component, and this has resulted in uplift along parts of the coastline during the last three million years. This uplift can be seen in a series of wave-cut **terraces** that now lie well above the modern shoreline (*Figure 4.13*).

See Chapter 1: Geologic History to learn more about changing plate boundaries off the West coast of North America.

The San Andreas Fault travels off the coastline north of San Francisco, eventually meeting up with the Mendocino fracture zone. The Klamath Mountains, which lie directly east of the fracture zone, are part of an accretionary wedge that has been substantially uplifted.

The subduction zone north of the Mendocino fracture zone is responsible for the formation of the Oregon Coast Range and the Olympic Mountains. These mountains are part of a 66-million-year-old accretionary wedge associated with the subduction zone. In Oregon, the wedge is composed largely of an ancient

volcanic arc, which was carried to the coast of Oregon on an older subducting slab. The Oregon Coast Range is lower in altitude than the coastal ranges north and south, partly because of slower uplift and partly because the wet climate of western Oregon quickly erodes the rock. Despite these conditions, marine terraces similar to those in California are found in this area. The Olympics were uplifted during the **Miocene**, around the same time as the most recent uplift in the northern Cascades.

Like the Central Valley of California, the Willamette Valley in Oregon and Puget Sound in Washington are parts of a forearc basin, but in this case they are associated with an active volcanic arc—the Cascades.

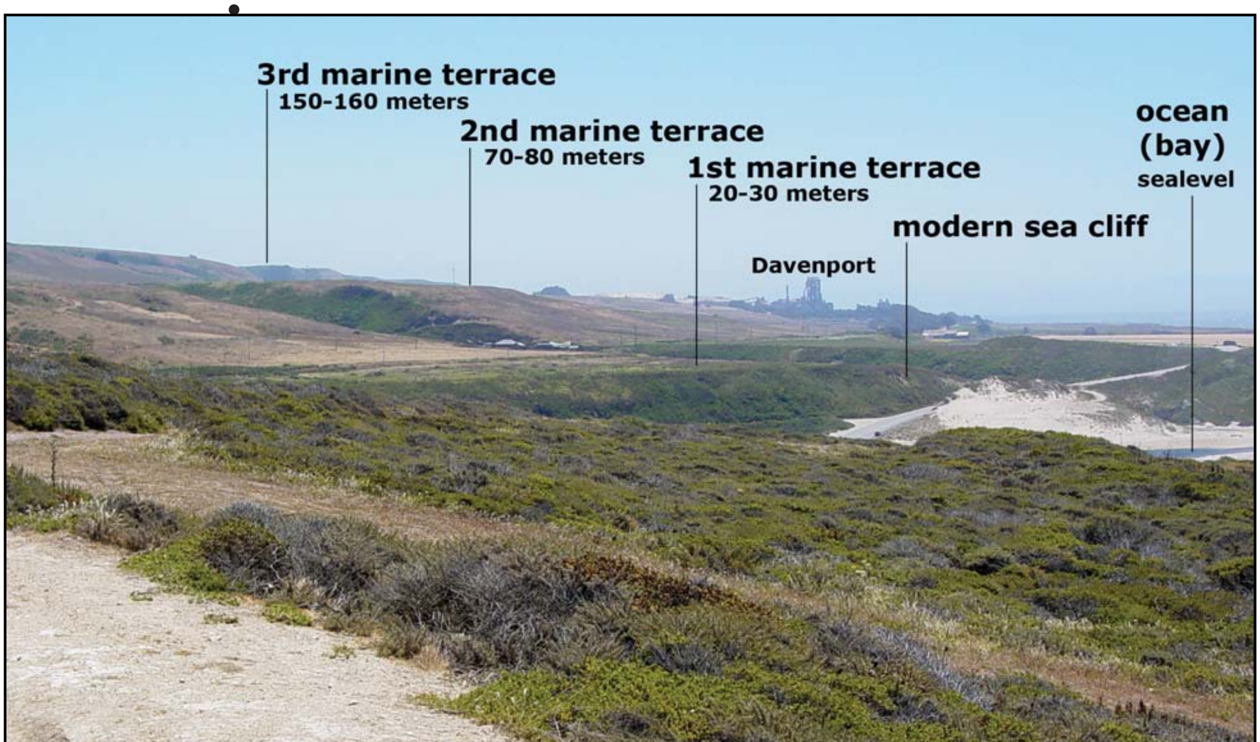


Figure 4.13: Marine terraces north of Santa Cruz, California. The third terrace is the oldest; the first is the youngest. These terraces indicate that the coastline has continued to rise, even though the predominant plate tectonic motion is translational.

Topography of Alaska
Region 6

Alaska is one of the most mountainous states in the US, and, along with California, has the highest relief (*Figure 4.14*). Mt. McKinley, at 6194 meters (20,322 feet), is commonly accessed by climbers and other tourists from the nearby town of Talkeetna (elevation 106 meters [348 feet]). This represents a difference of more than 6000 meters (almost 20,000 feet) within less than

96 kilometers (60 miles). There are, however, two non-mountainous areas of Alaska as well—the North Slope and the Interior. Much of Alaska's topography can be explained by its odd origins: continental Alaska is made up almost entirely of **accreted** terranes—bits and pieces of microcontinents and island arcs that collided together over geologic time.

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

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.*

North Slope, Brooks Range, and Seward Peninsula

The Yukon-Tanana terrane was responsible for the formation of the North Slope and Brooks Range when it collided with a part of Arctic Canada that rifted away,

Figure 4.14: Digital relief map of Alaska.

rotating counterclockwise into its present position. The forward edge of the Yukon-Tanana's ancient seabed was uplifted, forming the Brooks Range, while the trailing edge subsided. The rising Brooks Range shed copious amounts of sediment northward toward the Arctic Ocean, and the combination of subsidence and accumulation of sediment formed the coastal plain we call the North Slope. The Brooks Range is highest in the east because it consists

See Chapter 2: Rocks to learn more about the terranes that formed Alaska.

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

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

mainly of thrust sheets: giant slabs of rock that were piled on top of each other due to compressional forces acting on the rotating crust (*Figure 4.15*).

Figure 4.15: A massive thrust sheet in Gates of the Arctic National Park, Central Brooks Range, Alaska.

The Seward Peninsula extends from northwest Alaska and is a remnant of the Bering land bridge that connected Alaska to Siberia during the **Pleistocene**. The Seward Peninsula is actually composed of two terranes: the Seward terrane, which contains predominantly metamorphic rock, and the York terrane, made up of sedimentary rocks that were originally deposited in a shallow marine environment before their accretion onto the North American plate. These sedimentary rocks were deformed by thrust faulting during the Cretaceous.

Although Alaska was never buried under an ice sheet, as were much of Canada and the northern continental US, glaciation was extensive in the Brooks Range during the ice ages. The effects of these glaciers can be seen in the range's sharp peaks and U-shaped valleys.

Interior

The Interior is an expanse of flat, swampy areas and low, rolling hills. The geological origin of this area is murky because so little of its bedrock is exposed, but we do know it contains fragments of what was once ocean floor. Such rocks can be very vulnerable to erosion because the minerals they contain are more easily weathered. The area's low topography probably results from a combination of easily weathered rocks and an incomplete collision between the Brooks Range and terranes south of the Interior. The basin has also been filled with copious amounts of sediment from the Brooks Range, Alaska Range, and the Yukon River.

Southern Alaska

Southern Alaska comprises numerous terranes that have been added to North America since the Late **Triassic** (about 230 million years ago). In addition to

colliding with one another, the terranes were progressively pulled apart by major faults that formed due to changing plate motions between North America and the Pacific plate.

The Wrangell-St. Elias Mountains are mostly composed of a large terrane called Wrangellia, which collided with North America in the Cretaceous and has also been cut by large faults. This terrane makes up most of the Coast Range in southeastern Alaska, parts of the Alaska Range, and part of the Alaska Peninsula. It is still being rearranged, as witnessed by the frequent, large **earthquakes** along the Denali Fault system.

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

Some terranes have an extremely complex geology, and geologists have lumped them into composites made up of pieces with similar tectonic histories. The Mertie Mountains east of Fairbanks are included in the Yukon composite terrane, which was in place by the Late Jurassic. The Kuskokwim Mountains in southwestern Alaska include pieces of several composite terranes that were not assembled until much later, in the Paleogene. The Alaska Range, which includes Mt. McKinley, also comprises at least two terranes that were brought together by the Denali Fault system during the Late Cretaceous. The addition and movement of the Southern Margin composite terrane built the Fairweather, Chugach, and Kenai mountains; these ranges are part of an accretionary prism (*See Figure 4.12*). Subduction is still occurring along the Aleutian Trench, resulting in the formation of the Aleutian Islands. The subduction creates **stratovolcanoes** and plutonic igneous intrusions along the entire Aleutian Range, where some of the highest mountains are young volcanoes that erupt periodically.

stratovolcano • *a conical volcano made up of many lava flows as well as layers of ash and breccia from explosive eruptions.*

mass wasting • *a process in which soil and rock move down a slope in a large mass.*

Topography of Hawai'i
Region 7

The topography of the Hawaiian Islands changes systematically as a function of age. The eight major islands and 129 minor islands are generally larger and taller in their youth, decreasing in size and height as they age (*Figure 4.16*). The smooth, gently-sloping shield of a young volcano becomes progressively carved and steeper over time. These changes arise from several factors: constructive volcanic processes that dominate the early history of each island, **mass wasting** that occurs throughout the volcano's life cycle, and the erosion and weathering that dominate once volcanism ceases.

See Chapter 1: Geologic History for more detail on the stages of Hawaiian volcano-building.

It is often said that the volcanoes of Hawai'i are the largest mountains on Earth, and this is true, depending on how one measures size. The peak of Mauna Kea is 4205 meters (13,796 feet) above sea level, while Mauna Loa rises to 4169 meters (13,677 feet). The base of the volcanic edifice extends another 5000 meters (16,400 feet) to the sea floor. Additionally, the weight of the volcanoes depresses the seafloor downward into the mantle for another 8000 meters (26,000 feet). As

Region 7

seismic waves *• the shock waves or vibrations radiating in all directions from the center of an earthquake or other tectonic event.*

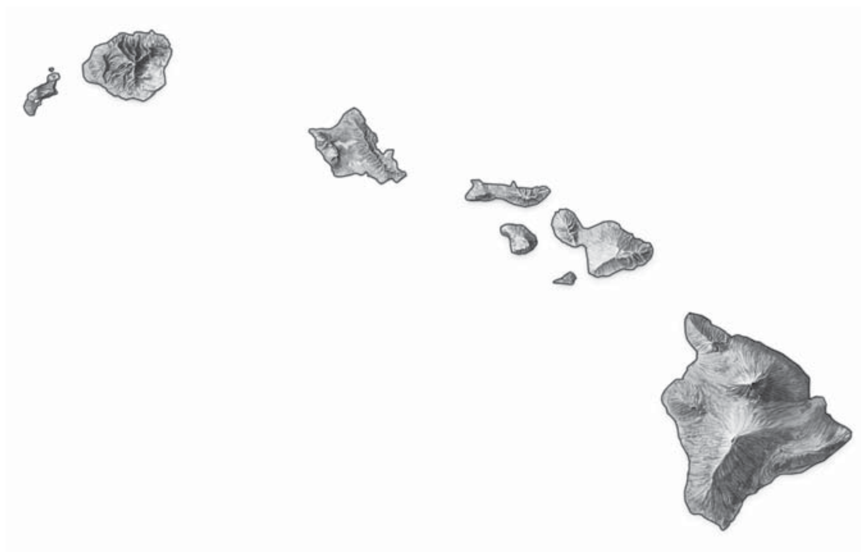


Figure 4.16: Digital relief map of Hawai'i.

a result, the total height of both Mauna Kea and Mauna Loa is nearly 17,200 meters (56,420 feet) (*Figure 4.17*).

Once a volcano grows large enough to emerge from the ocean, its terrestrial surface begins to reflect the interaction of several processes. Overall, lava flows create a smooth surface at a low angle (3˚ in the case of Mauna Loa). However,

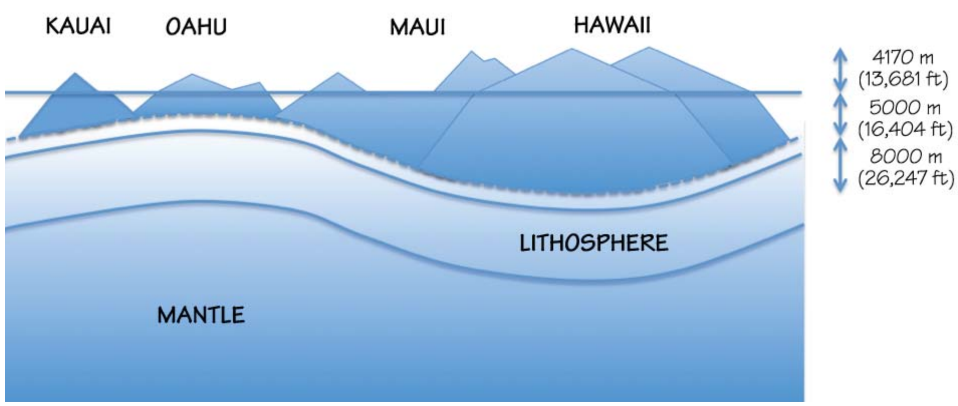


Figure 4.17: The weight of the Hawaiian Islands depresses the lithosphere into the underlying mantle. The total height of Mauna Loa is 4170 meters (13,681 feet) above sea level plus an additional 13,000 meters (42,651 feet) to the top of the oceanic plate on which it sits.

small-scale topography (tens of meters [yards] in size) is superimposed on the smooth slope as weathering and **seismic** activity affect the landscape. While the shield topography sets the basic form of the original volcanic surface, local variations can be important for the later development of stream valleys and other features.

Mass Wasting

Dramatic mass wasting events, known as **flank collapses**, remove huge amounts of volcanic rock from the islands and leave behind giant scarps. Some of Hawai‘i's most dramatic topographic features are the huge sea cliffs found on many of the islands as a result of these collapses (*Figure 4.18*). The cliffs in Kohala, Hawai‘i drop 125 meters (400 feet), while cliffs on Moloka‘i plunge 800 meters (2600 feet) into the ocean. When a flank collapse occurs on the **windward** side of an island, it creates a steep escarpment, which tends to enhance rainfall, maintaining high erosion rates and steepening dramatic cliffs in places like the Na Pali coast on Kaua‘i (*Figure 4.19*), the Ko‘olau range on O‘ahu, and the Waipi‘o area on Hawai‘i. On the **leeward** (dry) sides, incision and relief are notably less pronounced.

Flank collapses result from gravitational stress on the massive volcanic shield. Some of this stress is directed outward, and the stresses cause the development of fractures dipping away from the summit. These faults can slip rapidly, resulting in a massive collapse into the ocean. As well as altering the topography and size of the islands, these mega-**landslides** leave huge debris fields on the sea floor that can extend more than 100 kilometers (60 miles) away from the islands. Studies have shown that at least 15 giant landslides—among the largest ever found on Earth—dissected the Hawaiian Islands (*Figure 4.20*). These flank collapses have left all of the islands with their distinctive coastal cliffs (*pali* in Hawaiian), and at least some of the landslides appear to have

Figure 4.18: Cliffs on windward Kohala, Hawai‘i, viewed looking SE from Pololū valley. Most Hawaiian sea cliffs are the head scarps of mega-landslides.

flank collapse *• a dramatic mass wasting event that occurs when the flank of a shield volcano collapses under its own weight.*

windward *• upwind; facing into the prevailing winds, and thus subject to orographic precipitation.*

leeward *• downwind; facing away from the wind.*

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.*

Figure 4.19: The Na Pali coast, Kaua'i, Hawai'i

generated massive **tsunamis**. There is evidence across the Hawaiian Islands that rock and coral materials were deposited over 300 meters (1000 feet) above sea level by these events.

Examples of extensional collapse can be observed today—GPS measurements confirm that blocks of land on the flanks of Kīlauea are moving seaward at around 10 centimeters (4 inches) per year. This slow slip is punctuated by larger events that cause earthquakes. Flank collapse, first identified in Hawai'i, has since been recognized as a feature of other high oceanic **volcanic islands**, such as Tenerife in the Canary Islands and Réunion in the Indian Ocean. The last major flank collapse in Hawai'i occurred about 120,000 years ago, so we do not have a detailed picture of what one of these events looks like, nor of the warning signals that may occur prior to a large-scale failure.

Erosion and Valley Formation

Erosion in Hawai'i is primarily driven by water. Erosion is concentrated on the windward slopes of each volcano, where higher precipitation forms **perennial** streams. On young islands nearly all leeward streams are intermittent, and thus have only episodic erosive power.

Stream erosion incises the islands' surfaces and modifies **hanging valleys** left by flank collapses. Tall waterfalls are found where collapse generates steep topography more quickly than stream incision can wear it away (*Figure 4.21*). Stream valleys cut back into the flanks of the volcano, aided by pre-existing faults and underlying structures within the volcanic edifice.

The number and size of stream valleys provides a clear indication of the age of the volcano on which they form. For example, on Hawai'i Island, active Kīlauea

tsunami *• a series of ocean waves that are generated by sudden displacement of water, usually caused by an earthquake, landslide, or volcanic explosions.*

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

perennial *• continuous; year-round or occurring on a yearly basis.*

hanging valley *• a tributary valley that drops abruptly into a much larger and deeper valley.*

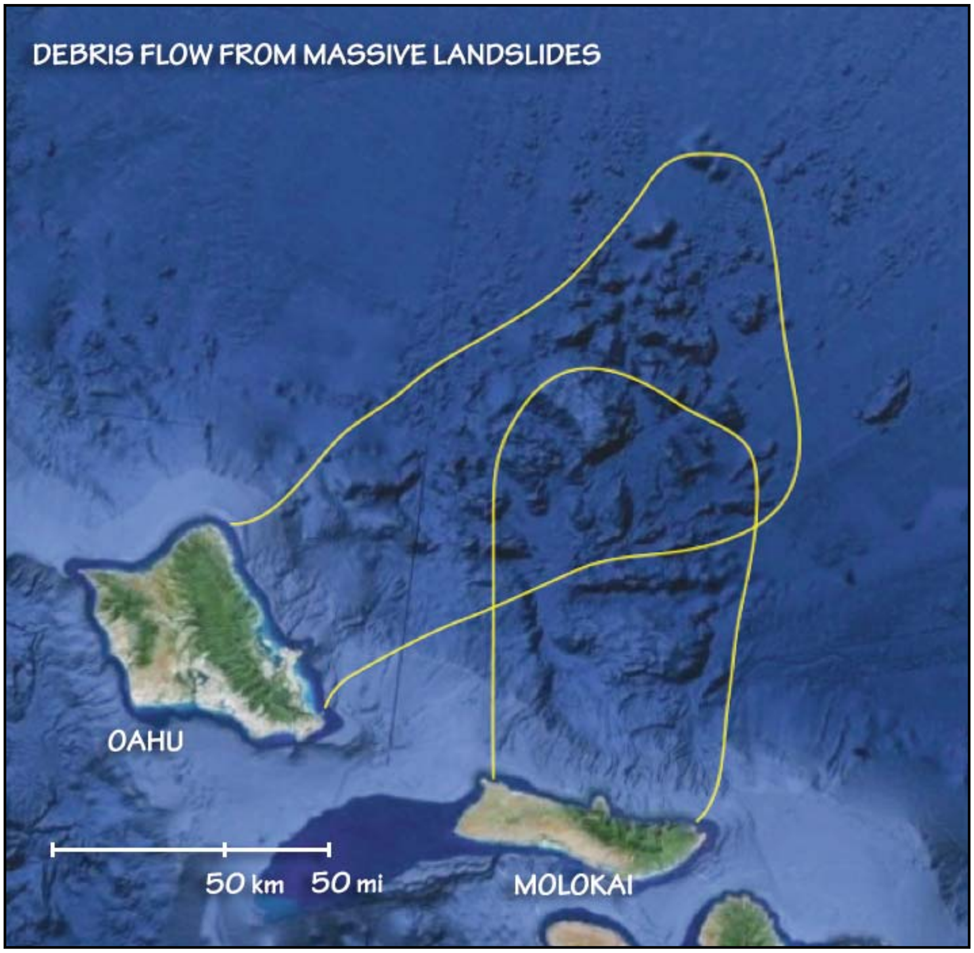


Figure 4.20: Debris flow fields from massive landslides off O'ahu and Moloka'i.

and Mauna Loa show very little incision, while dormant Mauna Kea has a considerable number of deep, yet narrow, river gulches on its windward side. The oldest volcano, Kohala (extinct), has spectacular erosional valleys on the windward side. On older islands, such as O'ahu and Kaua'i, the original shape of the volcano is difficult to see, as most of it has been removed.

Examination of the topographic map of Kohala Mountain shows frequent sharp bends in the upper reaches of windward streams (especially upper Waipi'o Valley). These bends mark the location of buried faults. Waipi'o Valley itself is eroded into the contact between Kohala and Mauna Kea volcanoes (*Figure 4.22*). Similarly, on Kaua'i, Waimea Canyon is located along an ancient fault system. Waimea Canyon is 16 kilometers (10 miles) long and up to 900 meters (3000 feet) deep, making it the largest canyon in the Hawaiian Islands (*Figure 4.23*). A similar fault dropped the east side of the island down relative to the west, creating the low-elevation plain of east Kaua'i.

Cinder Cones and Littoral Cones

The sequence of constructive volcanism accompanied by erosion and catastrophic landslides is overlain by the addition of late-stage eruptions. These

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

littoral cone • a volcanic ash or tuff cone formed when a lava flow runs into a body of water.

lava tube • a natural tube formed by lava flowing beneath the hardened surface of a lava flow.

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

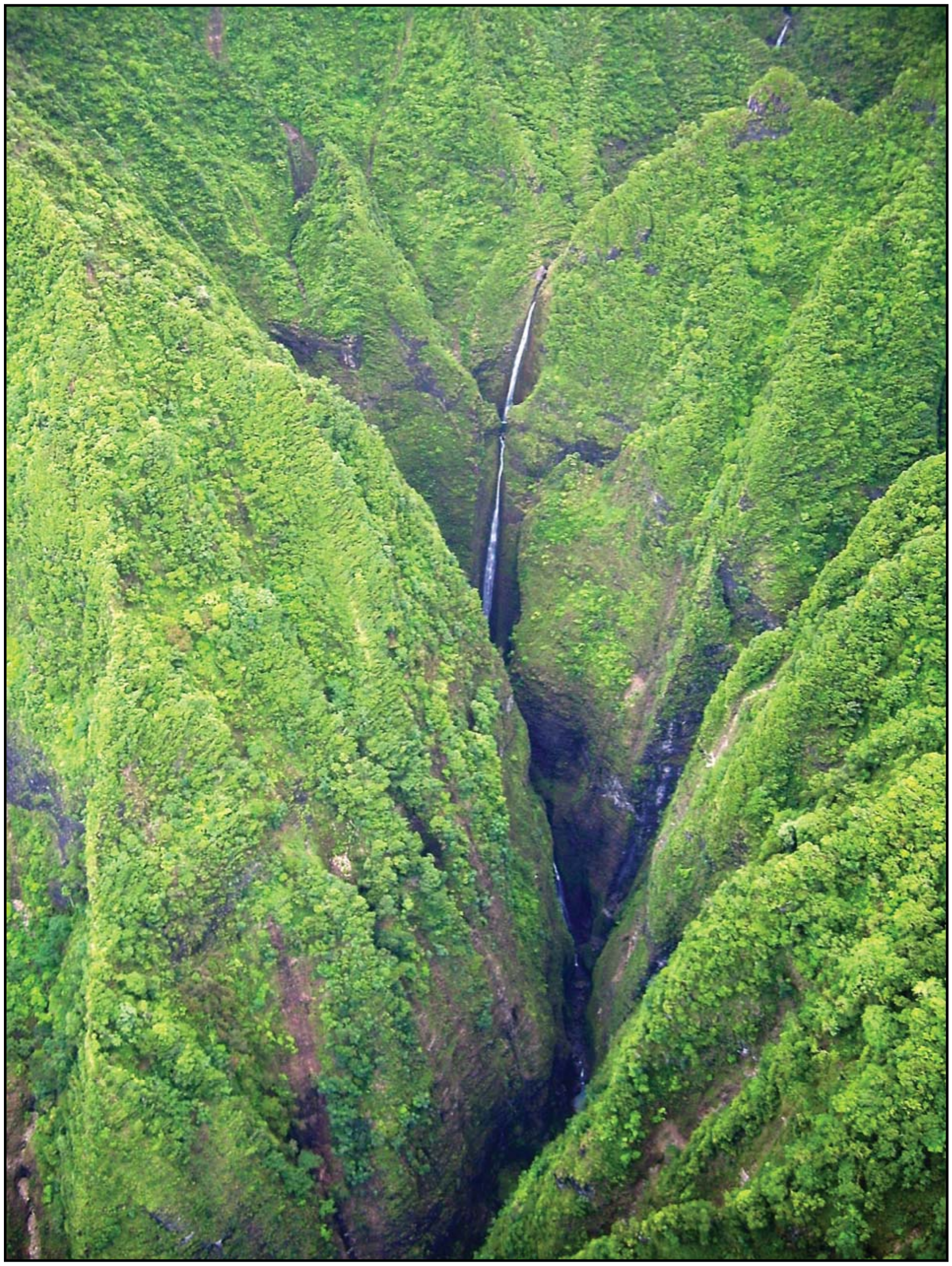


Figure 4.21: Sacred Falls State Park, O'ahu. Streams on the windward sides of all islands cut rapidly down through easily eroded basalts.

eruptions add topographic highs to the eroded flanks of older volcanoes and can create distinctive hills or *pu'u*. Cinder and **littoral cones** form some of the most iconic landscapes of Hawai'i—such as Diamond Head on O'ahu and the Haleakalā summit area on Maui (*Figure 4.24*).

Where active volcanoes touch the sea, large volumes of lava travel through **lava tube** systems into the ocean. The lava reacts explosively with the seawater, creating a steam-driven eruption that can throw blocks of hot rock a

hundred meters (330 feet) into the air and generate large quantities of **glassy** ash (*Figure 4.25*). The debris can readily build up into littoral cones, dozens of which formed in this way on the coastal stretches of the younger islands. Littoral cones are subject to vigorous wave erosion, which often cuts into the cone to form a protected bay (*Figure 4.26*).

Cinder cones erupt during all subaerial phases of volcanism; however, those formed during earlier shield building are generally covered by later eruptions.

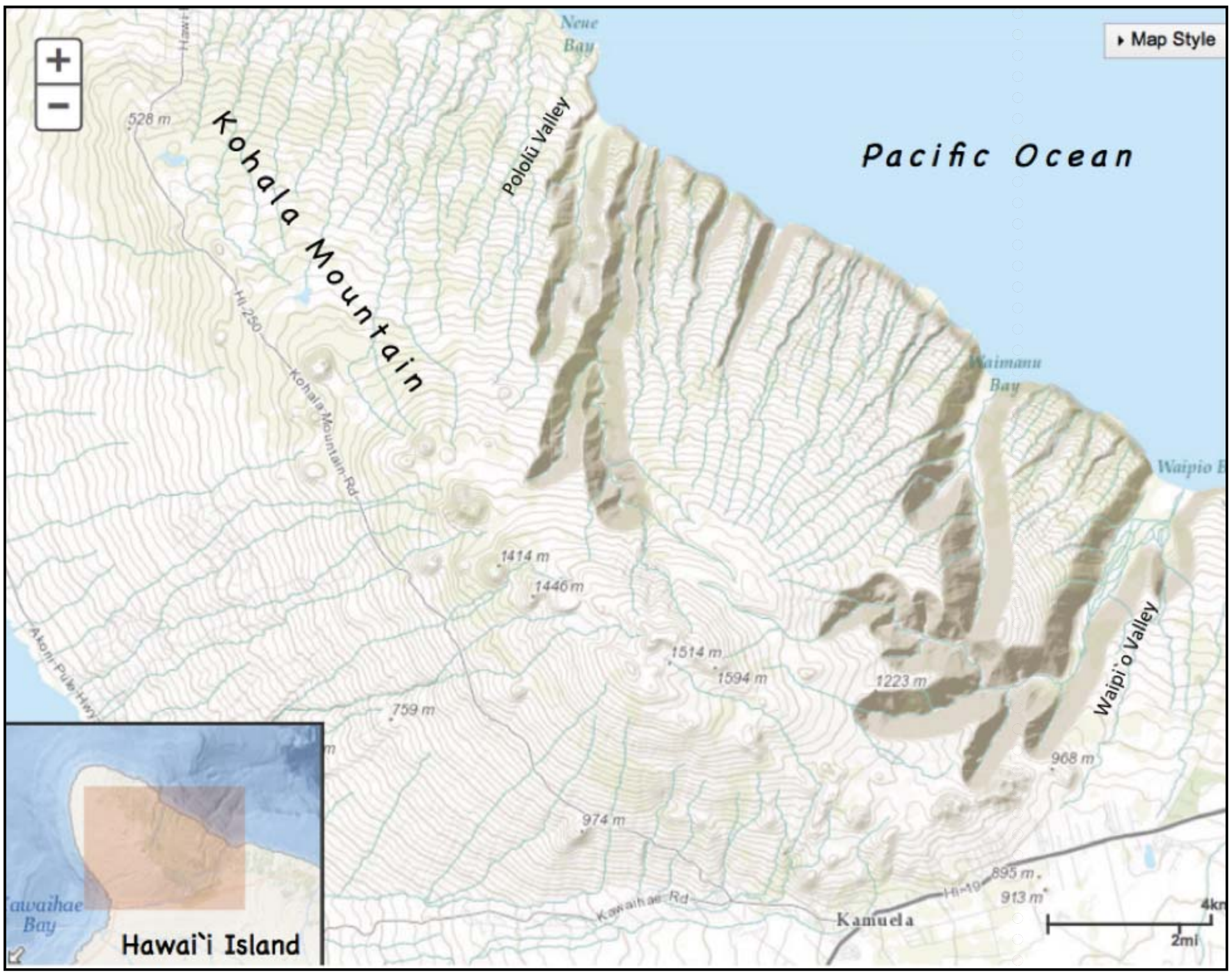


Figure 4.22: Topographic map of Kohala Mountain, Hawai‘i Island. The windward side of Kohala is deeply incised by perennial streams while the leeward side remains mostly undissected. The line of cinder cones extending NW-SE across the summit of the mountain marks Kohala's ancient rift zone.

Cinder cones that form during the post-shield stage of volcanism, as well as in the later post-erosional stage, are prominent landscape features. Volcanic rift zones are often marked by linear arrays of cinder cones. Post-erosional eruptions sometimes take place in shallow water where the mix of water and magma adds to the explosive nature of these events. Diamond Head on O‘ahu is an example of how lava-seawater interactions can build a substantial edifice composed of layered **cinders** and **volcanic ash** that also contains blocks of basalt and coral fragmented by steam explosions. Another example on O‘ahu is at Haunama Bay, where the cone was later breached by wave erosion and subsequently came to support a protected **reef** ecosystem (*Figure 4.27*).

See Chapter 1: Geologic History for more detail on the stages of Hawaiian volcanism.

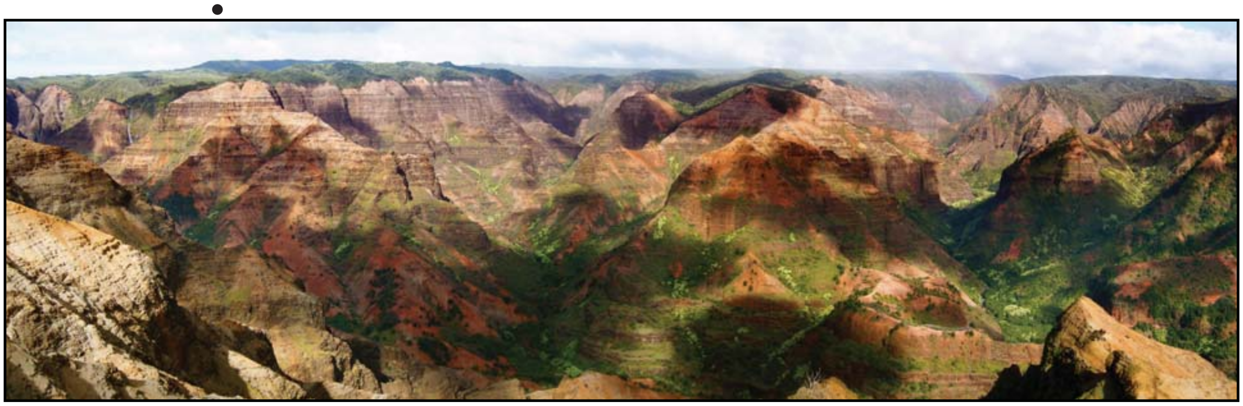


Figure 4.23: Waimea Canyon, Kaua‘i.

Figure 4.24: Haleakalā, Maui. The summit “crater” of Haleakalā formed by erosional—not volcanic—processes. Two headward-eroding valleys were carved into the sides of the volcano and were later covered by the younger cinder cones seen today.

Figure 4.25: At Kīlauea a lava tube empties into the ocean creating a jet of ash and steam. Repeated interaction of lava and seawater can form littoral cones.

Figure 4.26: Mahana littoral cone on Hawaiʻi Island, now breached by the ocean. The tephra here contains abundant olivine crystals that erode to form a "green sand beach."

Region 7

cinder *• a type of pyroclastic particle in the form of gas-rich lava droplets that cool as they fall.*

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

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.*

Figure 4.27: Hanauma Bay—a breached rejuvenation cone on O‘ahu.

Highest and Lowest Elevations (by state)

Alaska

Mt. McKinley, with an elevation of 6168 meters (20,237 feet), is the highest mountain in North America as well as Alaska. The mountain is located in Denali National Park, in the south-central part of the state, and it is considered the third most prominent peak in the world after Mt. Everest in the Himalayas and Aconcagua in the Andes. Alaska’s lowest points are along its coastlines, where the shore is at sea level.

California

California’s highest point—and also the highest point in the contiguous 48 states—is Mt. Whitney, at 4421 meters (14,505 feet) in elevation. Mt. Whitney is located at the southeastern end of the Sierra Nevada. Interestingly, it is only 85 miles northwest from Badwater Basin in Death Valley, which at 86 meters (282 feet) *below* sea level is the lowest point in all of North America.

Hawai‘i

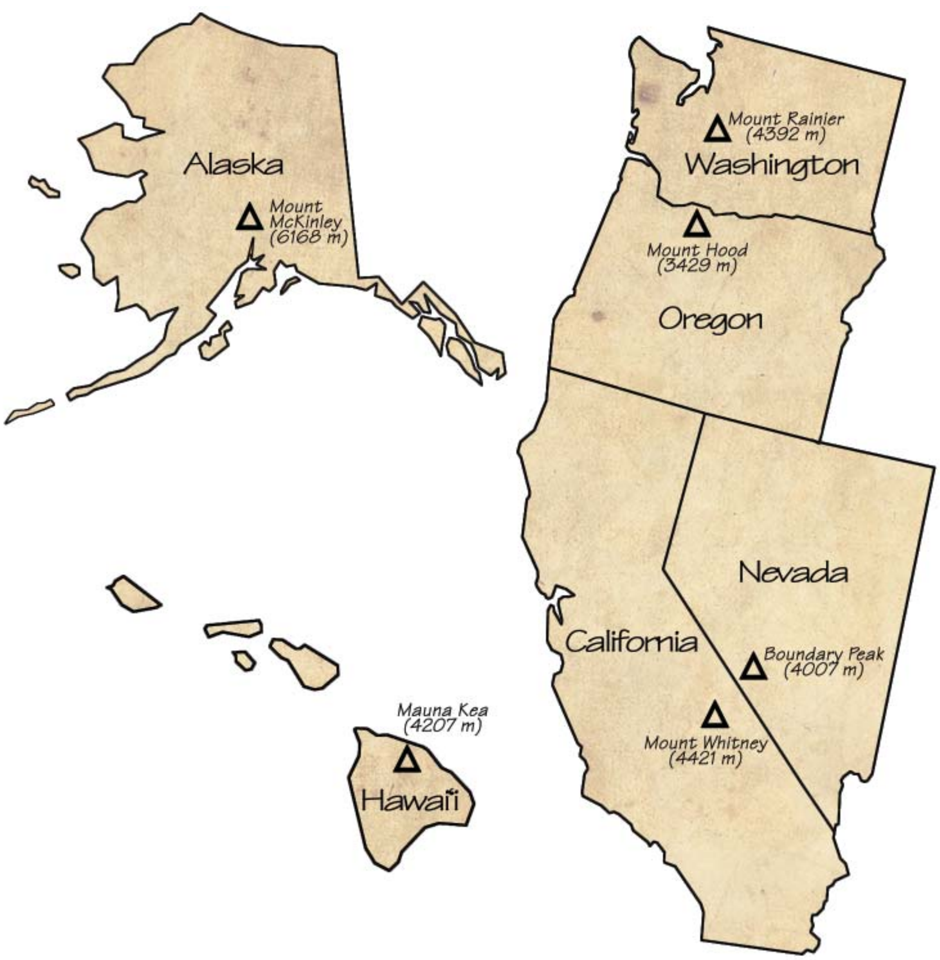
Mauna Kea, a dormant **shield volcano** on the island of Hawai‘i, is the state’s highest point at 4207 meters (13,803 feet) above sea level. A product of hot spot volcanism, much of this volcano’s bulk is below sea level—when measured from the ocean floor, its total height is actually 10,100 meters (33,100 feet). The lowest points in Hawai‘i are found at sea level along its coastlines, where the shoreline meets the Pacific Ocean.

Elevations

Nevada
At 4007 meters (13,147 feet) above sea level, Boundary Peak is Nevada's highest point, located less than 2 kilometers (1 mile) from the California border. Nevada's extreme southern border with California, on the Colorado River, is the state's lowest point at 147 meters (481 feet).

Oregon
Mt. Hood, about 80 kilometers (50 miles) east of Portland, is Oregon's highest point at 3429 meters (11,249 feet). A dormant volcano, Mt. Hood is the fourth highest peak in the Cascade Range. Oregon's lowest points are found at sea level along the coast, where the shoreline meets the Pacific Ocean.

Washington
Located 87 kilometers (54 miles) southeast of Seattle, the massive stratovolcano Mt. Rainier is Washington's highest point at 4392 meters (14,411 feet) in elevation. As well as being the highest peak in the Cascade Range, Mt. Ranier is considered one of the world's deadliest volcanoes due to its proximity to highly populated areas. Washington's lowest points are found at sea level along the coast, where the shoreline meets the Pacific Ocean.



shield volcano *• a volcano with a low profile and gradual slope, so named for its likeness to the profile of an ancient warrior's shield.*

Resources

Books

Wyckoff, J., 1999, *Reading the Earth: Landforms in the Making*. Adastra West, Mahwah, NJ, 352 pp.

Sawyer, J. O., 2006, *Northwest California: A Natural History.* University of California, Berkeley, CA, 247 pp. (Chapter 1, The Klamath: Land of Mountains and Canyons, http://www.ucpress.edu/content/pages/9691/9691.ch01.pdf.)

Websites

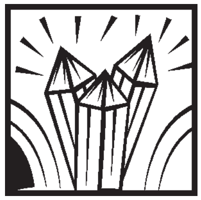
The Cascade Episode: Evolution of the modern Pacific Northwest, Burke Museum, http://www.burkemuseum.org/static/geo_history_wa/Cascade%20Episode.htm.

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

OpenLandform Catalog, Education Resources, OpenTopography, http://www.opentopography.org/index.php/resources/lidarlandforms. (High resolution topographic images that may be useful in teaching.)

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.



Chapter 5: Mineral Resources of the Western US

What is a mineral?

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

Elements: The Building Blocks of Minerals

Elements are the building blocks of minerals. The mineral quartz, for example, is made of the elements silicon and oxygen, 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 (*Figure 5.1*). 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 also be found throughout the West.

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

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

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

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

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

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

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

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5 Mineral Resources

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

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

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

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

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

erosion • *the transport of weathered materials.*

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

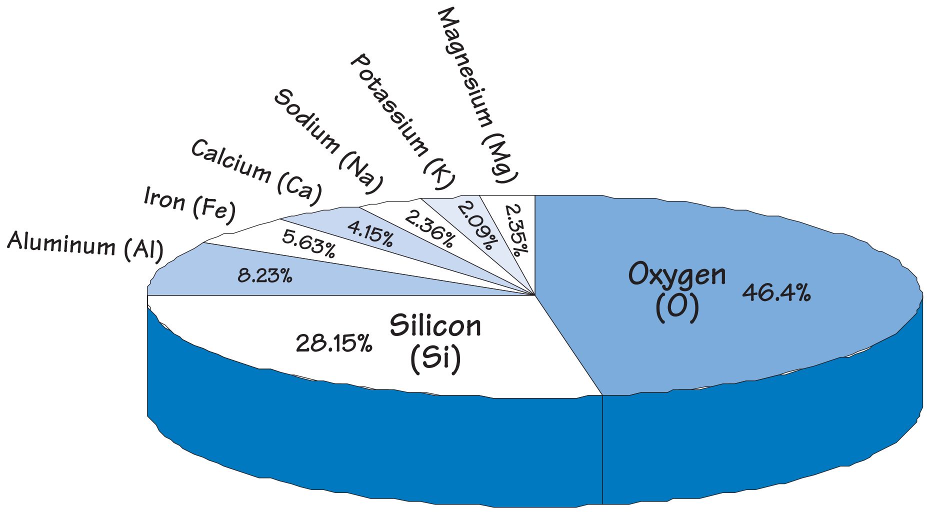


Figure 5.1: Mineral percentage by mass in the Earth's crust.

Metallic minerals are vital to the machinery and technology of modern civilization. However, many metallic minerals 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.

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

Mineral Identification

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

Hardness is a very useful property for identification, as a given mineral can only exhibit a narrow range of hardnesses, and it is easily testable, which quickly and simply minimizes the number of possibilities.

Hardness is important because it helps us understand why some rocks are more or less resistant to weathering and **erosion**. Quartz, with a rating of 7 on the **Mohs scale**, is a relatively hard mineral, but **calcite** ($CaCO_3$), rating 3 on the Mohs scale, is significantly softer. Therefore, it should be no surprise that

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. A fingernail has a hardness of around 2, a penny 3, window glass 5.5, and a knife blade 6.5.

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

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 is quite resistant due to its hardness and relative insolubility. Thus, quartz grains are the dominant mineral type in nearly all types of **sand**.

Color is helpful in identifying some minerals like sulfur, but it is uninformative or even misleading in others like garnet. **Luster** describes how light is reflected from a mineral's surface and can range from adamantine, seen in diamonds, to dull or earthy (effectively no luster), like **kaolinite**. **Crystal form**, if visible, can 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, and instead display **fracture** when broken. Mica and **graphite** have very strong cleavage, allowing them to easily be broken into thin sheets, while quartz and glass (the latter not being a mineral) have no cleavage, instead displaying a distinctive curved fracture form known as conchoidal. The **density** of a mineral may also aid in identifying it (e.g., metals tend to be very dense). Finding the exact density is straightforward, but it does require measuring the volume of the sample. Placing an unknown mineral in water (or other liquid) to find its volume by displacement can be a risky undertaking since several minerals react violently with water, and many more break down with exposure. A mineral's **streak** is obtained by dragging it across a porcelain plate, effectively powdering it. The color of the powder eliminates conflating variables of external weathering, crystal habit, impurities, etc. Some minerals are **magnetic** (affected by magnetic fields), while a few are natural magnets (capable of producing a magnetic field).

Review

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

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.*

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

fracture • *a physical property of minerals, formed when a mineral crystal breaks.*

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

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

5 Mineral Resources

Review

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

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

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

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.*

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 distinguishes a regular mineral from a gem?

Beauty, durability, and rarity of a mineral qualify it as a gemstone. Beauty refers to the luster, color, transparency, and brilliance of the mineral, though to some degree it is dependent on the skillfulness of the cut. Most gems, including tourmaline, topaz, and corundum, are durable because they are hard, making them scratch-resistant. On the Mohs scale of hardness, the majority of gemstones have values greater than 7. Isolated deposits of semi-precious gemstones can be found in most states.

Mineral Formation

Mineral deposits in the West range in age from over one billion years old to just a few thousands or tens of thousands of years, and their occurrence is related to different processes that operate in different geologic environments. 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 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 in the West 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 sedimentary layers on the ocean floor or layers of sediment 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 deposits formed through the concentration of a weathering-resistant mineral, while other minerals around it are eroded and dissolved. In contrast, mineral deposits formed by the concentration of minerals in moving waters are called **placer deposits**. In the Western US, placer deposits occur in rivers and streams that carry lighter sediment downstream but leave behind heavy minerals such as **gold**. Placer deposits can also occur on coastal beaches. The erosion of areas of small, low-grade gold veins and the subsequent concentration of the gold as stream sediment while the other minerals were carried downstream produced hundreds of placer deposits that were mined throughout the Western US during the 19th century. Mining of these deposits continues today.

Minerals in the West

The history of the Western States is driven in large part by the promise of mineral wealth. The rush for gold began in the 1840s, when much of the territory that would become California was ceded to the United States by Mexico. Gold discoveries in California resulted in Americans from the east and immigrants from around the world flocking to the area. The idea of acquiring wealth by finding gold became a backdrop for new communities and towns. As an area became either overcrowded or mined out, these gold seekers moved to new areas, eventually finding **silver** and gold in Nevada, and then gold and other

Review

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.*

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.*

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

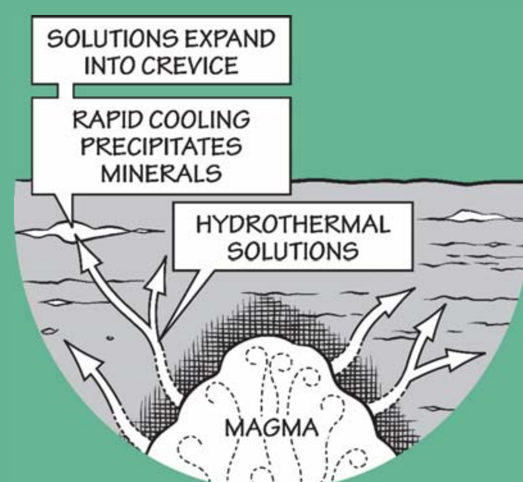
Review

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

__volcanic island__ • one of a string of islands created when molten rock rises upward through oceanic crust.

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. These hot water brines can have varying origins. As magma cools, it releases its mineral-enriched, super-heated water into surrounding rock. Rainwater becomes a hydrothermal solution by picking up salt as it filters through rocks. Seawater, which is already enriched in salt, often becomes a hydrothermal solution in the vicinity of volcanic activity on the ocean floor where tectonic plates are pulling apart. Rapid cooling of the hydrothermal solution over short distances allows concentrations of minerals to be deposited. Water moving quickly through fractures and openings in the rock, experiencing changes in pressure or composition, and being diluted with groundwater, can rapidly cool a hydrothermal solution.



minerals in Washington and Oregon. And finally, in the late 19th century, they headed to the Klondike and Alaska in search of new strikes. The minerals that early prospectors sought in rivers and streams are still being mined in many regions of the West.

Mineral Resources 5

Region 1

Many Western mineral deposits are the products of several different concentration processes, sometimes operating tens or hundreds of millions of years apart. There are a variety of geologic environments in which these mineral-concentrating processes have operated over the past billion years to produce the abundance and diversity of mineral deposits found in the West today (*Figure 5.2*), including **passive continental margins** (Arctic Coast of Alaska), **volcanic island** arcs (Aleutian Islands), mountain-building events (Sierra Nevada, Cascades, Brooks Range), and basins formed by rifting events (Basin and Range of Nevada).

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.*

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).*

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

Mineral Resources of the Basin and Range

Region 1

The Basin and Range region covers most of Nevada, some parts of eastern California, and a small part of southeastern Oregon. This province is defined by an alternating pattern of north-south trending **faults** and mountains with valleys in between. The Basin and Range, with its dry mountains and valleys, was initially seen as a barrier for those trying to reach the California gold fields. The little precipitation that does occur there quickly evaporates, flowing into short-lived lakes on the valley floors or sinking into the ground to become groundwater. These **climate** patterns have created abundant **evaporite** minerals such as salt; the geologic history of the region has also created the opportunity for large-scale mining of metallic minerals such as gold and silver, as well as of industrial materials, such as sand and gypsum (*See Figure 5.2*).

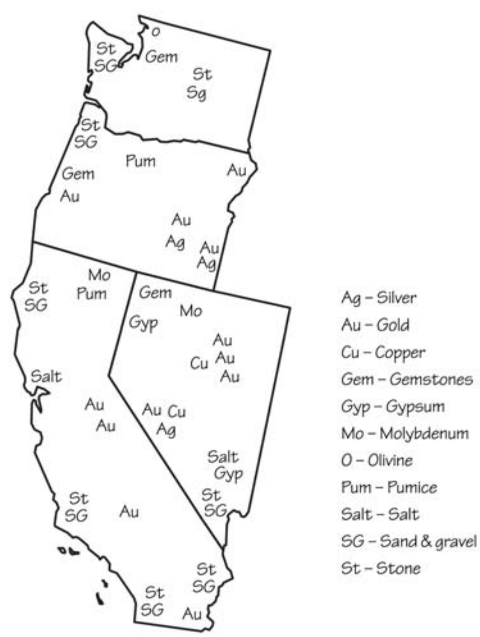


Figure 5.2: Mineral resources of Washington, Oregon, Nevada, and California.

Metallic Minerals

The primary metallic minerals mined in the Great Basin (*Figure 5.3*) are gold and silver. In 1849, Mormon prospectors found placer gold in streams leading into the Carson River. However, these prospectors were on their way west to California, so it wasn't until 1859, with the discovery of silver in Nevada's Comstock Lode, that mining began in earnest. The mining boom brought prospectors who worked the mines, settlers who started farms and ranches to feed the miners, and shopkeepers who kept them

5 Mineral Resources

Region 1

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

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

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

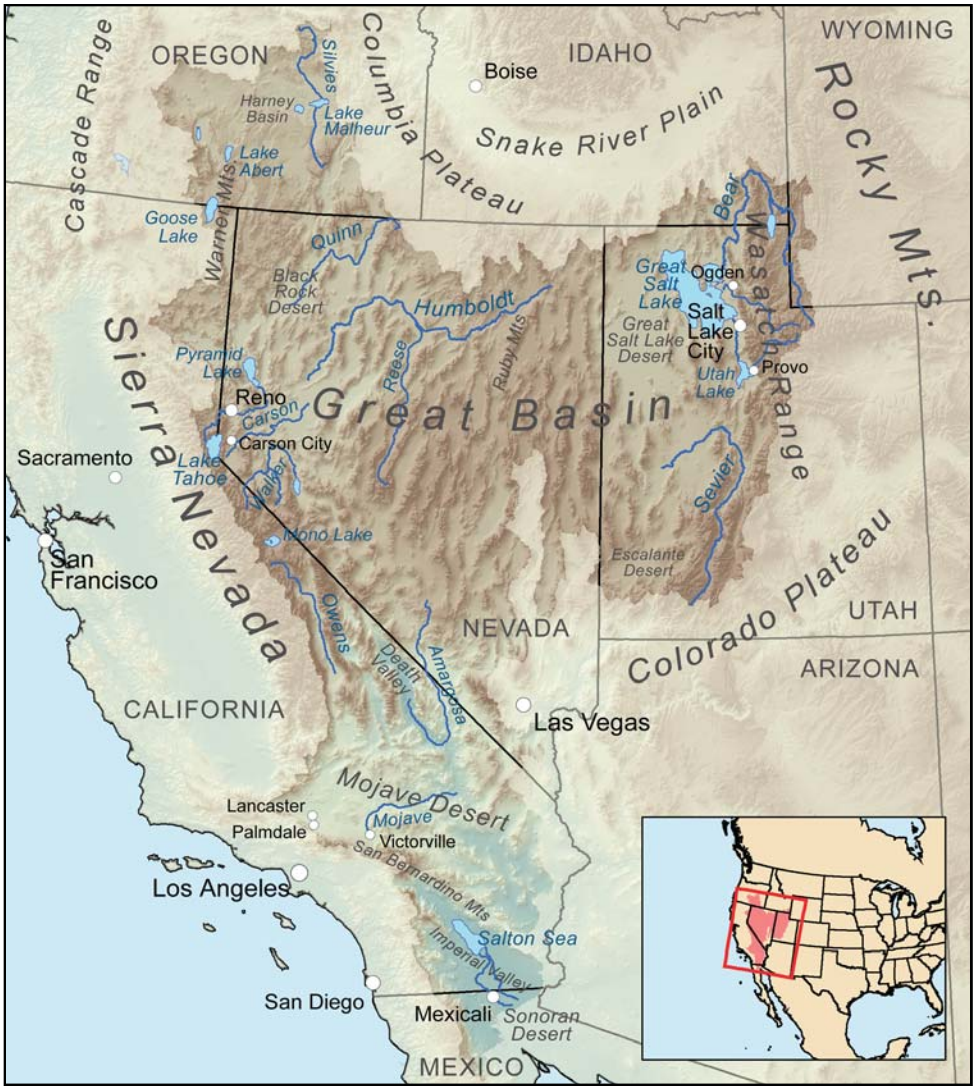


Figure 5.3: Extent of the Great Basin.

supplied. Between 1860 and 1880, the Comstock District produced more than six million tons of ore.

Gold mining in the Great Basin produces 79% of the gold in the United States today. The Carlin Unconformity in Eureka and Elko Counties, Nevada, is one of the several sedimentary rock-hosted gold regions in the Great Basin. The Unconformity is associated with a period of collision between a **terrane** and the North American **plate** about 350 million years ago, generating higher crustal temperatures and pressures and producing numerous hot springs. The hot springs acted as hydrothermal solutions, precipitating gold from the bedrock. The belt of gold mineralization is found primarily in material from the late **Eocene** (~36–40 million years ago). Originally, placer deposits were found, but in 1960 mining began on a large scale in both open pit and underground mines (*Figure 5.4*). Slightly south of the Carlin Unconformity is the Battle Mountain-Eureka

Region 1

Figure 5.4: An aerial view of Round Mountain gold mine, an open pit mine in Nye County, Nevada. Round Mountain existed as an underground mine beginning in 1906, eventually being converted to an open pit sixty years later. The pit is about 2500 meters (9200 feet) wide and 1493 meters (4900 feet deep.

Trend (here "trend" refers to an alignment of deposits), which has a similar geologic structure. Historically, mines in the area produced significant amounts of silver as well as gold.

Copper has been mined in several areas of the Great Basin. It is usually extracted in association with the other metals, like gold and silver. In White Pine County, Nevada, ore bodies produced by hydrothermal processes are being mined. The deposits are low-grade and include gold and silver as secondary products.

Low-grade gold deposits are more expensive to mine, as much more rock must be processed to extract a useful quantity of gold. Typically, precious metals are extracted from such deposits by using cyanide to leach them from crushed rock. This method is very slow, taking as long as two years to extract only 50% of the desired mineral.

Non-metallic Resources

In the northwest corner of the Basin and Range there are several mines that produce **opals**, which are used as **gemstones** (*Figure 5.5*). Opal is **silica**

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

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

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

pyroclastic *• rocks that form during explosive volcanic eruptions, and are composed from a variety of different volcanic ejecta.*

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

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.**

that lacks a crystalline structure, so it is not technically a mineral. These opal deposits formed over a period of 16 million years, in the silica-rich water of a wet, lush basin. The basin's forests were periodically buried under layers of **volcanic ash** and debris from **pyroclastic** flows. Over time, hot groundwater picked up silica-rich deposits that slowly replaced the carbon molecules in the buried **trees**. When the area was **uplifted** during the formation of the Basin and Range, erosion exposed the opal deposits.

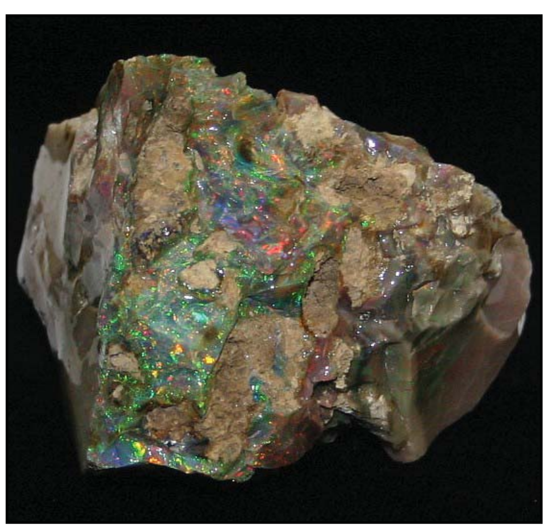


Figure 5.5: This rough opal was quarried in the Virgin Valley opal fields, located in Humboldt County, Nevada. The Smithsonian Institution's largest polished (160 carats) and unpolished (2585 carats) black opals both came from this area. (See TFG website for full-color version.)

In many places, salt deposits have formed where land-locked lakes evaporated. Because these **playas** capture all the salt and saline compounds that are washed out of the surrounding mountains, the deposits have become quite thick (and commercially viable). They are currently mined in southern Nevada and the southeast part of California. Gypsum also forms as an evaporite, and is found in similar settings.

Mineral Resources of the Columbia Plateau
Region 2

The Columbia Plateau covers a vast area of eastern Washington, northern Oregon, and southwestern Idaho. This region is the result of one of the world's largest accumulations of **lava**, with over 500,000 square km (193,000 square miles) covered by flood **basalts**. The majority of these flows occurred from 17 to 14 million years ago. Mineral resources within the Columbia Plateau are often hidden under these prodigious flows, so they tend to be found within river canyons or in **accreted terranes** that rise above the flood basalt. These terranes were brought to North America on the Pacific plate, when the coast was near the border of Idaho and eastern Washington and Oregon. As the Pacific plate **subducted** underneath the North American plate, the terranes were welded onto the growing plate. Some elevated portions of these terranes were not covered by the lava flows, allowing them to be accessed for their mineral resources (See *Figure 5.2*).

Metallic Resources

In the Columbia Plateau, gold is the most common metallic resource. In the Blue Mountains of Oregon, which are part of an exposed terrane surrounded by the basaltic flow, placer and **lode** gold was mined near John Day and Baker City. In the southwest corner of the region, intense volcanic and hot spring activity led to the hydrothermal formation of fine-grained gold deposits in Oregon's Owyhee Uplands.

See Chapter 4: Topography to learn more about how flood basalts affected the landscape of the Columbia Plateau.

Non-metallic Resources

The primary mineral resources found in the Columbia Plateau are glacial deposits of sand, **gravel**, and stone. These are used as building materials, and are also shipped outside the region for use elsewhere. Due to the large quantity of glacial deposits in the region, commercial-size quarries can be found in just about every county in Washington and Oregon that lies within the Columbia Plateau.

Regions 1–2

playa lake • *ephemeral or dry lakebed that occasionally contains only a thin layer of quickly evaporating water.*

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

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.*

lode • *an ore deposit that fills a fissure or crack in a rock formation.*

5

Mineral Resources

Regions 3–4

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

zinc • *a metallic chemical element (Zn, atomic number 30).*

Mineral Resources of the Northern Rocky Mountains
Region 3

In the far northeast corner of Washington State is a small arm of the Rocky Mountain system. The Rocky Mountains formed about 70 million years ago when an oceanic plate began subducting under the North American plate. The angle of subduction was significantly shallower than usual, causing the Rockies to form much farther inland.

Metallic Resources

Metallic resources are limited in this region. In Ferry County, Washington, mining operations began in the Kettle River-Buckhorn Mountain area. The mine is an underground facility designed to maintain as small a footprint as possible in order to minimize environmental impact. In the year 2013, the mine had a gold equivalent production (wherein silver production is converted to a gold equivalent) of 42 million grams (150,000 ounces).

The other metallic mining operation lies in Pend Oreille County, Washington. This mine accesses a **lead-zinc** ore body that is located in a narrow belt of sedimentary, volcanic, and metamorphic rocks.

Non-metallic Resources

Non-metallic resources in this region include sand, gravel, and stone. These materials are used as building materials for roads and other infrastructure in the region and are also shipped outside the region. Commercial-size quarries are found in the area.

Mineral Resources of the Sierra-Cascade Mountains
Region 4

The Cascade-Sierra Mountains form a nearly uninterrupted barrier along the western edge of the United States. Interestingly, these two ranges have very little in common. The Sierra Nevada are composed of granitic intrusions (**plutons**) that once formed the molten core of an arc-shaped chain of volcanoes during the **Mesozoic**. Erosion wore away the volcanoes, leaving the granite exposed (*Figure 5.6*). Then, less than five million years ago, these granitic blocks began to rise along their eastern edge, tilting to the west in the process. The modern Sierra, as a result, have a gently sloping west side and

See Chapter 1: Geologic History for more detail on mountain-building in the Mesozoic.

a very steep east side. The Sierra are all that remains of an ancient volcanic arc, but the Cascades form an active volcanic arc that stretches from British Columbia to northern California. Thirteen major volcanic centers are strung along this arc. Between these large volcanoes lie thousands of short-lived volcanoes. In the North Cascades, the geologic picture is more complicated, as modern volcanoes are superimposed on a series of accreted terranes.

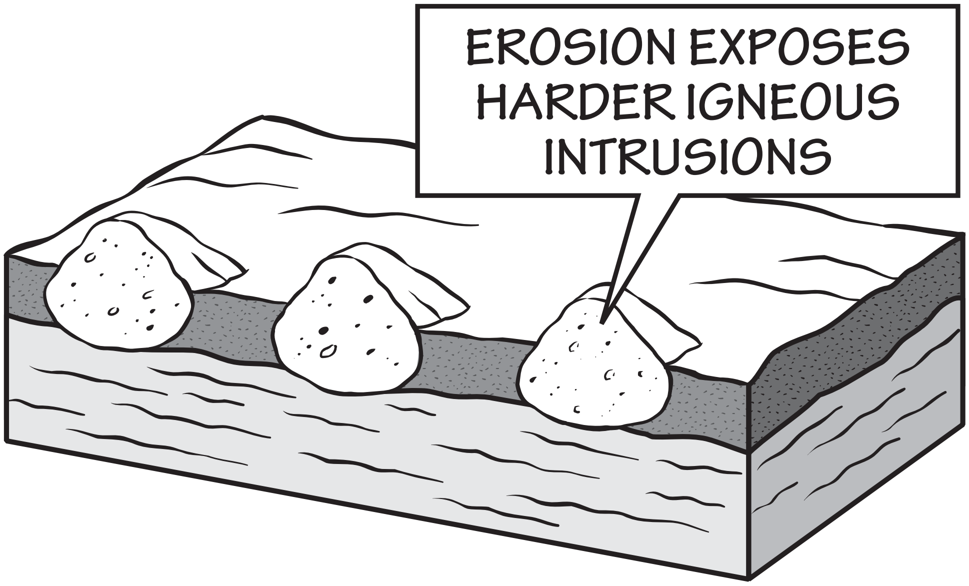


Figure 5.6: Igneous intrusions (plutons) are exposed after millions of years of erosion.

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

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

Metallic Resources

Gold formation in the Sierra Nevada occurred within saturated sediments. Hydrothermal fluids were heated at depth, causing them to rise through the overlying rock. The fluids cooled as they rose to the surface, concentrating metals like gold. This gold, in the foothills of the western Sierra Nevada, was the source of the California Gold Rush of 1848–1849. The initial find at a mill on Sutter's Creek led to thousands of prospectors arriving from around the world in hopes of striking it rich. Eventually, the gold that was relatively easy to find was depleted, and miners either moved on to other gold fields or began looking for less convenient gold sources.

Gold is still mined in the Sierra Nevada today, but on a much smaller scale. In California's Amador, El Dorado, Placer, and Nevada counties, there are several small operations that employ 20 or fewer employees. In addition, there are several designer mines that make jewelry out of gold-intruded quartz (*Figure 5.7*). The quartz is cut and polished so the gold veining shows.

In the southern Cascades, in and around Jackson County, Oregon, a number of small gold mines were developed after the 1850s. Many of these were placer

pumice *• a pyroclastic rock that forms as frothing and sputtering magmatic foam cools and solidifies.*

cinder *• a type of pyroclastic particle in the form of gas-rich lava droplets that cool as they fall.*

porosity *• 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.*

aggregate *• crushed stone or naturally occurring unlithified sand and gravel.*

Figure 5.7: A sample from a quartz-gold vein mined near the Harvard Open Pit Mine in the Sierra Nevada foothills, California. (See TFG website for full-color version.)

claims that brought in dredges to move and process larger amounts of material from the riverbeds. Most of these claims were abandoned by the 1920s. Today, small placer claims are still worked along the rivers and streams that flow from the Cascades to the Pacific Ocean.

In the northern Cascades, silver, copper, and gold mining was a prominent industry in the late 19th and early 20th centuries. One of the largest copper mines in the country, the Howe Sound Holden Mine in Holden, Washington, produced $66 million worth of ore before it was shut down in the 1950s as mineral prices dropped. Today, the US Forest Service and Rio Tinto mining group are engaged in a multi-million-dollar project to remediate environmental problems at the Holden Mine area, including the disposal of old mining waste and dismantling the old buildings (*Figure 5.8*).

Other metals, including silver and zinc, have been found throughout the Sierra Nevada and Cascade Range, but not in quantities that currently make them commercially viable.

Non-metallic Resources

In the Sierra Nevada and Cascade Range, gravel, stone, and sand are quarried for use in building roads, houses, and other infrastructure. In addition, **pumice** and volcanic **cinders** are quarried in the volcanic southern Cascade Range. These deposits are notable for having a lower density and higher **porosity** than most other rocks (*Figure 5.9*); this makes them commercially valuable for use as a lightweight yet strong construction material. Pumice can also be used as lightweight **aggregate**, insulators, absorbents, and abrasives. Pumice and cinders are quarried in Deschutes County, Oregon, near the town of Bend. Further south in Klamath County, Oregon, pumice is also quarried commercially.

Mineral Resources 5

Region 4

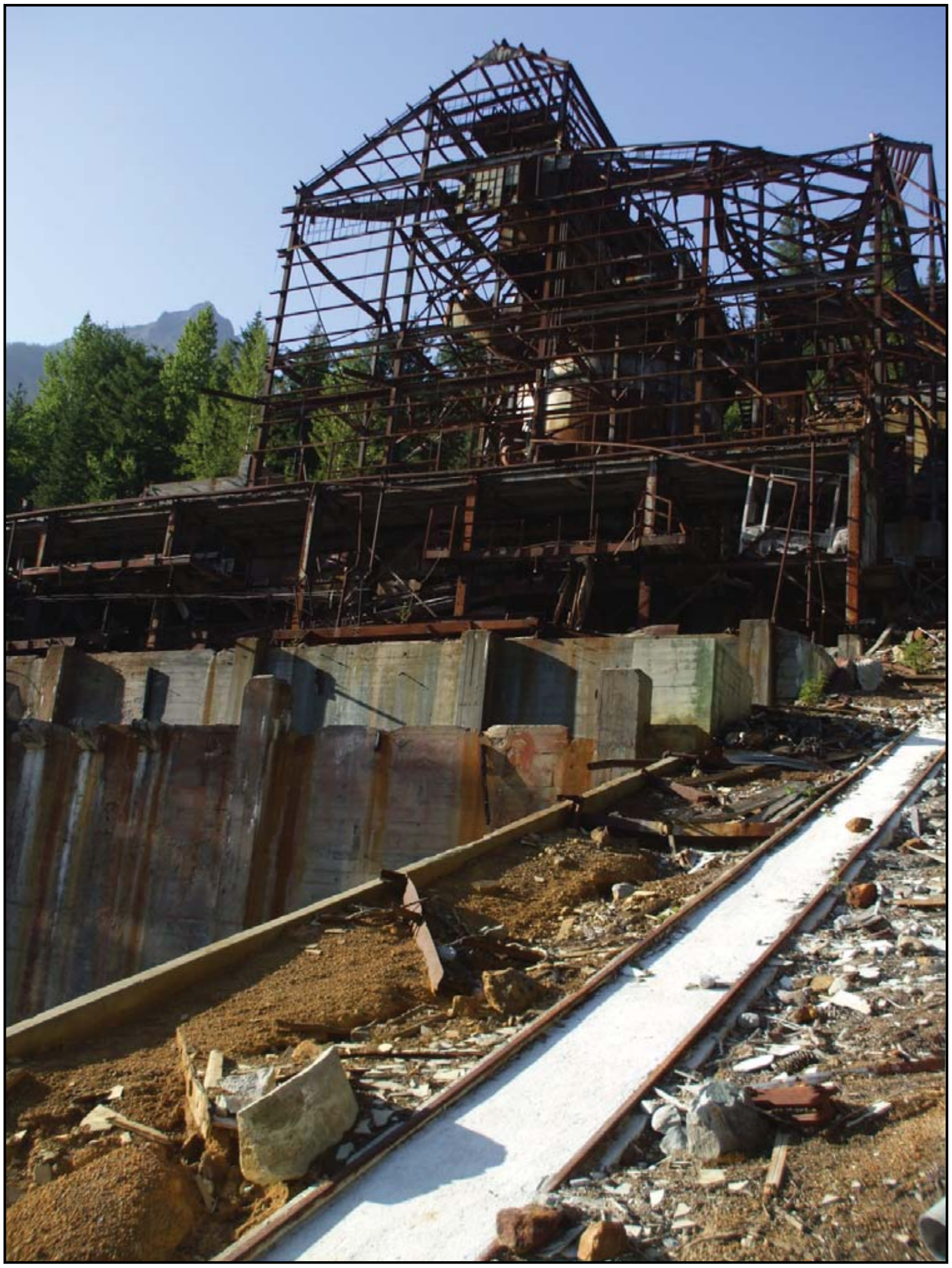


Figure 5.8: The skeleton of an old mill building at the Holden Mine site.

olivine • *an iron-magnesium silicate mineral* $((Mg,Fe)_2SiO_4)$ *that is a common constituent of magnesium-rich, silica-poor igneous rocks.*

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

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

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

Near the Canadian border in the northern Cascades, the Twin Sisters **dunite** contains one of only two **olivine** mines in the United States. Dunite is olivine-rich **ultramafic mantle** rock, and is rarely found at the surface. Olivine has a high **heat** tolerance, making it ideal for use in foundries when casting objects and when lining kilns, furnaces, incinerators, and reactors. It is also a good material for sandblasting and for other abrasive uses. In Whatcom County, olivine is

Figure 5.9: A close-up of a pumice stone, revealing its highly porous and vesicular texture. These gas bubbles make the rock so lightweight that it is able to float. Field of view is 2.7 centimeters (1 inch) across.

mined mostly for abrasive purposes, although a small amount of foundry-grade material is also produced.

Mineral Resources of the Pacific Border

Region 5

The Pacific Border is defined by a series of mountain ranges that run along the coast. These mountains include (from north to south) the Olympic Mountains, the Oregon Coast Range, the Klamath Mountains, the California Coast Range, the Transverse Range, and the Peninsular Range. Much of the area formed due to Pacific plate subduction, as sea bottom sediments, basaltic upper crust, and ultramafic lower crust were scraped onto the overriding North American plate and subsequently metamorphosed, uplifted, and finally eroded.

Metallic Resources

Placer gold deposits were mined along the coast of Oregon and California. In southern Oregon, gold was originally found near the mouth of the Rogue River, and these beach deposits were extensively mined starting in the 1850s. There are still a few gold mining operations upriver on the Rogue, and gold can still be panned on the beach (*Figure 5.10*).

Figure 5.10: Gold panning near Jamestown, California.

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

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

***slate** • a fine-grained, foliated metamorphic rock derived from a shale composed of volcanic ash or clay.*

In the Klamath Mountains of southern Oregon and northern California, sedimentary deposits from the **Devonian** and **Carboniferous** periods form tightly folded **slates**. These slates are riddled with highly siliceous intrusions that contain copper and zinc. These minerals were mined extensively from the 1890s to about 1920.

Non-metallic Resources

As cities like Los Angeles and San Francisco began to grow along California's coast, there was a demand for cheap building materials for roads, buildings, and other infrastructure. As a result, the quarrying of materials, including sand, gravel, and stone, became an important industry, and these materials are produced throughout this region. Large stones are used as breakwaters and jetties to protect coastal infrastructure from battering waves. Interestingly, the famous sandy beaches of Southern California no longer receive sand from the inland mountains. The growth of Los Angeles has interrupted the rivers that used to transport eroded sediments from the mountains to the beaches. As a result, rock is quarried from the mountains, mechanically pulverized into sand-sized grains, and then trucked to the beach.

Salt is produced in the San Francisco Bay—ponds are filled with saltwater from the bay, which is then allowed to evaporate (*Figure 5.11*). It takes over four years for this process to turn saltwater into harvestable salt. The salt was originally used for paper pulp production, livestock, and food preservation,

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

Figure 5.11: Salt evaporation ponds on the western shore of San Francisco Bay. Different microorganisms thrive in varying levels of salinity, causing the ponds to change in color. Low-salinity ponds are inhabited by blue-green algae, while saltier waters support orange brine shrimp and red bacteria. (See TFG website for full-color version.)

but today it is sold as table salt. Bittern, a byproduct of the salt purification, consisting of magnesium chlorides, sulfates, and other chemical compounds, is sold as dust control for construction sites and vineyards.

Further north, **agate** can be found along many beaches in Washington and Oregon. This semi-precious gemstone is collected and used for jewelry and other decorative purposes.

Mineral Resources of Alaska

Region 6

Alaska encompasses a large landmass that contains a wide variety of mineral resources. However, difficulties associated with a lack of transportation and challenging environmental conditions (extreme cold, snow, and darkness) have limited the amount of mining that can occur there. Despite these obstacles, mineral resources continue to play an important role in the state's development (*Figure 5.12*).

Alaska can be divided into separate areas, classified mainly by their differing modes of formation (*Figure 5.13*). Northern Alaska formed as the Yukon-Tanana terrane collided with the North American plate about 200 million years ago. This movement uplifted sections of the Arctic Sea floor, forming the Brooks Range

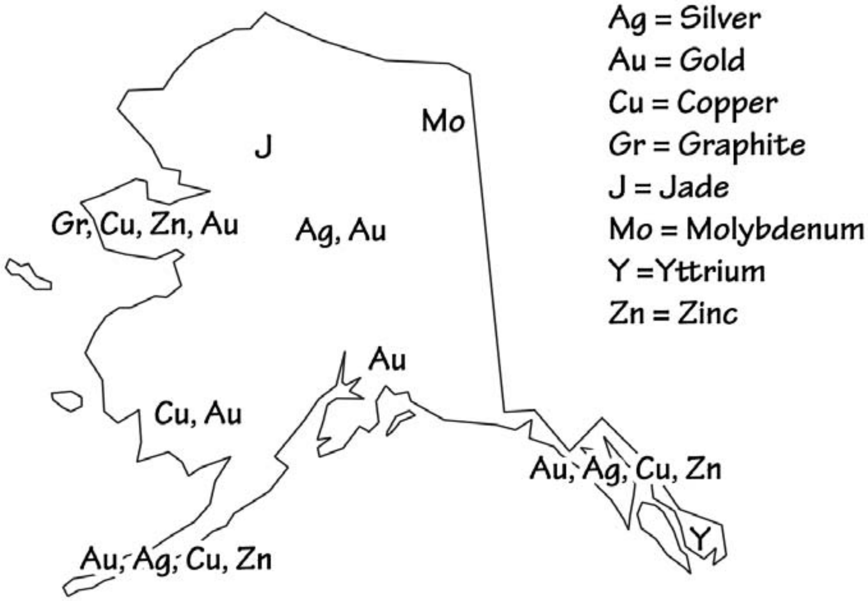


Figure 5.12: Mineral resources of Alaska.

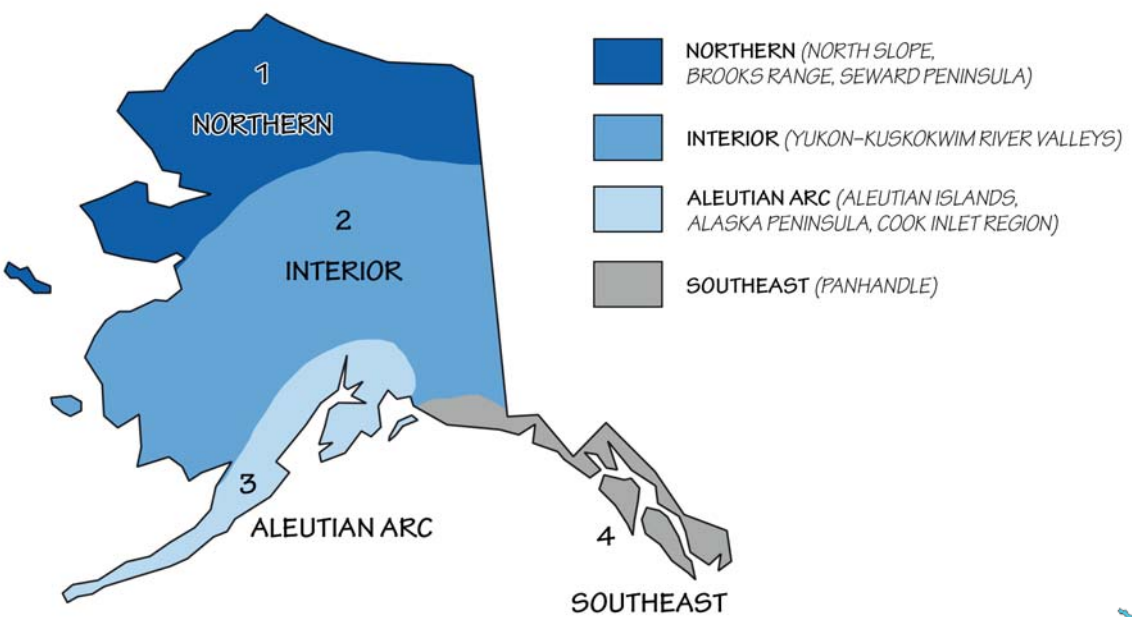


Figure 5.13: Common subdivisions of Alaska

Region 6

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

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.

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

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

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

and White Mountains, and leaving behind the Arctic Plain (North Slope) between the Brooks Range and the Arctic Ocean. Major **oil** and gas development has taken place on the Arctic Plain.

See Chapter 7: Energy for more about Alaska's oil and gas resources.

Mineral deposits, including zinc, silver, gold, graphite, and jade, are found in and around the Brooks Range and the White Mountains.

Alaska's Interior lies between the Brooks Range to the north and the Aleutian Arc (and associated Alaska Range) to the south. It consists of sediment-covered crustal material from the Yukon-Tanana terrane. Two major river systems run through the Interior, along with a number of smaller rivers and tributaries, contributing to erosion and depositing sediments throughout. Placer gold mining brought prospectors to the area in the late 19th century, and mining remains an important industry there today.

The Aleutian Island Arc lies along the southern edge of the North American plate in Alaska. This area is an active subduction zone, where the Pacific plate subducts beneath the North American plate. As the subducting plate descends and begins to melt, water is released from the oceanic crust; this leads to melting of the overlying mantle and the generation of volcanism. The result is an arc of volcanic islands that stretches 2500 kilometers (1550 miles) from the Alaskan mainland through the Aleutians to Russia's Kamchatka Peninsula. The arc is relatively young and continues to change as a result of regional volcanism. Some small-scale mineral development has occurred, and exploration of the area's resources is ongoing.

Southeast Alaska is one of the state's most geologically complex areas. It consists of a narrow archipelago of about 1100 islands and a thin strip of the Pacific Coast Range mountains, about 965 kilometers (650 miles) long with an average width of 193 kilometers (120 miles). Much of the land is mountainous, rising directly from sea level to great heights, and subsequently carved by recent glaciations. Since the last **ice age**, the removal of vast quantities of glacial ice from the landscape has allowed the land to rebound, elastically springing back to its former height (before it was **compressed** by the **glaciers**). This process, known as **isostasy** or isostatic rebound (*Figure 5.14*), has elevated the ocean shelf as much as several hundred meters (yards) above sea level. Physical structures in the area are generally oriented from the northwest to the southeast. The islands have long axes in these directions, forming strips of land that are roughly parallel to each other. Rocks in Southeast Alaska can be subdivided into 10 groups: five **terranes** that have distinct geologic records and five rock groupings that are depositional, intrusive, or of unknown connection to the terranes. Most of the area is accessible only by plane or ship, making mineral development difficult. There are exceptions, however, such as large gold mining operations in the Juneau area and historical garnet mining near Wrangell.

Region 6

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

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

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

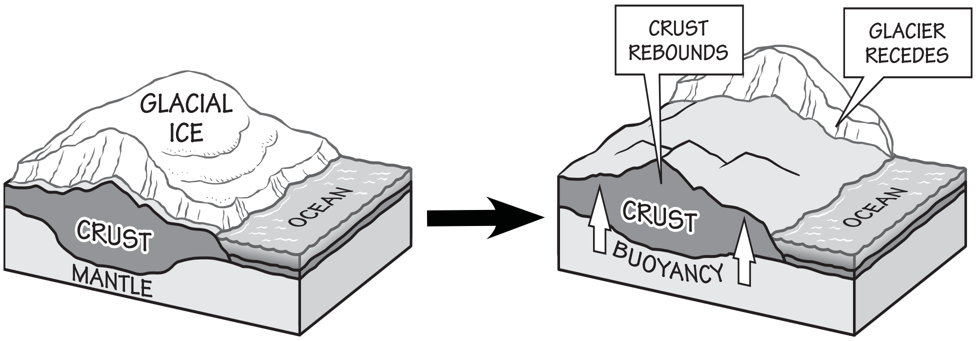


Figure 5.14: Isostatic rebound resulting from glacial retreat.

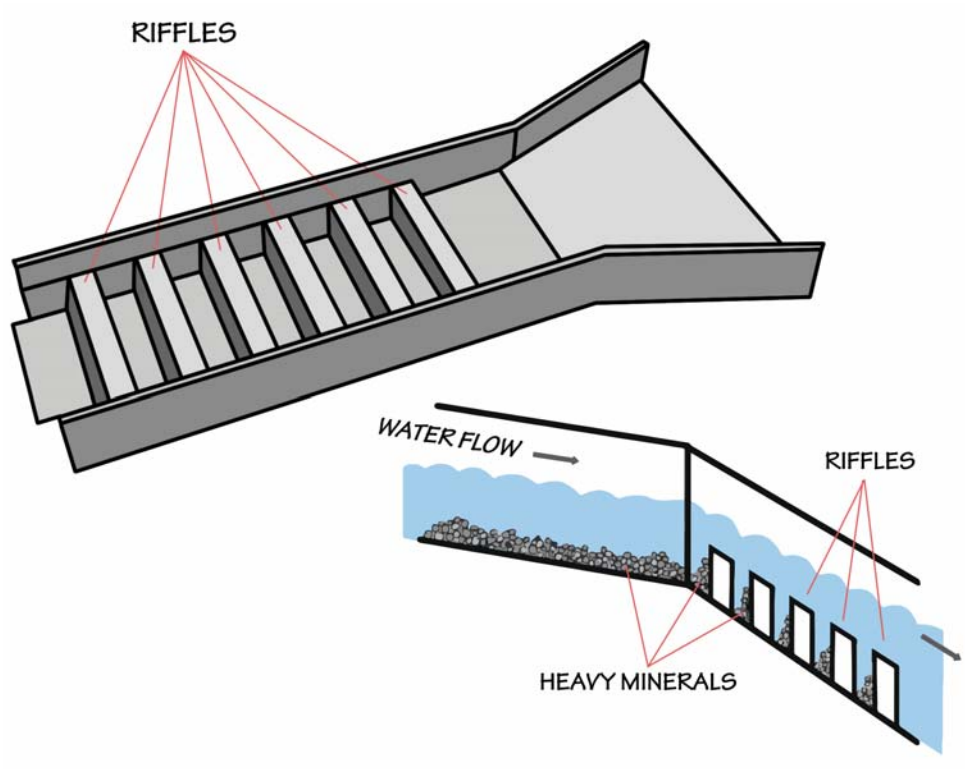


Figure 5.15: A sluice is a long tray through which water containing gold is directed. The sluice box contains riffles, or raised segments, which create eddies in the water flow. Larger and heavier particles, such as gold, are trapped by the eddies and sink behind the riffles where they can later be collected.

Mineral Resources of Northern Alaska

Metallic Minerals

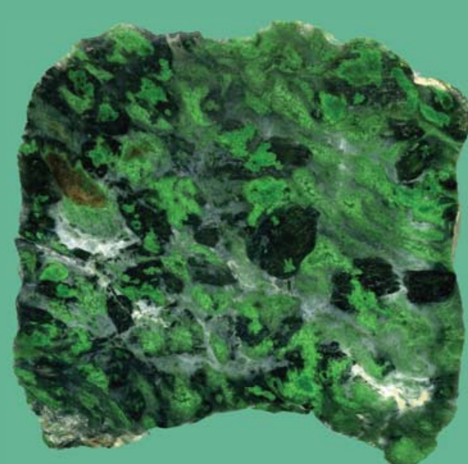
In the southern part of the Brooks Range, mineral deposits are found in **Paleozoic**-age metamorphosed sedimentary rocks that contain similarly aged basalt **dikes**. In several areas close to the Dalton Highway, small mining operations extract small quantities of placer gold. Near Coldfoot, larger-scale operations use hydraulic pumps to blast frozen gravel from hillsides that is then washed in large sluice operations (*Figure 5.15*).

On the western end of the Brooks Range, mineral deposits are found in Paleozoic black **shales**, creating a sulfide ore zone from which zinc and lead are mined. Because this area is north of the Arctic Circle, extreme winter conditions (with temperatures as low as -51°C [-59°F]) make mining in this area difficult.
The placer gold found on the beaches of Seward Peninsula became the center of a gold rush in the late 19th century. The beaches around what eventually became the community of Nome were staked out and mined. Later, dredges were built on the rivers around Nome. Today, the beaches and ocean shelf around Nome are still home to a number of placer mining operations.

Non-metallic Minerals
Northeast of Nome on the Seward Peninsula, a graphite mine—the Graphite Creek Deposit—is under development. The graphite here formed through

Jade

The word "jade" is applied to two minerals that look similar and have similar properties: jadeite (a kind of *pyroxene*) and nephrite (a kind of amphibole). The two minerals are so similar that they weren't distinguished from one another until 1863. 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 the *active plate boundaries* of both Alaska and the western continental U.S.



Late Triassic chromian jade, which contains both pyroxene and amphibole.

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

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

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

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

active plate boundary • *the boundary between two plates of the Earth's crust that are colliding, pulling apart, or moving past each other.*

metamorphism in the late **Jurassic** to early **Cretaceous**. It is generally found as flakes dispersed throughout the host rock, but can also be found in highly concentrated pockets.

Jade found in the Kobuk area has been mined in small amounts since the 1940s, and is used for jewelry and small, carved objects. The jade is found in ultramafic and mafic rocks formed in the middle to early Jurassic periods.

Mineral Resources of Interior Alaska

Metallic Minerals

Prospectors first came to Alaska's interior following the Klondike gold rush in the late 19th century. Miners who arrived to the Klondike too late to stake claims, or simply chose to move on, would travel down the Yukon River. Eventually, near Fairbanks, placer gold was found in the creeks and streams that feed into the Yukon and Tanana Rivers. These early claims led to massive dredging operations in the early 20th century (*Figure 5.16*). Today, two large gold mines

Figure 5.16: An abandoned gold dredge in Chatanika, Alaska, northeast of Fairbanks.

are found in this area. The Pogo Mine near Delta Junction is in high-grade **gneiss** intruded by Cretaceous granitic bodies. Closer to Fairbanks, the Fort Knox Mine is found in a granite body known as the Fort Knox pluton. The gold is found in quartz veins, which are the precipitated remains of hydrothermal fluids that once circulated through the pluton. Although the gold has been concentrated in the quartz veins, the ore must be further processed in order to separate the gold from the quartz.

More recently, at the Pebble Deposit in the Kuskokwim River drainage, copper, **molybdenum**, and gold have been found in veins and within granitic rocks. In part of the deposit, these minerals are partially exposed at the surface, while other portions are concealed beneath younger volcanic and sedimentary rock.

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

molybdenum • *a metallic chemical element (Mo) which has the sixth-highest melting point of any element.*

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

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.*

Non-metallic Minerals

Large amounts of sand and gravel (aggregate) are extracted throughout the area for use in road building and construction. Besides building new roads, aggregate is used to cope with the effects of **climate change**: as **permafrost** melts, **soil** compacts and overlying roads and infrastructure become unstable, requiring solid material to fill in the gaps. Large stone is also quarried for use as **rip-rap** along riverbanks in populated areas.

See Chapter 9: Climate to learn more about the effects of melting permafrost.

Mineral Resources of the Aleutian Arc

Metallic Minerals

Little is known about metallic deposits on the Aleutian Islands, and mining has occurred only in small pockets. On Unga Island, close to the Alaska Peninsula, gold and silver have been found in quartz deposits. Further out in the Aleutians, on Salt Island, the indigenous peoples collected native copper from the basaltic rocks for use as tools (such as awls, needles, and knives) and decoration.

Figure 5.17: An old mining cabin in Hatcher Pass, Alaska, the home of Independence Mine. The first mining claims in this area were staked in 1906.

Metallic mineral deposits are more common on the Alaska Peninsula itself, and also in the Cook Inlet. Placer gold deposits have been found on the beaches of the Alaska Peninsula and Kodiak Island, as well as in small creeks throughout the area. Deposits of copper and molybdenum have been found in the Pyramid Mountain area and are being explored for possible development.

In Cook Inlet, small placer deposits led to gold rushes during the early 20th century, and major mining operations started targeting underground deposits.

Along Turnagain Arm, near Anchorage, gold was found in Crow, Hope, and Six-Mile creeks. Placer mines were developed, and some individuals still mine these small claims (*Figure 5.17*). North of Anchorage, in the Talkeetna Mountains, placer gold was found in creeks. As prospectors moved to the headwaters of these creeks they found surface veins of gold, which led to underground mining at Independence Mine. The mine reached peak production in 1941 with a workforce of over 200 men blasting nearly 20 kilometers (12 miles) of tunnels and producing 975,677 grams (34,441 ounces) of gold. In 1942, shortly after the United States entered World War II, the War Production Board decided that gold was non-essential to the war effort. Gold mining throughout the United States was halted as a result—Independence Mine continued to operate, however, because of the presence of **scheelite**. Scheelite is a source of tungsten, a strategic metal for the war effort, and it was found in the same gold-bearing quartz veins being excavated by the mine. Since the production of scheelite was low, the mine closed in 1943. After the war, the price of gold dropped—mining at Independence was no longer profitable, and the mine closed for good in 1951.

Non-metallic Minerals

Non-metallic minerals found in this area are used in the road and building industries. Large amounts of sand and gravel are extracted for use in road building and construction. In the Matanuska Valley and the Anchorage area, rivers and glaciers left large sedimentary deposits that provide an inexpensive source of sand and gravel.

After World War II, the city of Anchorage grew quickly, and it therefore needed building materials. A pumice mine was developed nearby, on volcanic Augustine Island. From 1946 to 1949, pumice was mined and transported by barge to Anchorage to be used as an additive in cement and concrete. The mining ended when Mt. Augustine erupted, destroying the roads and several structures on the island.

Mineral Resources of Southeast Alaska

Metallic Minerals

Alaskan gold was first discovered in the southeastern part of the state, as prospectors had been following the gold fields north from California in the 30 years since the finds at Sutter's Mill in 1848–1849. By the 1870s, gold had been found in small amounts near Wrangell and Sitka. In 1880, a major strike took place in what would become Juneau, the state capital. At the far north of Southeast Alaska, the Kennecott Copper Mine was developed starting in 1900, and produced millions of tons of ore over 27 years of operation (*Figure 5.18*). In addition to copper, the mines also produced a significant amount of silver.

Today, gold is the primary metal mined in Southeast Alaska, although recent discoveries of silver, zinc, and lead in commercial quantities have led to new mines. Southwest of Juneau, on Admiralty Island, a large mine at Green Creek has been developed in **schists** metamorphosed from volcanic and sedimentary rocks—this mine produces gold, silver, copper, lead, and zinc produced by magmatic and hydrothermal processes.

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

rip-rap • *rock and rubble used to fortify shorelines, streambeds, pilings, and other structures against erosion.*

scheelite • *a yellow-brown mineral that is often found in association with quartz.*

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

fuel • *a material substance that possesses internal energy that can be transferred to the surroundings for specific uses.*

rare earth elements • *a set of 17 heavy, lustrous elements with similar properties, some of which have technological applications.*

Figure 5.18: The 14-story concentration mill at the Kennicott Copper Mine, built in 1906. Today, the mill and mines are located in Wrangell-St. Elias National Park & Preserve.

Non-metallic Minerals

A number of non-metallic minerals are currently mined in Alaska's southeast. Near Wrangell, a garnet-bearing schist wall has been mined for specimen-grade garnets since the early 1900s (*Figure 5.19*). The mine is currently owned

Figure 5.19: A 2.5 centimeter (1 inch) wide garnet from Wrangell, Alaska.

by the local Boy Scout Troop, which collects and sells the garnets to tourists. Further north at Gypsum Creek, a mine produces gypsum from the Paleozoic Iyoukeen Formation. At the southernmost end of the Panhandle, on Prince of Wales Island, Bokan Mountain is being explored for heavy **rare earth elements**. Surveys have shown that about 40% of the area (by weight) is composed of these rare elements, including dysprosium (used in **nuclear** reactors and data storage), terbium (used in solid-state devices and **fuel** cells), and yttrium (used in the production of lasers, electrodes, and superconductors).

nuclear • *a reaction, as in fission, fusion, or radioactive decay, that alters the energy, composition, or structure of an atomic nucleus.*

Mineral Resources of Hawai‘i
Region 7

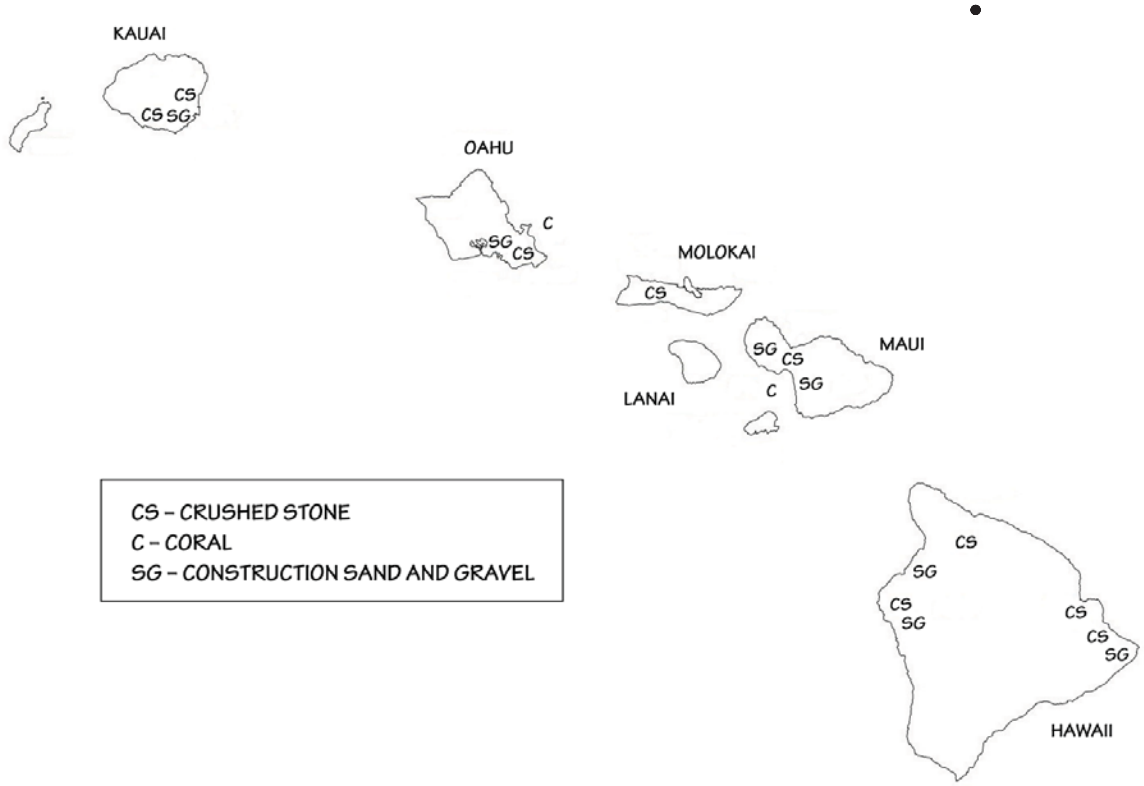


Figure 5.20: Mineral resources of Hawai‘i.

The uniform geology of the Hawaiian Islands does not produce the variety of mineral resources seen in many other parts of the world (*Figure 5.20*). However, human development has spurred demand for building materials, which, in turn, has driven the development of basalt and limestone resources. In ancient times, Hawaiians used dense basalt for tools and implements. Evidence of

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

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

quarry sites once used for these purposes can be found throughout the islands. The Hawaiians also used basalt rocks for building hut bases and ceremonial walls (*Figure 5.21*).

Figure 5.21: Impressive ancient dry stone construction at Pu'uhonua O Hōnaunau National Historical Park, Hawai'i Island.

The arrival of Europeans and the subsequent development of the Hawaiian Islands led to an expansion of the construction industry, ultimately requiring more materials. More recently, some companies have been working to develop deposits of extremely weathered soils for their aluminum potential.

The US Geological Survey divides the current utilized mineral resources of Hawai'i into three categories: crushed stone, construction sand/gravel, and gems.

Crushed stone is Hawai'i's largest mineral resource, making up over 85% of the state's mineral production resources (*Figure 5.22*). Crushed basalt is used for a variety of purposes in the construction industry, such as in road bases and as an aggregate in concrete, drainage, and stone retaining walls. Sand made of cinder from cinder cones is also sought after as a landscaping material. Limestone from emerged **Pleistocene**-age **reefs**, and the coastal carbonate sand dunes that fringe O'ahu and older Hawaiian islands, has been used to make cement products.

The "gems" mined in Hawai'i are limited to black and precious corals. Approximately $150,000 a year of this material is taken from the waters off the

Figure 5.22: Crushed stone quarry nestled in the hills of O‘ahu.

Figure 5.23: Coral bracelet.

coasts of O‘ahu and Maui to be used for jewelry production (*Figure 5.23*).

It is often thought that the olivine (peridot) sold in stores around the islands is sourced from the local rocks, but collecting and selling olivine is considered disrespectful in traditional Hawaiian custom. It is therefore illegal to extract it from most sites, and the olivine sold in Hawai‘i is actually sourced from locations outside the islands.

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Chapter 6:
Glaciers in the Western US

The vast majority (nearly 97%) of the **glaciers** in the United States are found in the Western States. Although the bulk of these are found in Alaska, small glaciers are found as far south as California and Nevada. These glaciers have a profound impact on the West's scenery, geology, and water resources. Furthermore, ongoing research into how they 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.

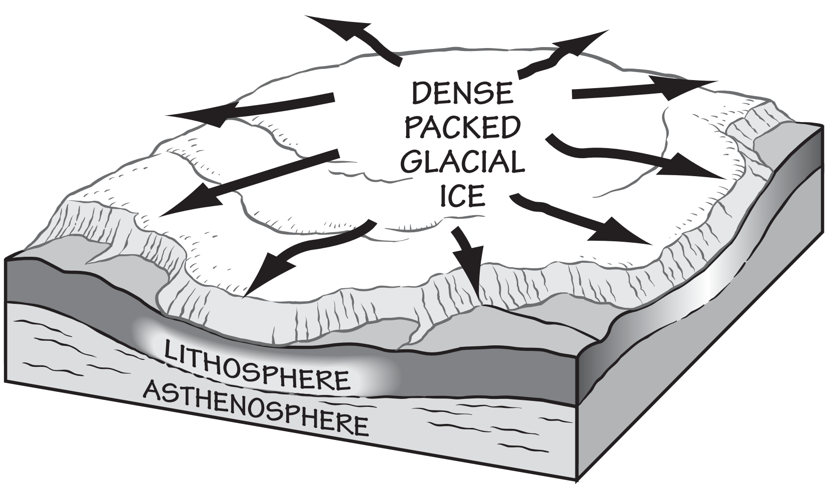

Figure 6.1: As dense glacial ice piles up, a glacier is formed. The ice begins to move under its own weight and pressure.

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.*

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

calving • *when ice breaks off from the end of a glacier.*

CHAPTER AUTHOR

Frank D. Granshaw

6 Glaciers

Review

Most broadly, there are two types of glaciers: smaller alpine glaciers and larger continental glaciers (*Figure 6.3*). 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.

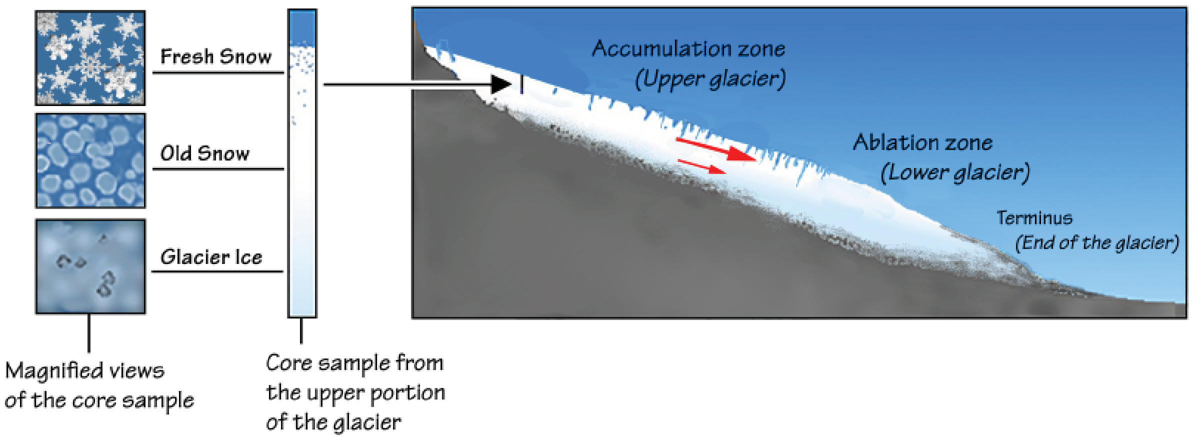

Figure 6.2: Cross section of an alpine (valley) glacier showing snow being converted into glacial ice and the two major zones of a glacier's surface. The red arrows show the direction and relative speed of different parts of the glacier. The longer the arrow, the faster the ice is moving.

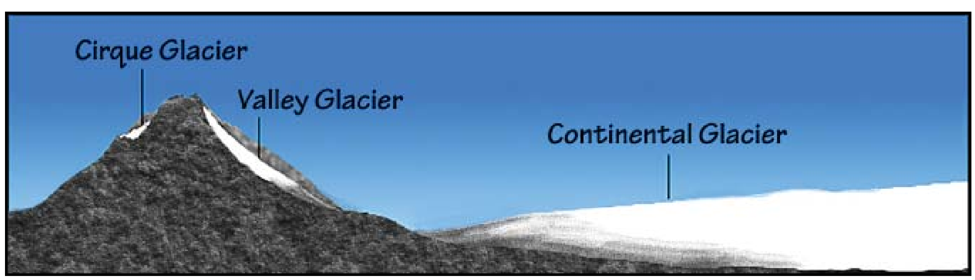

Figure 6.3: The cirque and valley glaciers shown here are types of alpine glaciers. Both alpine and continental glaciers flow downhill. Although this is obvious with an alpine glacier, it is not as much so with a continental glacier. In the case of the latter, the glacier flows from its thicker middle to its lower edges.

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**, such as the Juneau Ice Field in Alaska). 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**,** such as the Malaspina Glacier of Alaska.

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.*

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

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

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

Glacial Landscapes

The interaction of the glaciers with the landscape is a complex process. Glaciers alter landscapes by **eroding**, transporting, and depositing rock and sediment. They 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 6.4*).

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

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

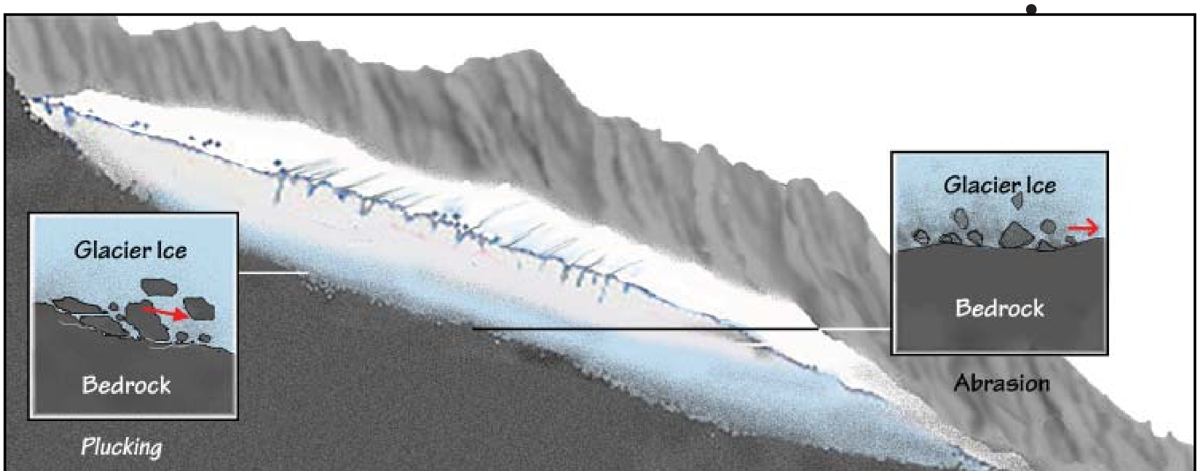

Figure 6.4: Rock and sediment derived by plucking and abrasion. These loose materials are subsequently transported to a glacier's ablation zone where they are deposited by melting ice.

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

The nature of the glacier causing the erosion is also crucial. Because continental glaciers spread from a central accumulation zone, they can't go around peaks in their path, so they instead slowly crush and scrape them away. For the most part, this results in flatter landscapes. Conversely, alpine glaciers tend to follow the existing topography, flowing downhill. This frequently causes them to scour existing low places, making them lower still. While this gouging increases the overall **relief** of an area, anything directly in the path of the ice is flattened.

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

Glaciers

Landscapes

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.*

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

fjord • *a deep, narrow, glacially scoured valley that is flooded by ocean water.*

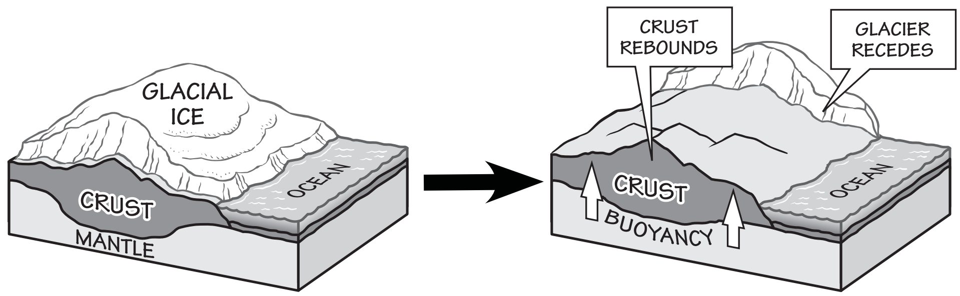

Figure 6.5: Isostatic rebound resulting from glacial retreat.

in a process known as **isostasy** (*Figure 6.5*)**.** Dramatic results include marine **reefs** lifted high above sea level and marine sediments found as coastal bluffs.

Glacial erosion can produce rugged mountainous areas with knife-edge ridges (**arêtes**), pointed rocky peaks (**horns**), and bowl-shaped depressions (cirques). These landscapes are most visible in areas where glaciers have retreated (*Figure 6.6*).

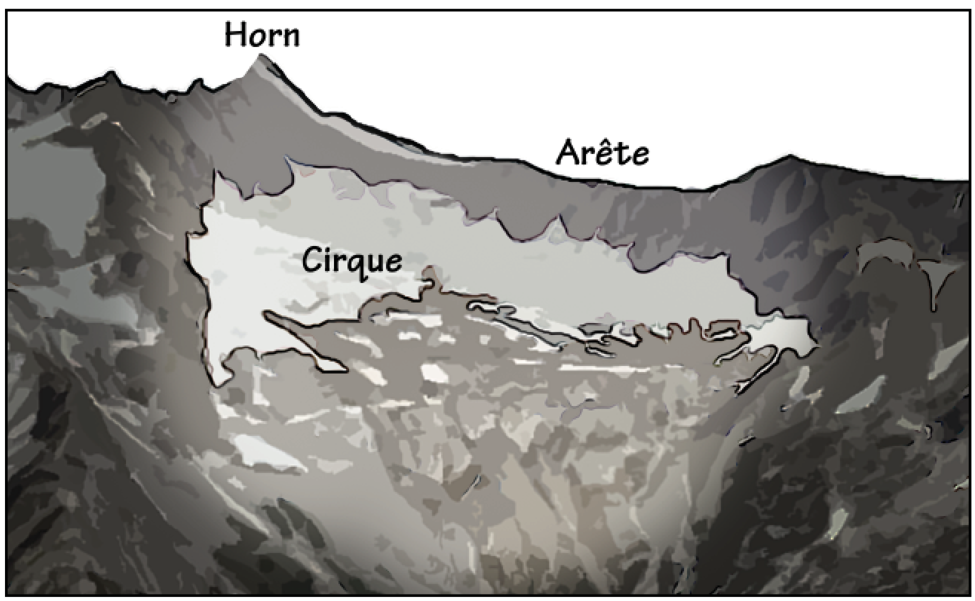

Figure 6.6: Glacial features in Cascade Pass—North Cascades National Park, Washington.

Valley glaciers carve long, U-shaped, steep-walled valleys (*Figure 6.7*). A river, in contrast, will erode a sharp notch, creating V-shaped valleys. As the glaciers retreat from these valleys, they leave behind thick layers of **till**, a chaotic mix of rock and sediment that covers the valley floor. If the valley is flooded with seawater as a glacier recedes it becomes a **fjord** (*Figure 6.8*).

Figure 6.7: A glacial valley on Steens Mountain, Oregon.

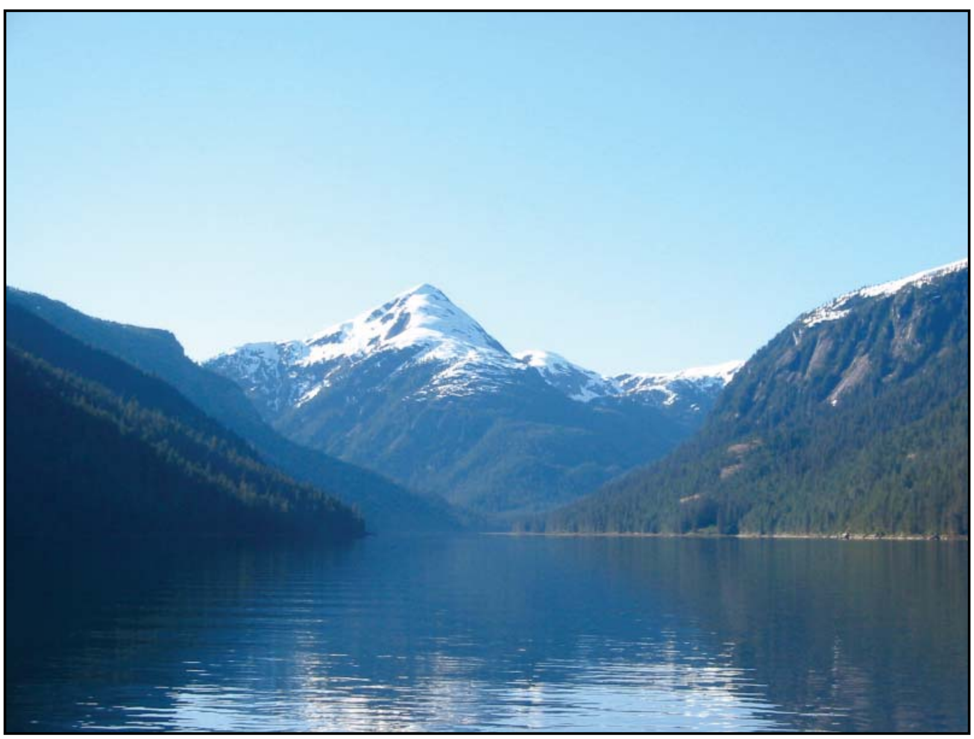

Figure 6.8: Misty Fjords National Monument in the Tongass National Forest, Alaska.

Climate

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

Drift-covered plains with lakes and low ridges and hills appear near the end, or 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-shaped hills called **drumlins** (*Figure 6.9*) are composed largely of till and reflect the final flow direction before the glacier receded. Small **kettle** lakes are formed by blocks of ice that calved from the glacier as it melted onto the outwash plain (*Figure 6.10*).

Figure 6.9: A drumlin field.

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

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

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).*

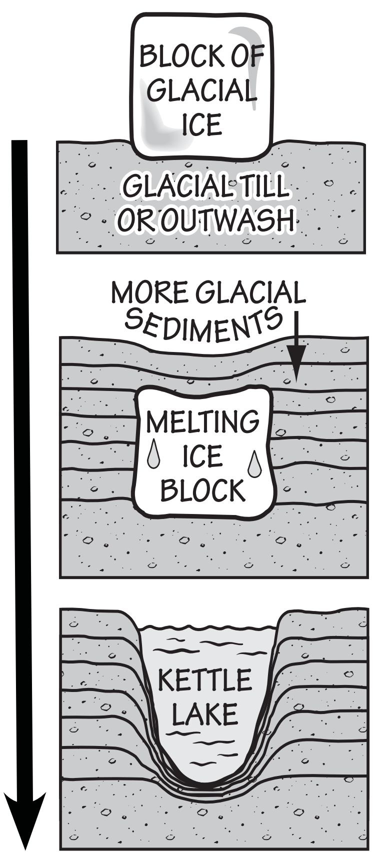

Figure 6.10: Steps in the formation of a kettle lake.

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." We are therefore living in an ice age right now! The current ice age began about 34 million years ago when ice sheets were first forming on Antarctica, followed by Greenland at least 18 million years ago, and finally on North

America, which defined the beginning of the **Quaternary** period (about 2.6 million years ago). When most people use the phrase "the ice age," however, they are referring to the **last glacial maximum** that saw much of North America and Europe covered in ice thousands of meters (yards) thick, while many kinds of large, woolly mammals roamed the unfrozen portions of those continents.

Age of the Quaternary

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

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

Ice on a Schedule

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

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

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

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.*

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

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

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

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

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

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

Astronomic Cycles and Ice Sheets

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

weathering; the 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

When glaciers advance over the land, the historical rock records are largely erased with each glacial advance. Therefore, to investigate the details of any associated climate change we must seek environments that record climate change but are preserved. Since the 1970s, the international Deep Sea Drilling Project has provided a treasure trove of data on coincident changes in the ocean, preserved in sediments at the ocean bottom (*Figure 6.11*). In the 1980s, coring of ice sheets in Greenland and Antarctica provided similarly high-resolution data on atmospheric composition and temperature back nearly one million years. The data from these programs have revealed that the Earth experienced dozens of warming and cooling cycles over the course of the Quaternary period.

Because of the large number of alpine glaciers in the Western States, this area is one of the world's "hotbeds" for glacier and climate research. Much of this work involves making regular inventories of existing glaciers and their

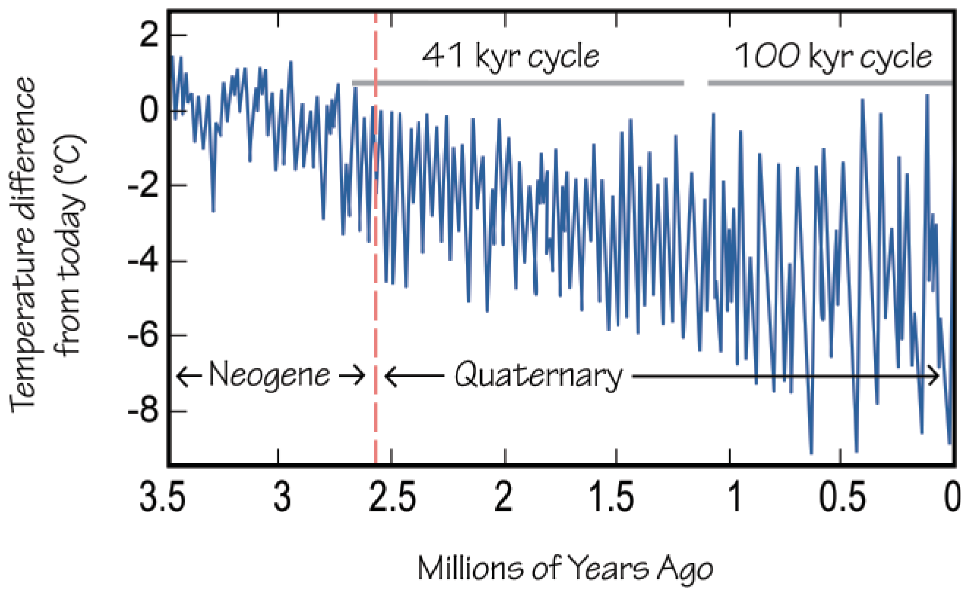

Figure 6.11: Ocean bottom temperatures from 3.6 million years ago to present, based on chemical analyses of foraminifera shells. Notice how the amplitude of glacial-interglacial variations increases through time, and how the lengths of the cycles change.

characteristics to determine how they are impacted by global, regional, and local climate changes. Equally important is determining the impact of the 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 Cascades or Sierra Nevada.

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.

A Brief History of Glaciers in the West

During the Pleistocene, continental glaciers covered much of Canada, Alaska, and the northern edge of the continental United States (*Figure 6.12*). Besides carving vast sections of the northern landscape and depositing huge quantities of sediment in low-lying areas, their impact was felt farther south as glacial outburst floods and winds laden with glacial **loess** reached deep into Washington and Oregon. Furthermore, in the colder climate of the Pleistocene, large ice caps mantled mountain ranges as far south as Central California, while large freshwater lakes flooded a number of present-day desert valleys in Nevada, California, and Oregon.

History

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

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

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

Glaciers

History

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

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

Figure 6.12: Extent of glaciation over North America at the Last Glacial Maximum.

As the last Pleistocene ice age came to a close, both the **Cordilleran Ice Sheet** and the alpine ice caps to the south retreated, leaving behind rugged mountain ranges, deep glacial valleys and bays, and plains covered with thick deposits of glacial sediment. Equally important was the impact of glacial retreat on coastlines. As global ice diminished, sea level rose, radically altering the location and character of the Western coasts.

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 Western States.

Alpine Glaciers in the Western States

During the late Pleistocene, alpine glaciers could be found in all seven regions of the Western States, including Hawai'i. 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.

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

Today, alpine glaciers are found largely in the mountains of Alaska and some of the higher ranges in Oregon, Washington, and California. Although the majority of the remaining glaciers tend to be small cirque glaciers or larger valley glaciers, a few large ice caps remain in southeastern Alaska. Modern glacier settings range from non-volcanic mountains like the Olympics and Sierra Nevada to active **volcanic** peaks found in the Cascade Range and the Aleutian Islands. As one moves farther south in the Western States, the glaciers tend to get smaller and higher. For instance, in southeastern Alaska, large outlet glaciers flow out of the massive Juneau Ice Field into the Pacific Ocean through a network of majestic fjords (*Figure 6.13*). In contrast, in the Sierra Nevada, a collection of small cirque glaciers perch precariously in mountains at well over 2700 meters (9000 feet) above sea level.

Figure 6.13: Mendenhall Glacier, flowing from the Juneau Ice Field.

One of the hallmarks of the alpine glaciers of the Western States is the rugged mountain terrain they carve. As these glaciers retreat, they not only expose characteristic U-shaped valleys, but they also reveal a diverse collection of peaks, bowls, ridges, and lakes scraped into bedrock. For instance, in the North Cascades of Washington and in the Wallowa Mountains of Oregon, glaciers

History

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

have carved a series of horns, arêtes, and cirques (*Figure 6.14*). Below these prominent features, we often find chains of lakes that form as meltwater ponds up behind lateral and terminal **moraines**. Likewise, in the Yosemite Valley of the Sierra Nevada, a network of small Pleistocene glaciers merged like streams flowing into a large river. As the glaciers retreated, they left behind a collection

Figure 6.14: The glacially sculpted features of the Wallowa Mountains in Oregon.

Figure 6.15: Upper Yosemite Falls in California plunges 440 meters (1420 feet) from a hanging valley into the Yosemite chasm.

of smaller U-shaped valleys (known as **hanging valleys**) that drop abruptly into a much larger valley. This is the principal reason that such spectacular waterfalls are found in the Yosemite Valley (*Figure 6.15*).

Glaciers also impact landscapes as they melt and deposit sediment, creating features such as Lake Wallowa in the Blue Mountains of northeastern Oregon. Lake Wallowa formed when a large glacier emptied into a broad basin and produced a high moraine that completely surrounded the lower part of the glacier. As the glacier retreated, the depression behind the moraine filled with meltwater, forming the present-day lake.

Among the most dramatic glacial deposits found in the Western States are those produced by glacial outburst floods. These floods occur when a pocket of meltwater that has developed underneath a glacier suddenly breaks through the restraining ice. As the torrent rushes downhill, it picks up rock, sediment, vegetation, and any other debris it can carry, forming a fast-moving slurry that is a significant hazard for many mountain communities. With a number of glaciers in the Cascades and Alaska situated on steep, debris-covered volcanoes, glacial outburst floods are all too common.

Glaciers and Deserts

The arid climate of the Basin and Range and Columbia Plateau may seem like an unlikely place to study glaciers, but even these regions did not escape the influence of the last ice age. The cooler climate of the late Pleistocene glaciation allowed ice caps to mantle entire mountain ranges, while meltwater ponded in basins between these ranges to form numerous, large, shallow, **pluvial lakes**, such as Lake Bonneville, which covered much of the Basin and Range.

As the climate warmed, the ice caps disappeared, leaving in their wake a multitude of cirques and U-shaped valleys. At the base of the mountains, moraines and deposits of till testify to the lower extent of the glaciers, while glacial drift deposits and dry waterfalls reflect the power of the meltwater streams issuing from them. The pluvial lakes are now gone, leaving behind **salt** flats and pockets of fine-grained lake sediment buried under the coarser desert sediment. In many of the West's deserts, wave-cut benches that resemble bathtub rings are visible around the upper perimeter of the basins.

Continental Glaciation in the Western States

Continental glaciers are now only a geologic memory in the Western States, yet the picture was much different during the Pleistocene. Nearly 20,000 years ago, the Cordilleran Ice Sheet covered nearly all of western Canada and parts of the United States. In Alaska, it covered only the southern half of the state, a result of **weather** patterns that drove snow-laden storms away from the state's northern section. In northern Washington, outlet glaciers and **ice lobes** reached down through the Okanogan Highlands and Puget Sound before spilling out onto the lowlands of the Columbia Plateau and southern portions of the Sound. In the vicinity of the North Cascade and Olympic ranges, the outlet glaciers merged with the ice caps that had formed over the range.

History

pluvial lake *• a landlocked basin that fills with rainwater or meltwater during times of glaciation.*

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

weather *• the measure of short-term conditions of the atmosphere such as temperature, wind speed, and humidity.*

ice lobe *• a broad, rounded section of a continental glacier that flows out near the glacier's terminus.*

6 Glaciers

History

One result of the Pleistocene glaciations were huge, U-shaped valleys in the Okanogan Highlands, North Cascades, and Olympics that were carved by outlet glaciers of the Cordilleran Ice Sheet. In Puget Sound, a large lobe, along with the meltwater draining it, sculpted a complex system of fjords while dumping masses of drift nearly 300 meters (1000 feet) thick. This flowing ice and water also sculpted hundreds of drumlins and bedrock hills into linear shapes that marked the flow direction of the ice. Farther to the east, in the Columbia Plateau, the deposits were sculpted into snake-like ridges called **eskers**. These are believed to be the result of streams flowing through tunnels at the bottom of the glacier that filled up with sediment. In the northern section of the plateau, house-sized boulders (**erratics**) left behind by the receding ice force farmers to creatively plow their fields. In other parts of the plateau, **silt** blown from the outwash plains (loess) was deposited well over a hundred miles south of the ice sheet terminus.

Another way the Cordilleran Ice Sheet shaped the Columbia Plateau was by numerous catastrophic floods emanating from the Pleistocene-age glacial Lake Missoula. These flows, sometimes called the Bretz Floods after the geologist who discovered them, would periodically race across the plateau, scouring bedrock and transporting massive amounts of sediment and rock to the Willamette Valley and beyond. The cause of the floods is commonly attributed to meltwater lakes dammed by glacial ice that drained as their ice dams abruptly failed. During the Pleistocene, similar floods occurred in east and south central Alaska and in the Sierra Nevada.

Glaciers and Coastlines

Glaciers have shaped the coastlines of the Western States in three ways. In Alaska, where they reach to the sea, outlet glaciers carve intricate systems of fjords, creating exceedingly rugged coastlines. Since many of these glaciers flow into the ocean, they lose mass by calving. In this way, they create countless **icebergs** that deposit a chaotic mix of rock and sediment on the seafloor as they melt. Though these sediments are not readily visible in Alaska, they are common along the coast of Washington.

Another way that glaciers have shaped the West Coast is through the rise and fall of sea level. Approximately 20,000 years ago, the coast of Oregon, Washington, and California was 65 to 130 kilometers (40 to 80 miles) farther west than it is now, since sea level was nearly 90 meters (300 feet) lower. At that time, the coast was most likely a broad plain that gradually rose to the base of the present-day coastal mountain ranges. As the ice sheet retreated, increased meltwater flowed back into the sea. As the sea rose, the shoreline advanced eastward towards the mountain ranges, eventually resulting in a shoreline characterized by rocky headlands, small beaches, and large **estuaries**. As present-day glaciers diminish in size and sea level continues to rise due to changes in global climate, several factors complicate our predictions of how the coastlines of the Western States will change. Chief among these is the slow rise of the crust at the western edge of North America due to **plate tectonics** and **subduction**. Another significant influence is the continuing slow rebound of the northern half of North America, brought about by the disappearance of

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

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.*

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

iceberg • *a large chunk of ice, generally ranging in height from 1 to 75 meters (3 to 246 feet) above sea level, that has broken off of an ice sheet or glacier and floats freely in open water.*

estuary • *a place where freshwater and saltwater mix, created when sea level rises to flood a river valley.*

plate tectonics • *the way 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.*

the great Pleistocene ice sheets. The degree to which these factors will offset rising sea levels is both a practical and theoretical concern, given the vast number of people living on or near the coastline of the Western States.

Glaciers in Hawai‘i

Since Hawai‘i is a tropical **volcanic island**, most people do not think about glaciers or snow ever having existed there. However, glacial deposits—moraines and till—beginning from approximately 70,000 years ago are preserved on the flanks of Mauna Kea volcano. Similar deposits may have once existed on Mauna Loa as well, but they have since been covered by **lava** flows. Due to the immense height of these volcanoes, snowfall still accumulates on both Mauna Kea and Mauna Loa in winter (*Figure 6.16*).

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

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

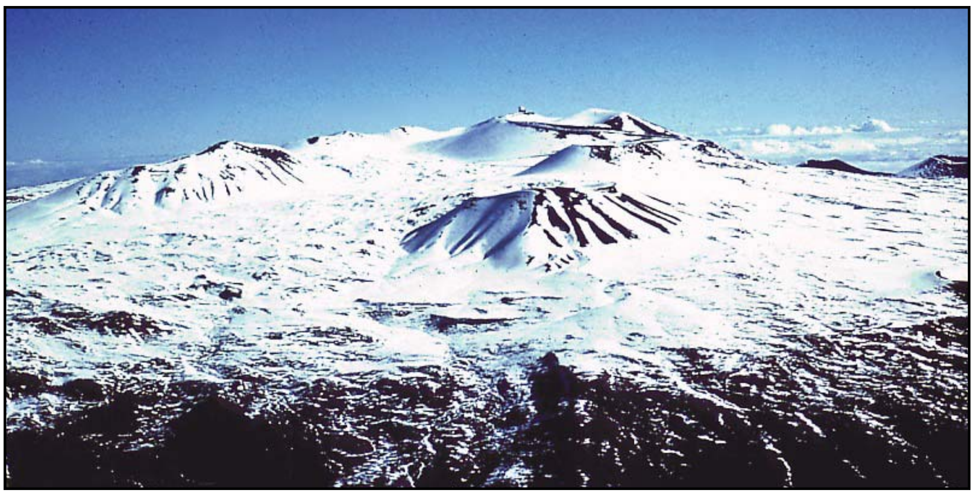

Figure 6.16: Snowfall on the peaks of Mauna Kea in winter.

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Resources

Activities

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Glacier Power, Earth Observing and System Data and Information System (EOSDIS), NASA, https://earthdata.nasa.gov/featured-stories/featured-research/glacier-power. (Middle school glacier education resources.)

Impact of Change in Glacier Ice, Alaska Seas and Rivers Curriculum, Alaska Sea Grant, https://seagrant.uaf.edu/marine-ed/curriculum/grade-8/investigation-2.html. (Grade 8 lesson plan on glacier retreat.)

Learning about Glaciers, Glacier Research Group, Glacier Research Group, Portland State University Geology Department, http://glaciers.us/Learning-About-Glaciers. (High school and college level educational resources.)

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Chapter 7:
Energy in the Western 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 only slightly longer. Our energy **system** (how we get energy and what we use it for) has changed and is changing remarkably quickly, though some aspects of the energy system are also remarkably resistant to change.

***Exceptions include the use of sails on boats by a very small percentage of the world's population to move people and goods, and the Chinese use of natural gas to boil brine in the production of salt beginning roughly 2000 years ago.**

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

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

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

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

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

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

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

CHAPTER AUTHORS

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7 Energy

Review

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

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

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

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

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

What do different units of energy mean?

Heat is energy, and heat is at the root of all the ways that we move materials or generate light, so measurements of heat can be thought of as the most basic way to measure energy. The **British Thermal Unit** (abbreviated Btu or BTU) is the most commonly used unit for heat energy and is approximately the amount of heat required to raise one pound of water by one degree Fahrenheit. A Btu is also about the amount of energy released by burning a single wooden match. One Btu is also equal to 1055 joules. A **joule** is the energy expended (or work done) to apply a force of one newton over a distance of one meter. A typical apple weighs about a newton, so lifting an apple one meter takes about a joule of energy. That means that one Btu—the energy contained in a wooden match—would be all the energy required to lift an apple 1000 meters, or a 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. A kilowatt-hour (kWh) is the amount of energy required to light ten 100-**watt** light bulbs for one hour. *Figure 7.1* compares different ways to make and use one kWh.

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

Energy

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Review

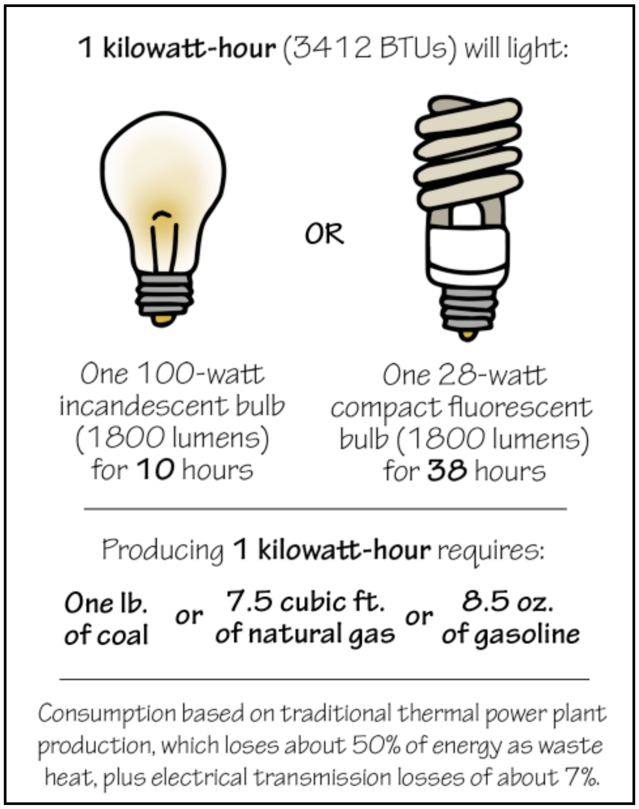


Figure 7.1: Examples of uses and sources of 1 kilowatt-hour.

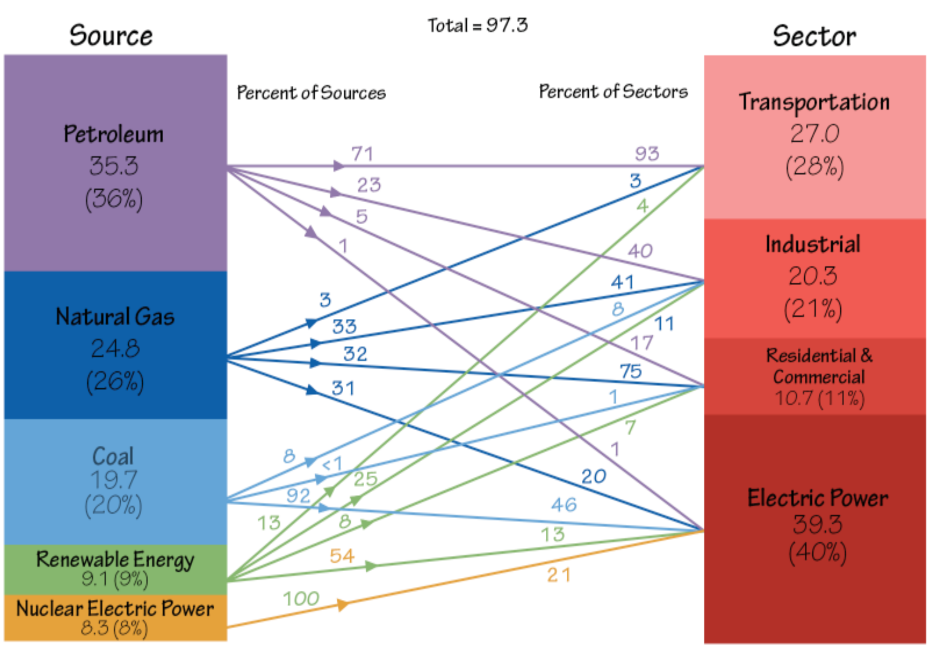


Figure 7.2. US energy production sources and use sectors for 2011. Petroleum provides more energy than any other source, and most of it is used for transportation. More energy is used to generate electricity than for any other use, and electricity is generated by all five energy sources. Nuclear is unique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

7 Energy

Review

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

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

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

nuclear • *a reaction, as in fission, fusion, or radioactive decay, that alters the energy, composition, or structure of an atomic nucleus.*

How do we look at energy in the Earth system?

The concepts used to understand energy in the Earth system are fundamental to all disciplines of science; energy is an interdisciplinary topic. One cannot study physics or understand biomes, photosynthesis, fire, evolution, seismology, **chemical reactions**, or genetics without considering energy. In the US, every successive generation has enjoyed the luxury of more advanced technology (e.g., the ability to travel more frequently, more quickly, and over greater distances), and we require more and more energy to maintain these new lifestyles and to power new technologies.

Figure 7.2 shows the sources and uses of energy in the US, by sector. The Energy Information Administration (EIA) categorizes energy as coming from one of five sources (**petroleum**, natural gas, coal, **renewable energy,** and **nuclear** electric power) and being used in one of four energy sectors (transportation, industrial, residential & commercial, and electric power). All of the energy that powers our society comes from one of these five sources and is used in one of these four sectors.

The more we come to understand the Earth system, the more we realize that there is a finite amount of consumable energy, and that harvesting certain resources for use in energy consumption may have wide ranging and permanent effects on the planet's life. Understanding energy within the Earth system is the first step to making informed decisions about energy transitions.

Becoming "Energy Literate"

Energy is neither lost nor gained within the universe, but rather is constantly flowing through the Earth system. In order to fully understand energy in our daily lives—and make informed decisions—we need to understand energy in the context of that system. Becoming energy literate gives us the tools to apply this understanding to solving problems and answering questions. The Seven Principles of Energy, as detailed in "*Energy Literacy: Energy Principles and Fundamental Concepts for Energy Education"* are:

***Energy Literacy: Energy Principles and Fundamental Concepts for Energy Education* is a publication of the US Department of Energy. It can be accessed for free online; see Resources for more information.**

1	**Energy is a physical quantity that follows precise natural laws.**
2	**Physical processes on Earth are the result of energy flow through the Earth system.**
3	**Biological processes depend on energy flow through the Earth system.**

4	**Various sources of energy can be used to power human activities, and often this energy must be transferred from source to destination.**
5	**Energy decisions are influenced by economic, political, environmental, and social factors.**
6	**The amount of energy used by human society depends on many factors.**
7	**The quality of life of individuals and societies is affected by energy choices.**

Each principle is defined by a set of fundamental concepts that can help clarify ties to curriculum. Keeping these energy principles in mind when we teach others about energy can help us contextualize and make relevant our own energy consumption and its effect on the Earth system.

Energy in the Western Regions

The primary energy resources in the contiguous Western states come from renewable sources, such as solar, wind, and hydroelectric power. California is the exception to this rule, with 54% of its energy production stemming from fossil fuels, and 15% from nuclear power.

Alaska's energy production relies solely on fossil fuels, and Hawai'i's solely on renewables.

Fossil Fuels

Fossil fuels—oil, natural gas, and coal—are made of the preserved organic remains of ancient organisms. Petroleum typically forms from the remains of aquatic life, primarily one-celled photosynthetic organisms, which can accumulate in sediments. Coal forms primarily from the accumulation of land plants. In either case, organic matter is only preserved when the rate of accumulation is higher than the rate the rate of decay. This happens most often when the oxygen supply is sufficiently low enough 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.

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

Fossil Fuels (continued)

The history of surface environments, evolution of life, and geologic processes beneath the surface have all influenced where fossil fuel deposits formed and accumulated. The largest oil and gas reserves were at one time nutrient-rich seas with abundant surface phytoplankton and organic-rich bottom sediments; the largest coal beds were swampy environments where fallen forest trees and leaves were buried in stagnant muds.

Energy in the Basin and Range
Region 1

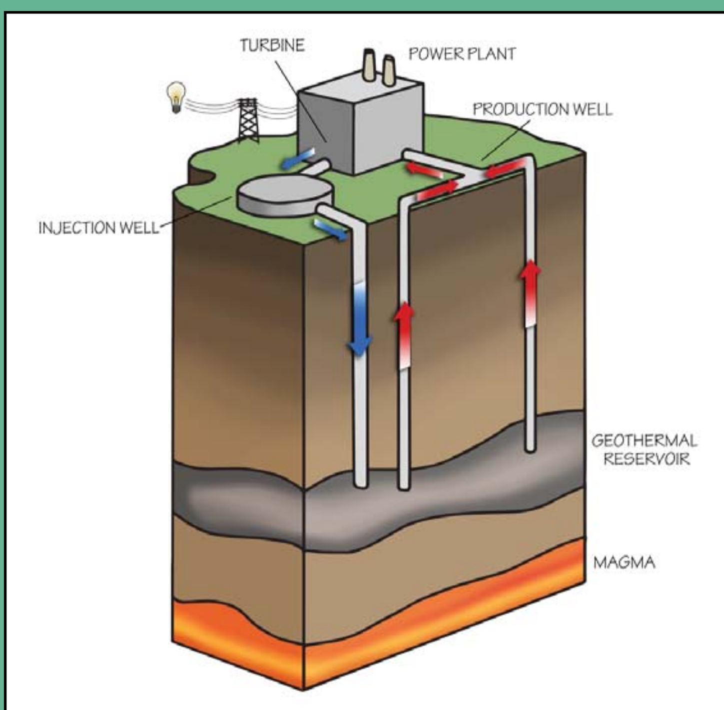
The Basin and Range region is named for its erratic and abrupt changes in elevation and **topography**. Not surprisingly, deserts, mountain ranges, lakes, and valleys can be found within this region. A famous geologist from the 1880s, Clarence Dutton, once said the parallel valleys and mountains looked like an "army of caterpillars crawling northward." With some of the lowest and highest points in the contiguous US, the region is prime for wind, hydroelectric, and solar energy production. Although natural gas provides much of the region's power, most of this resource is imported from elsewhere.

Unfortunately, because this area is home to some of the most unusual and inhospitable ecosystems in the world (the Mojave Desert and Death Valley, among others) and its large cities are located hundreds of miles apart, the human population has been spread out over long distances of deserts and mountain ranges, making the delivery of petroleum and natural gas products difficult. Further complicating these difficulties is the fact that the presence of pipelines in the region remains highly controversial. However, this region is rich in tectonic activity, and several research projects are underway by the USGS to study the possibility of significantly increasing the harvest of geothermal energy. The Sedimentary Geothermal Research Project, headed by a team from the USGS and the Utah Geological Survey, has tested several sites and found temperatures of 93°C (200°F) a mere 3.2 kilometers (2 miles) below the surface. Therefore, the area has the potential to become a major energy provider for the eastern and central parts of this region in the next decade.

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 butane becomes steam, which is used to power the turbine.

Region 2

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

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

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

fuel • *a material substance that possesses internal energy that can be transferred to the surroundings for specific uses.*

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

Energy in the Columbia Plateau
Region 2

Nestled between the Cascade and Rocky Mountain ranges, the Columbia Plateau was an **inland sea** for tens of millions of years, until about 15 million years ago when **volcanic** activity deposited layer upon layer of **lava**. Because of its topography, this region is tops in the nation for hydroelectric power generation. The Columbia Plateau is more than 80% powered by renewable energy, with wind energy production second only to hydroelectric.

The Grand Coulee Dam is the largest hydroelectric plant in the US (*Figure 7.3*). The Grand Coulee was built from 1933 to 1942 and was originally designed to irrigate the Northwest. However, the advent of WWII significantly raised the need for energy in the region when the Northwest became a manufacturing hub for the war. A third power station was added to the complex in 1974, making it the largest, most productive hydroelectric plant in the nation.

Hydroelectricity uses the gravitational force of falling or rushing water to rotate turbines that convert the water's force into energy.

Figure 7.3: The Grand Coulee Dam.

Regions 3–5

Energy in the Northern Rocky Mountains
Region 3

The tall mountains of the Rockies provide ample resources for harvesting hydroelectric power, and much of the energy produced here is from hydroelectric plants. The forests also provide some biomass and **fuel** for wood-burning power plants, and wind makes up a portion of the power generated in this area.

Energy in the Cascade-Sierra Mountains
Region 4

Just like the Rockies, these two tall mountain ranges provide perfect opportunities for hydroelectric power. There are hundreds of hydroelectric power plants throughout the region, which provide the area with a majority of this renewable energy. Although there are also thousands of acres of forests, some of the region is protected by the National Forest Service, including Sequoia National Forest, home to some of the largest and oldest **trees** in the world. One of the most famous environmental conservationists, John Muir, helped promote the preservation of the area, which resulted in the founding of Yosemite National Park. Much of this region is managed wood forest, and although hydroelectric energy is by far the major source of energy, several wood-burning power generation plants can also be found here. Wind, biomass, and several solar power plants round out the energy production profile for the region.

Energy in the Pacific Border
Region 5

Including both the Coastal Range and the San Joaquin Valley, the Pacific Border's topographic variation allows for a variety of energy production methods. The Coastal Range provides ample hydroelectric and wind energy capability, and the flat desert lands of the San Joaquin Valley makes the generation of solar power profitable. The vast acreage of forests also provides material for biomass and wood burning power plants.

Coastal California has long been a resource for the extraction, export, import, and refining of oil and gas, with the ports of Long Beach, Los Angeles, and San Francisco being the main hubs. Ranking third in the nation for crude oil production, refineries and terminal storage facilities dot the area. And with the "car culture" and lack of public transportation in most of California, the demand for and flow of oil has continued unabated over the last century.

7 Energy

Region 5

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

***Monterey Formation** • a distinctive light-colored sedimentary rock unit that formed in the Miocene seas.*

***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.*

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

California's vast oil production is the result of several large sedimentary basins, complex geology creating significant traps, and more recently, the development of large offshore oil fields (*Figure 7.4*). California's first productive well was drilled in the Central Valley in 1865. This area, east of San Francisco, became the scene of heavy drilling activity through the rest of the 1800s, providing enough oil for the nearby market of San Francisco. The Los Angeles Basin, first drilled in 1892, ultimately turned out to contain the most productive fields in the state. By the early 1920s, California was the source of one-quarter of the world's entire output of oil, due in large part to the high productivity of the Long Beach Field.

Figure 7.4: Oil and gas production in the Western US.

The source for most of California's oil is **sandstone** from coastal marine deposits, particularly the **Monterey Formation** (formed during the **Miocene** epoch, but which also includes other units into the **Pliocene**). This oil has generally been tapped through conventional drilling in places where the oil migrated to and became trapped in other formations. The Monterey Formation is porous, and is estimated to retain a large but uncertain amount of oil that could be reached through unconventional drilling, such as horizontal drilling and hydraulic fracturing. Although there is economic interest in such drilling, there is also concern about associated environmental impacts.

Nuclear power also plays a part in the region's energy production, but when the San Onofre Nuclear Power Plant in Southern California was decommissioned in 2012, the state's nuclear energy production was cut in half, from about 4000 MW to about 2000 MW. Because of the loss of this power source, California has had to rely more heavily on natural gas-powered energy plants, and the California Air Resources Board estimates that through the loss of the "clean" nuclear energy and an increase in the use of natural gas, air pollution in the area has increased by about 25%. The Diablo Nuclear Facility in San Luis Obispo, California and the Columbia Generating Station in Richland, Washington are the only two operating nuclear energy plants on the West Coast.

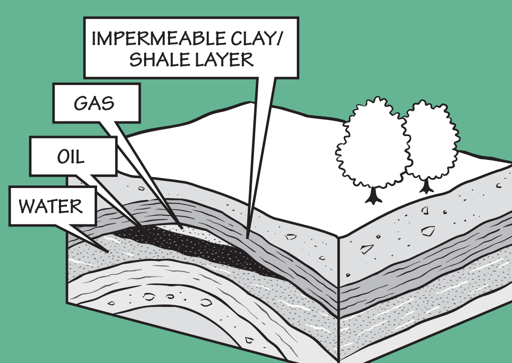
Despite the Pacific Border's reliance on fossil fuels, California, Oregon, and Washington are nevertheless leading the way by providing incentives and programs to significantly decrease energy consumption and increase

Oil and Gas

Oil and gas form from organic matter in the pores of *sedimentary rocks*. Shale in particular is often organic-rich, because organic matter settles and accumulates in the same places that fine *clay* and *silt* particles settle out of the water. Further, such quiet waters are often relatively stagnant and low in oxygen, thus organic matter decay is slow. Because oil and gas are under pressure, they will move to areas of lower pressure, gradually upward, through tiny connections between pore spaces and natural fractures in the rocks.

Often, natural gas and oil are trapped below the surface under *impermeable* layers that do not have sufficient spaces for liquids and gases to travel through. Folds or "arches" in impermeable layers, or *faults* in rock layers, are common ways of trapping oil and gas below the surface. Most oil and gas has been extracted using the "conventional" technique of seeking such reservoirs and drilling into them, allowing the gas or oil to come to the surface through a vertical well.

Some impermeable layers contain oil and gas that has never escaped. In the 2000s, the fossil fuel industry began to access these resources through a method, known as high-volume slickwater hydraulic fracturing, that creates thousands of small fractures along impermeable rock layers. The method has greatly increased oil and gas production, but has also been a very controversial topic involving the issues of environmental impact and carbon emissions.



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

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

permeability • *a capacity for fluids and gas to move through fractures within a rock, or the spaces between its grains.*

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.*

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

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

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

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

renewable energy production and use. Although Washington and Oregon lead the nation in hydroelectric power generation, both states have initiated significant financial incentives for increasing photovoltaic, biomass, and wind energy production. California currently ranks 48th in the nation in terms of per capita consumption of energy, and its incentive programs and resources for geothermal and other renewable sources of energy have ranked first in the nation in these categories. California is also first in large-scale wind energy production in the US. In fact, the Altamont Pass Wind Farm, with 4930 wind turbines that produce 1.1 terawatt-hours (TWh) yearly, is the largest array of wind turbines with the greatest production capacity in the world. In addition, The Geysers geothermal field in California is currently the world's largest complex of geothermal power plants, containing 22 plants that generate an average of 955 MW (*Figure 7.5*).

Figure 7.5: The Sonoma Calpine 3 power plant, one of 22 power plants at The Geysers field in the Mayacamas Mountains of Sonoma County, northern California.

Energy in Alaska
Region 6

Alaska has the lowest population density of any state in the Union, with only a little over one person per square mile. Many people live in rural areas, and with about 20% of the state covered by **glaciers** and water, getting energy to the population is challenging. Running electrical lines throughout the state's 1.72 million square kilometers (663,000 square miles) is not feasible when considering the number of people the lines would serve. Therefore, most people in rural areas use heating oil and/or wood for heat and energy.

In the late 1960s, oil was discovered in Prudhoe Bay on Alaska's North Slope, and it has proved to be the largest recoverable oil field in the US. The source of this oil is rocks ranging from **Mississippian** to **Paleogene** in age, but particularly organic-rich marine coastal deposits from **Mesozoic** marine coastal

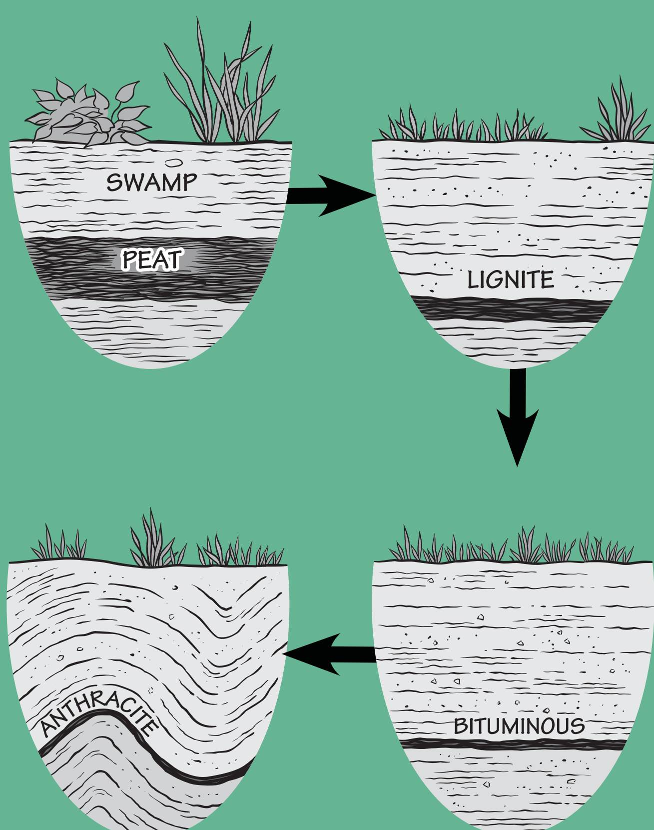
Energy 7

Region 6

Coal

As leaves and wood are buried more and more deeply, pressure on them builds from overlying sediments, squeezing and compressing them into coal. The coal becomes gradually more enriched in carbon as water and other components are squeezed out: *peat* becomes *lignite*, *bituminous* and eventually *anthracite* coal, which contains up to 95% carbon. Anthracite has the fewest pollutants of the four types of coal, because it has the highest amount of pure carbon. By the time a peat bed has been turned into a layer of anthracite, the layer is one-tenth its original thickness.

The *Carboniferous* period takes its name from the carbon in coal. A remarkable amount of today's coal formed from the plants of the Carboniferous, which included thick forests of trees with woody vascular tissues.



peat • *an accumulation of partially decayed plant matter.*

lignite • *a soft, brownish-black coal in which the alteration of plant matter has proceeded farther than in peat but not as far as in bituminous coal.*

bituminous coal • *a relatively soft coal containing a tarlike substance called bitumen, which is usually formed as a result of high pressure on lignite.*

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.*

deposits. Significant amounts of oil and gas were trapped under the Barrow Arch, a regional belt of **metamorphic** and **igneous rock** that formed a cap for the oil reservoir. After significant negotiations with the native populations of Alaska, the Trans-Atlantic Pipeline was finished in 1977, running from the Prudhoe Bay some 800 miles south to Valdez, Alaska, at the Prince William Sound. This produced a boom in oil extraction in the state. Production from the Prudhoe Bay oilfields has dwindled over the years, however, and the largest energy source consumed in Alaska is now natural gas.

Alaska has significant coal reserves in just one active mine, near Healy. The coal was deposited in terrestrial environments during a much warmer and wetter Miocene **climate** than is found there today.

Alaska Energy Authority's (AEA) Alternative Energy and Energy Efficiency (AEEE) program manages and funds projects and initiatives totaling $188 million in state and federal funding. Many of these projects seek to lower the cost of power and heat to Alaskan communities while maintaining system safety and reliability.

__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.

__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).

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

Energy in Hawai'i
Region 7

Having no fossil fuel resources of its own, Hawai'i has been highly reliant on the importation of fossil fuels for its energy needs. However, with its mild tropical climate, Hawai'i had the second lowest per capita energy use in the US in 2010. The majority of Hawai'i's energy demand in 2010 was for transportation, due in large part to heavy commercial and military aviation fuel use. That year, Hawai'i imported 94% of its energy and had the highest electricity prices in the nation.

The Hawaiian government, however, is working on changing that reliance through the use of other energy initiatives. Hawai'i has just one geothermal power plant, which is located on Hawai'i Island and taps into the heat from Kīlauea volcano. The Puna Geothermal Venture plant generates around 265 gigawatt hours (GWh) of energy a year, which is around 23% of the electricity required on the island. Additional areas around the **rift** zones of volcanoes on Maui are currently under study for similar such power plants. There is potential to generate the entire state's power needs, but it would require considerable infrastructure involving the laying of cables between islands to connect the power grids. Even with these considerable outlays, however, the cost of production is still lower than that of fossil fuels.

Hawai'i has the potential to generate all its electricity needs using wind-generated power. A study in 2010 by the National Renewable Energy Laboratory (NREL) showed that onshore wind generation could produce 12 billion kWh a year—considerably more than the 10 billion KWh that was used in Hawai'i in 2011. Offshore wind generation potential is even higher. There are currently six

Region 7

operating "wind farms" in Hawai'i, which include arrays on Oahu, Maui (*Figure 7.6*) and Hawai'i. The largest is Kawailoa Wind Farm on the northern shore of Oahu, which has 30 windmills that generate a total of 69 MW per year.

Figure 7.6: Kaheawa Wind Farm, Maui.

biofuel *• carbon-based fuel produced from renewable sources of biomass like plants and garbage.*

Hawai'i has the world's largest commercial electricity generator that is fueled exclusively by **biofuels**. Since existing power plants use expensive, imported liquid fossil fuels, converting to biodiesel was cost-efficient by comparison. The biodiesel is produced using waste agricultural materials and waste oils from restaurants.

Solar photovoltaic (PV) capacity increased 150% in Hawai'i in 2011, moving the state up to 11th in terms of PV capacity. Still, solar power provides only a few percentage points of overall electricity production in Hawai'i, but new projects are being planned on almost all the major islands.

The first hydroelectricity was generated near Hilo on Hawai'i Island in the 1880s, but today there are only a few small hydropower plants used in the state (mainly to power sugar mills and other small industry), with the largest on Hawai'i Island on the Wailuku River in Hilo.

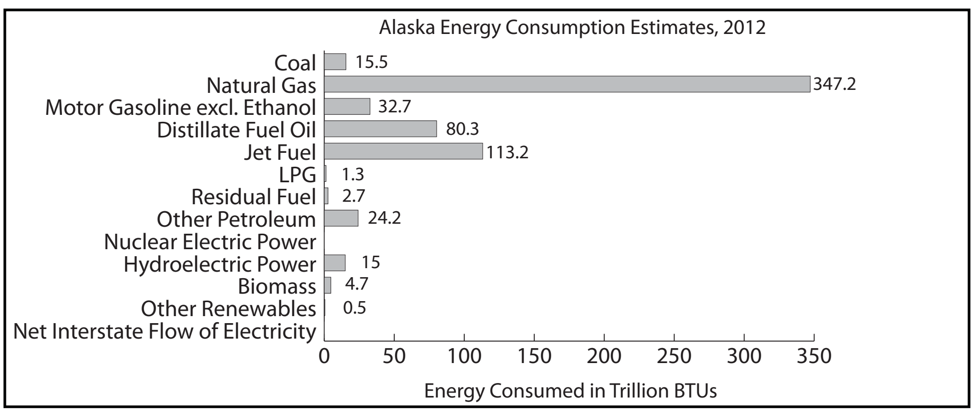
State Facts

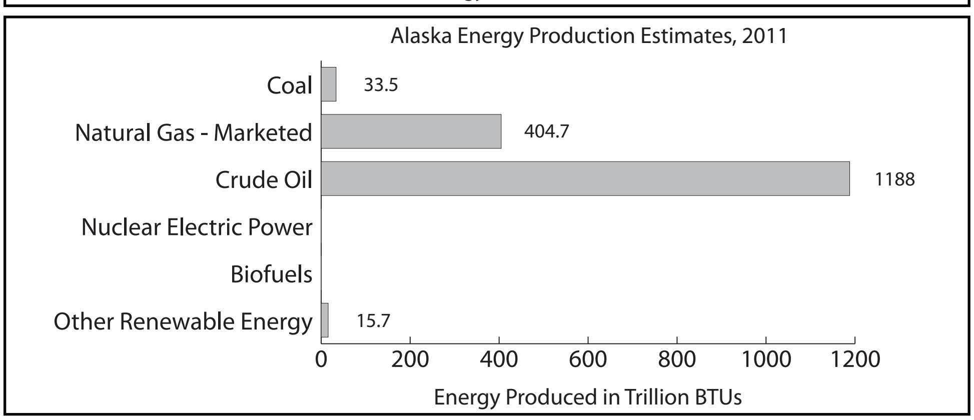
Energy Facts by State

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 Western US (from http://www.eia.gov/state/).

Alaska

- Alaska's electricity infrastructure differs from that of the lower 48 states in that most consumers are not linked to large interconnected grids through transmission and distribution lines; rural communities in Alaska rely primarily on diesel electric generators for power.
- Alaska is one of eight states generating electricity from geothermal energy sources.
- The Kenai liquefied natural gas (LNG) export facility is the only existing LNG export terminal in the United States.
- When Federal offshore areas are excluded, Alaska's crude oil production of 0.6 million barrels per day ranked second in the nation, after Texas, in 2011.
- In 2011, Alaska ranked fourth in the United States for the total amount of electricity generated from petroleum liquids.





State Facts

California

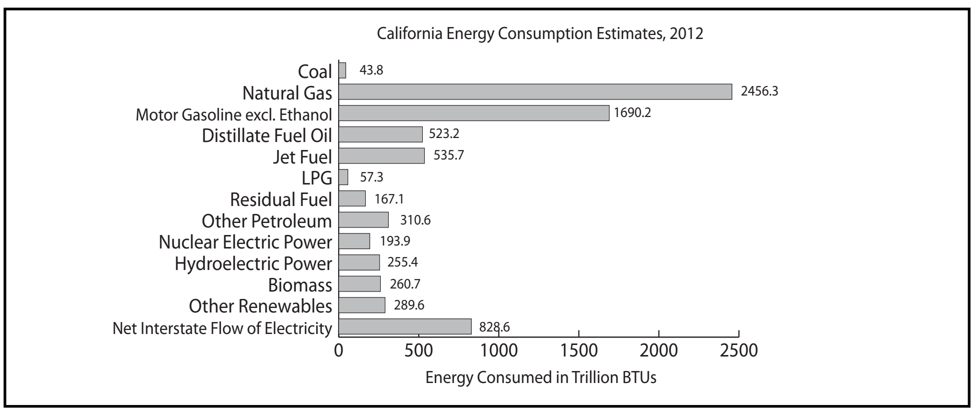
- Average site electricity consumption in California homes is among the lowest in the nation (6.9 MWh per year), according to EIA's Residential Energy Consumption Survey.

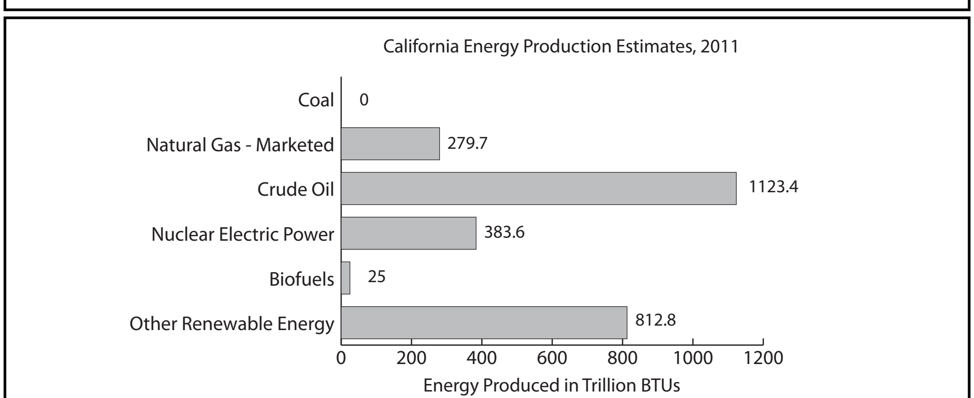
- In 2010, California's per capita energy consumption ranked lowest in the nation; the state's low ranking was due in part to its mild climate and energy efficiency programs.

- Excluding federal offshore areas, California ranked third in the nation in crude oil production in 2011, despite an overall decline in production rates since the mid-1980s.

- California also ranked third in the nation in 2011 in refining capacity, with a combined capacity of almost two million barrels per day from its 20 operable refineries.

- In 2011, California ranked first in the nation as a producer of electricity from geothermal energy, third in conventional hydroelectric generation, and first for net electricity generation from other renewable energy resources.





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Energy

State Facts

Hawaiʻi

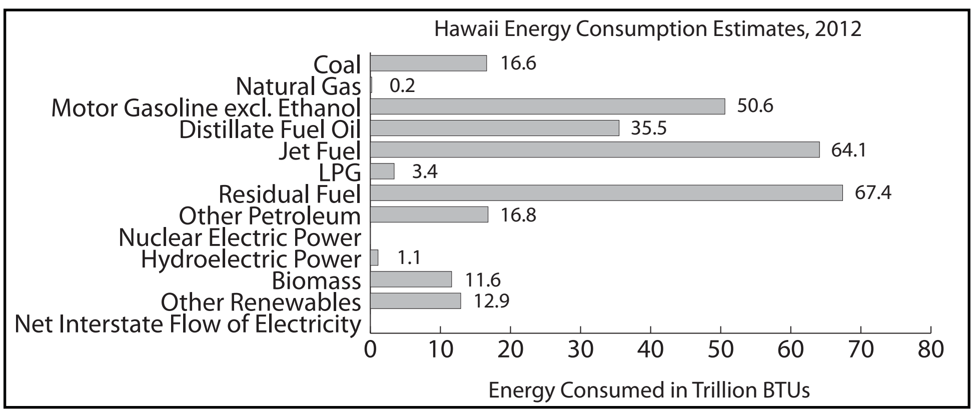
- Hawaiʻi has the world's largest commercial electricity generator fueled exclusively with biofuels; the state's energy plan aims for an agricultural biofuels industry that, by 2025, can provide 350 million gallons of biofuels.

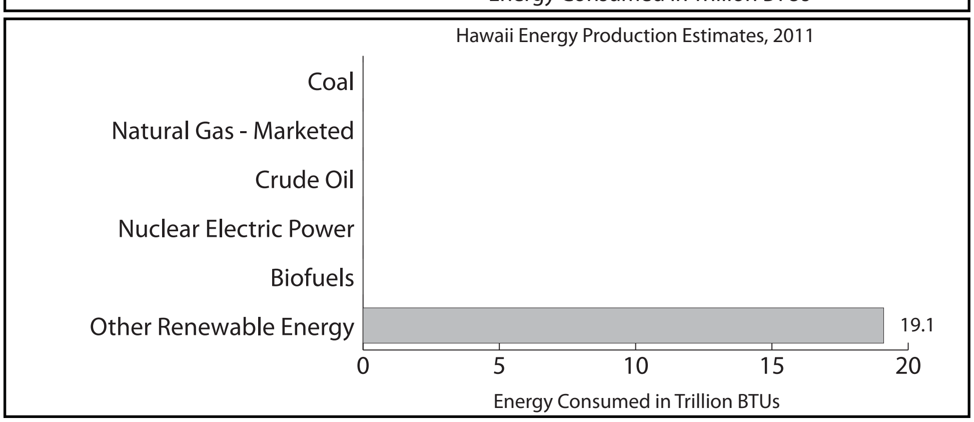
- Thanks to its mild tropical climate, Hawaiʻi had the second lowest per capita energy use in the nation in 2010. The transportation sector led Hawaiian energy demand in 2010, due in large part to heavy commercial and military aviation fuel use.

- In 2010, Hawaiʻi imported 94% of its energy and had the highest electricity prices in the nation.

- Hawaiʻi is one of eight states with installed geothermal capacity; in 2011, 25% of its renewable net electricity generation came from geothermal energy.

- Solar photovoltaic (PV) capacity increased 150% in Hawaiʻi in 2011, making it 11th in the nation in PV capacity.





Energy

7

State Facts

Nevada

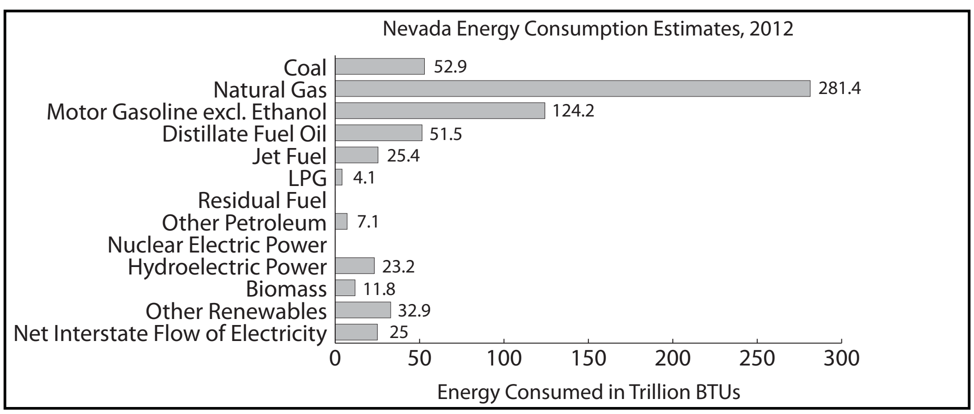
- More than 90% of the energy Nevada consumes comes from outside the state.

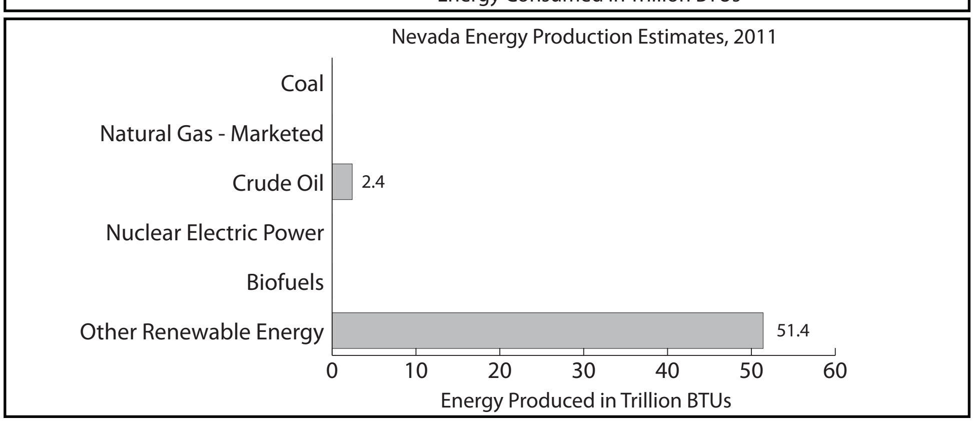
- The state's Energy Portfolio Standard requires that 25% of electricity come from renewable energy resources by 2025; in 2011, 16% of net electricity generation came from geothermal, solar, and hydroelectric power sources.

- Nevada generated two-thirds (67%) of its electricity from natural gas in 2011.

- Nevada ranked second in the nation in net electricity generation from both geothermal and solar energy in 2011; approximately 9.1% of Nevada's net electricity generation came from those two sources.

- The 640-kilometer (400-mile) UNEV pipeline, opened in 2012, lets petroleum products from Salt Lake City area refineries flow to Las Vegas; previously, Las Vegas obtained petroleum products only from three California pipelines.



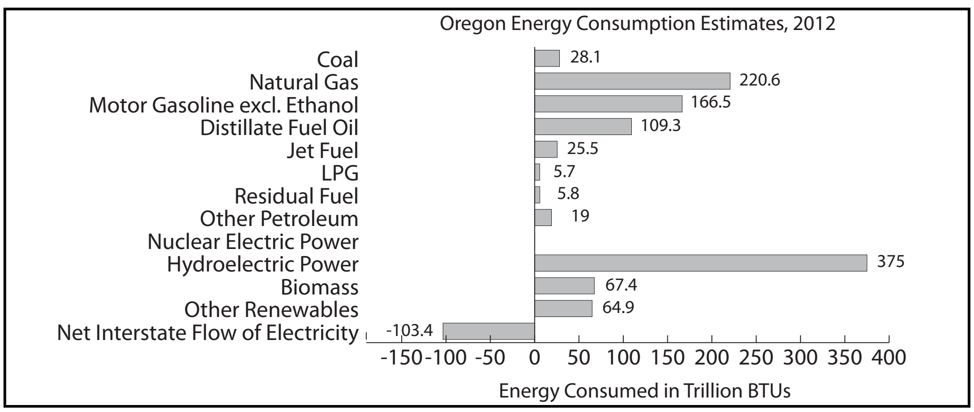


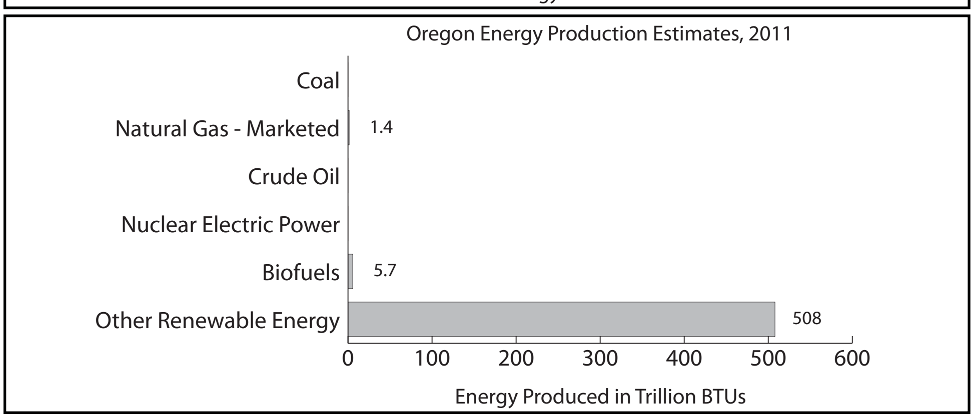
7 Energy

State Facts

Oregon

- Major transmission lines connect Oregon's electricity grid to California and Washington, allowing for large interstate electricity transfers.
- The owners of the Jordan Cove Energy Project at Coos Bay, after getting liquefied natural gas (LNG) import approval, decided to seek approval to become the first West Coast LNG export terminal outside of Alaska.
- Oregon is one of the nation's leading generators of hydroelectric power, ranking second in 2011, after Washington, in net electricity generation from conventional hydroelectric power. In 2010 and 2011, Oregon's abundant hydroelectric power contributed to below-average residential electricity prices in the state.
- In 2011, 80% of Oregon's net electricity generation was from conventional hydroelectric power plants and other renewable energy resources.

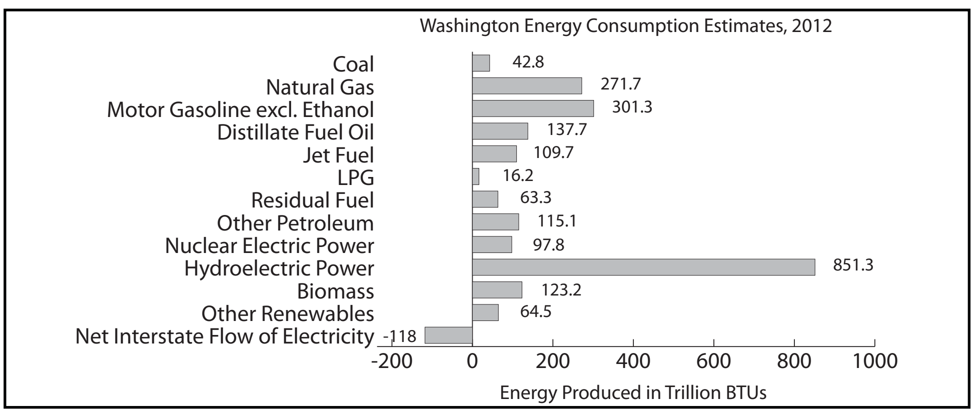


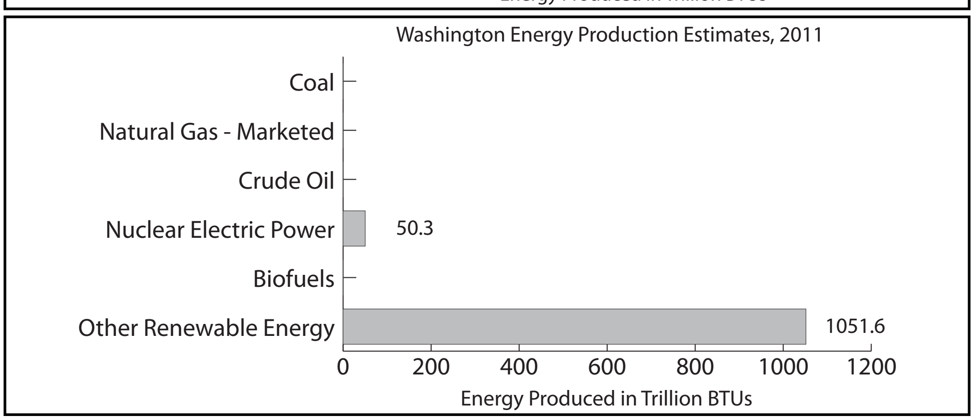


State Facts

Washington

- The Grand Coulee Dam on Washington's Columbia River is the largest hydroelectric power producer in the United States, with a total generating capacity of 6809 MW.
- The State of Washington's Energy Independence Act requires large electric utilities to obtain 15% of their electricity from new renewable energy resources by 2020 and to undertake cost-effective energy conservation.
- In 2011, Washington was the leading producer of electricity from hydroelectric sources and produced 29% of the nation's net hydroelectricity generation.
- Although not a crude oil-producing state, in 2011, Washington ranked sixth in the nation in crude oil refining capacity.
- Washington ranked sixth in the nation in net generation of electricity from wind energy in 2011.





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Energy

Climate Change

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.*

Energy and Climate Change

The Future of Energy in the US

Americans have come to rely on a diverse and abundant energy system, one that provides a continuous supply of energy with few interruptions. However, **climate change** is projected to play a big part in changing the supply, production, and demand for energy. Increases in temperature will see an increase in energy used for cooling, while projected increases in the occurrence of **hurricanes**, floods, **tornados**, and other extreme **weather** events will continue to have a significant effect on the infrastructure of power grids and energy delivery systems. Drought and water shortages are already beginning to affect energy production and supply. In the Northeast, mild winter temperatures prior to the winter of 2013–2014 had decreased energy demands for heat, but they did not fully offset increased demands for cooling, and the regionally harsher winter of 2013–2014 saw increased demands for heating fuels. These disruptions affect us both locally and nationally, are diverse in nature, and will require equally diverse solutions.

See Chapter 9: Climate for more information about climate change.

Energy is a **commodity**, and supply and demand around the world will also affect the US energy system. As the global population grows and industrialization of the world continues, demand for energy will increase even further as resources are depleted. These factors could significantly affect US energy costs through competition for imported and exported energy products. Mediation of our energy production could have a huge positive impact on climate change. Unfortunately, there is no energy production system or source currently available that is truly **sustainable**. All forms of energy have negative impacts on the environment, as do many of the ways in which we use them.

Until we have a sustainable means of producing and delivering energy, we need to consider which means of energy production and transport make the least impact; we are faced with a sort of “energy triage.” The answer to this problem will be multifaceted, depending in large part on what energy resources and delivery methods are available in each part of the US. The sources of energy that provide the least impact for the best price in the West are probably not the same in other areas.

Adaptation—changing our habits of energy use and delivery—can also make it easier for our existing energy infrastructure to adjust to the needs brought on by climate change. Investing in adaptation can pay off in the short term by reducing risks and vulnerabilities, thus minimizing future risks. Increasing sustainable energy practices (including harvesting and production) and improving infrastructure and delivery methods can go a long way toward not only decreasing the effects of climate change, but also our energy security.

Some of these changes are grounded in the development of new technologies for energy production and energy **efficiency**; others may be related to changes in behavior. These changes in technology and behavior may go hand in hand; 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.

__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.

In closing, some key points to keep in mind regarding the future of energy are:

1. Extreme weather events are affecting energy production and delivery facilities, causing supply disruptions of varying lengths and magnitudes and affecting other infrastructure that depends on energy supply. The frequency and intensity of extreme weather events are expected to increase.

2. Higher summer temperatures are likely to increase electricity use, causing higher summer peak loads, while warmer winters are likely to decrease energy demands for heating. Net energy use is projected to increase as rising demands for cooling outpace declining heating energy demands.

3. Both episodic and long-lasting changes in water availability will constrain different forms of energy production.

4. In the longer term, sea level rise will affect coastal facilities and infrastructure on which many energy systems, markets, and consumers depend.

5. As we invest in new energy technologies, future energy systems will differ from the present in uncertain ways. Depending on the way in which our energy system changes, climate change will introduce both new risks and new opportunities.

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Chapter 8: Soils of the Western 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. Soils are the principal medium of plant growth, and they provide habitat for a myriad of organisms—particularly decomposers. Soils store and purify water, and they exchange gasses with the **atmosphere**. Soils support agriculture and natural ecosystems, 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 the Earth as distinguished from rock—where vegetation grows. The word is derived (through Old French) from the Latin *solum,* which means "floor" or "ground." It is the most basic resource upon which all terrestrial life depends, and soil is one of the most important resources we have. The West 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 the nutritious organic matter that helps soil to nourish future plant growth. The second important component of soil is the sediment derived from the **weathering** of rock that is then transported by **wind**, water, or gravity. Both of these components influence the texture (*Figure 8.1*) and consistency of the soil, as well as the **minerals** available for consumption by plants.

All soils may seem alike, but there can be vast differences in soil properties even within small areas. A single acre may have several different soil types, each with its own assets and drawbacks. Some types of soil are clayey or prone to flooding, while others are stable enough to be used as a foundation for buildings. The most identifiable physical properties of soils are texture, structure, and **color**, which provide the basis for distinguishing soil **horizons**. Texture refers to the percentage of **sand**, **silt**, and **clay** that makes up the soil. The textures have specific names, as indicated in *Figure 8.1*.

Generally, the best agricultural soils are those with about equal amounts of clay, silt, and sand. A soil of that type would be called a **loam**. Soils that are mostly sand do not hold water very well and dry quickly. Soils with too much clay may never dry out.

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

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

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.*

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.*

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8

Soils

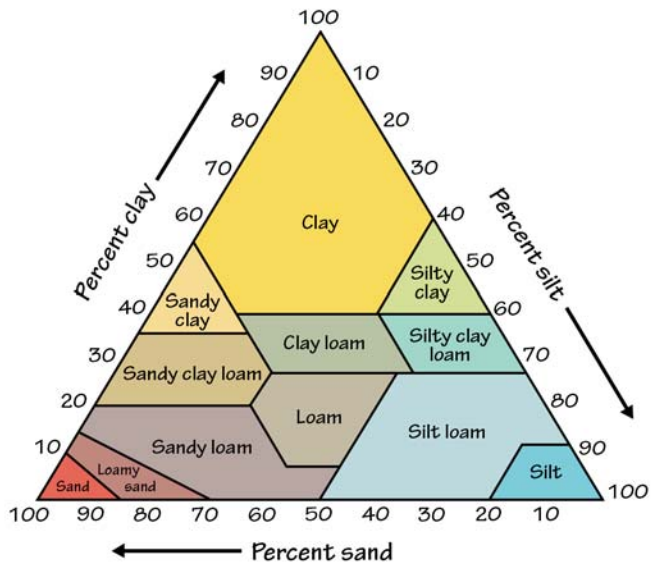

Figure 8.1: Soil texture triangle.

Soil structure refers to the way the soil forms clumps. These clumps are known as **peds**. The peds are identified by the shape of the soil clods, which take the form of balls, blocks, columns, and plates. These structures are easiest to see in recently plowed fields, where the soil is often granular and loose or lumpy.

Soil color is its most obvious physical property. The color is influenced by mineral content, the amount of organic material, and the amount of water it routinely holds. The colors are identified by a standard soil color chart called the Munsell chart.

Five main variables affect the characteristics of soil worldwide:

1. *Parent material* is the original geologic material from which the soil formed. This can be bedrock, preexisting soils, or other materials such as **till** or **loess**.

2. *Climate* strongly determines the temperature regime, amount of moisture, and type of **biota** that interact with the **parent material**. This will affect the extent of chemical and physical weathering on the soil-forming material.

3. *Topography*, or landscape, of the area is related to the relative position of the soil on the landscape; this includes the presence or absence of hills and the slopes between high and low areas. **Topography** influences natural drainage. Gravity moves water down slopes to depressions or streams and pulls free water downward through the soil. Soils on hills tend to be dry, and soils in depressions and valleys are often wet or saturated. 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

Review

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

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

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.*

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.*

is reset. Other areas that are more arid and have a flatter topography, such as the deserts in the Basin and Range region of Nevada, 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 like the forests in the Cascade-Sierra region.

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 that had 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. For its part, organic matter impacts the water-holding capacity of the soil, the soil's fertility, and root penetration.

5. *Time* is required for soils to develop while the four elements mentioned above interact. The effects of time can be seen when comparing soils on a glaciated area to either soils formed on recent flood plain deposits or soils in a non-glaciated area at the same latitude.

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 in soil water can come from the atmosphere, where it dissolves in rainwater. Even more CO_2 usually comes from the soil itself, where respiring organisms produce it. 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**.

A second important type of weathering reaction is **oxidation**. In Hawai'i, for example, **basalts** mostly contain ferrous iron (Fe^{2+}), which tends to give minerals a green to black color. As this iron reacts with oxygenated soil and water, the iron is converted to ferric iron (Fe^{3+}), which generates strong red-orange colors. Ferric iron is not very soluble (as anyone knows who has ever tried to "wash off" rust), and it tends to accumulate in weathered soil profiles. The striking "red dirt" soils in Hawai'i are excellent examples of oxidation acting on ferrous iron-rich basalt (*Figure 8.2*).

Review

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

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).*

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

titanium • *a metallic chemical element (Ti).*

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.*

8 Soils

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.*

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

Figure 8.2: A highly weathered Oxisol, west Kaua'i. Chemically this soil consists primarily of aluminum, iron, and titanium oxides and hydroxides. Erosion, probably caused by overgrazing, has led to a loss of organic matter at the surface. This soil has a low water-holding capacity, is highly acidic, and has very low nutrient content. These harsh conditions have prevented recolonization by plants.

In highly weathered settings, the mineral soil has lost most of its nutrients, and the store of nutrients that remains is mostly found in organic matter. In weathered soils, only the top 25 cm (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 to mature. More mature soils will develop a variety of horizons unique to their environmental conditions, creating 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 8.3*).

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

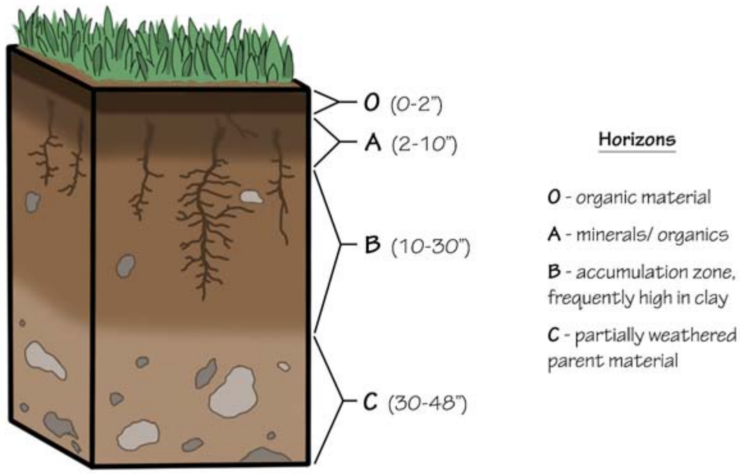

Figure 8.3: A typical soil profile shows the transition from the parent material (horizon C and the bedrock below it) to the highly developed or changed horizons (O through B). Not every soil profile will have all the horizons present.

soil taxonomy, and it was developed by the United States Department of Agriculture (USDA) with the help of soil scientists throughout the country. It provides a convenient, uniform, and detailed classification of soils throughout the country, allowing for an easier understanding of how and why different regions have developed unique soils.

In soil taxonomy, all soils are arranged into one of 12 major units, or **soil orders**. These 12 orders are defined by diagnostic horizons, composition, soil structures, and other characteristics. Soil orders depend mainly on **climate** and the organisms within the soil. These orders are further broken down into 64 suborders based on properties that influence soil development and plant growth, with the most important property being how wet the soil is throughout the year. The suborders are, in turn, separated into great groups (300+) and subgroups (2400+). Similar soils within a subgroup are grouped into even smaller families (7500+), and the similar soils within families are grouped together into the smallest category of all: a series (*Figure 8.4*). There are more than 19,000 soil series described in the United States, with more being defined every year.

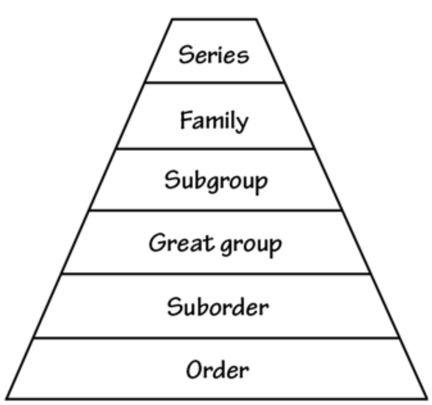

Figure 8.4: Soil taxonomy.

Review

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

8 Soils

Review

The 12 soil orders

Name	Description	Controlling Factors	Percentage of global ice-free land surface	Percentage of US ice-free land surface
Alfisols	Highly fertile and productive agricultural soils in which clays often accumulate below the surface. Found in humid and subhumid climates.	climate and organisms	~10%	~14%
Andisols	Often formed in volcanic materials, these highly productive soils possess very high water- and nutrient-holding capabilities. Commonly found in cool areas with moderate to high levels of precipitation.	parent material	~1%	~2%
Aridisols	Soils formed in very dry (arid) climates. The lack of moisture restricts weathering and leaching, resulting in both the accumulation of salts and limited subsurface development. Commonly found in deserts.	climate	~12%	~8%

The 12 soil orders (continued)

Entisols	Soils of relatively recent origin with little or no horizon development. Commonly found in areas where erosion or deposition rates outpace rates of soil development, such as floodplains, mountains, and badland areas.	time and topography	~16%	~12%
Gelisols	Weakly weathered soils formed in areas that contain permafrost within the soil profile.	climate	~9%	~9%
Histosols	Organic-rich soils found along lake coastal areas where poor drainage creates conditions of slow decomposition and peat (or muck) accumulates.	topography	~1%	~2%
Inceptisols	Soils that exhibit only moderate weathering and development. Often found on steep (relatively young) topography and overlying erosion-resistant bedrock.	time and climate	~17%	~10%

The 12 soil orders (continued)

Mollisols	Agricultural soils made highly productive due to a very fertile, organic-rich surface layer.	climate and organisms	~7%	~22%
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%

The 12 soil orders (continued)

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%

Dominant Soils of the Contiguous Western States

Alfisols: These soils tend to develop in cooler, more forested environments, and they commonly form a band separating more arid areas from humid areas. The Sierra Nevada are a perfect example of this, as they separate the arid Basin and Range from the more humid California coast and are, not surprisingly, dominated by Alfisols (*Figure 8.5*).

Figure 8.5: Alfisols of the contiguous Western US.

Review

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

Andisols: These form almost exclusively in the **volcanic** portions of the Pacific Northwest. They can be both weakly and heavily weathered soils that contain sediments derived from volcanic material. The presence of volcanic glass is diagnostic of this soil class (*Figure 8.6*).

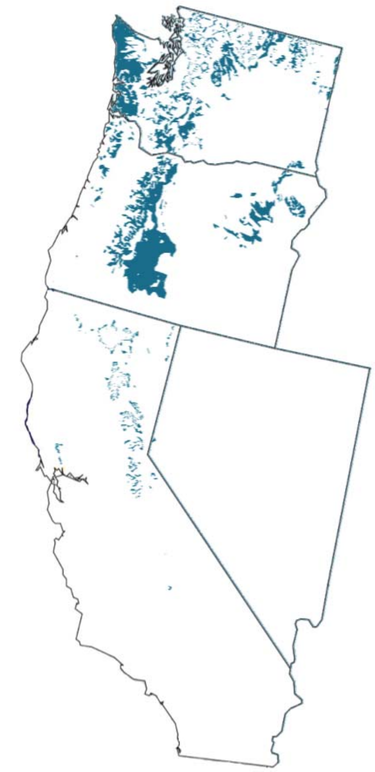

Figure 8.6: Andisols of the contiguous Western US.

Aridisols: Very dry soils that form in arid environments such as the Basin and Range region. Water content is very low or even nonexistent for most of the year, and this soil type is unsuitable for plants that are not adapted to store water or to survive extreme drought (*Figure 8.7*).

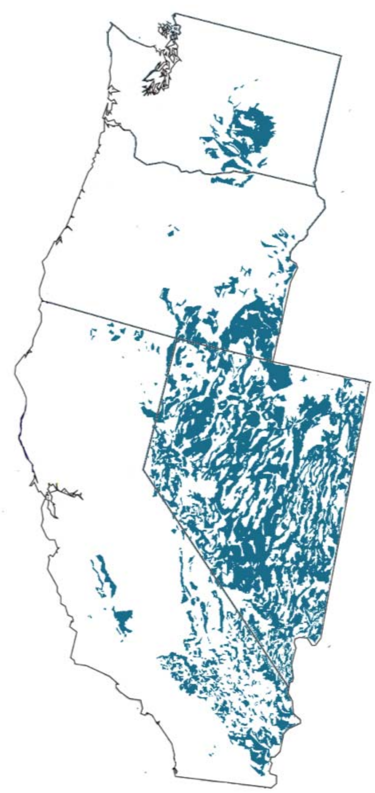

Figure 8.7: Aridisols of the contiguous Western US.

Review

topsoil • the surface or upper layer of soil, as distinct from the subsoil, and usually containing organic matter.

Inceptisols: Soils of cooler and wetter areas that have had calcium, magnesium, aluminum, and iron removed during development. Scattered throughout the US, they have a strong presence on the West Coast, especially in Oregon and northern California (*Figure 8.8*).

Figure 8.8: Inceptisols of the contiguous Western US.

Mollisols: The surface horizon of these soils tends to be very dark in color and almost black in some cases. The base-rich **topsoil** is widely used as cropland in the US, especially in the Columbia Plateau (*Figure 8.9*).

Figure 8.9: Mollisols of the contiguous Western US.

8 Soils

Review

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

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.*

peat *• an accumulation of partially decayed plant matter.*

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

boreal *• a cold temperate region relating to or characteristic of the sub-Arctic climatic zone.*

cinder *• a type of pyroclastic particle in the form of gas-rich lava droplets that cool as they fall.*

leeward *• downwind; facing away from the wind.*

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

Dominant Soils of Alaska

Andisols: These acidic soils are associated with **volcanic ash** and debris deposits. They are especially prevalent along the southern Aleutian Islands, where they support low vegetation, and in the southeastern panhandle, where they support forests.

Entisols: These are soils with poorly developed horizons of recent origin. In Alaska, they are common along the banks of the Yukon and other large rivers, but they are also the relatively productive agricultural soils in the Matanuska-Susitna area, Alaska's "breadbasket."

Gelisols: These are soils of cold climates that contain **permafrost**. Gelisols are found throughout Alaska and are by far the most common soils in the state. Decomposition of organic matter occurs at a very slow rate in these soils.

Histosols: These soils contain high concentrations of organic matter, due to their development in wetland environments with poor drainage and a slow rate of decomposition. They are associated with **peat** bogs and mucks in southern Alaska and the Alaska panhandle, where permafrost is less common.

Inceptisols: These are soils with poorly developed horizons, associated with both Alaska's interior highlands and parts of the western coastal plains.

Mollisols: These are usually the dominant soils of grasslands, and, as such, are very uncommon in Alaska. They support forests with large proportions of spruce, birch, and aspen **trees** that are found sprinkled along the Pacific Coast.

Spodosols: These are acidic soils with an accumulation of iron and aluminum in the humus. These soils support cool, moist **coniferous** stands of forest and are associated with **boreal** forests. These are found primarily along Alaska's southern coast.

Dominant Soils of Hawai'i

Andisols: The most abundant soil type in Hawai'i, these soils formed from volcanic ejecta such as ash and **cinders**—materials that weather to form clay minerals. These soils are extremely rich in organic material in their upper horizons, and have a large water-holding capacity. This makes them highly productive soils for agriculture, and they are easy to cultivate. They do lose some fertility in areas of higher rainfall (over 150 centimeters [60 inches] annually), as the heavy rains wash nutrients from the soil.

Aridisols: These desert soils are formed in areas where the rainfall is so low that vegetation is almost completely absent, such as on the **leeward** side of the islands. They are shallow with no developed horizons, and they become saturated with **salts**, as there is no rainfall to wash the salts away. With irrigation, however, they can become useful agricultural soils.

Review

Figure 8.10: The dominant soil orders of Alaska. (See TFG website for full-color version.)

Entisols: These are poorly developed soils with a high mineral component and no real developed horizons. They occur on sands formed from coral **reefs** or on **alluvium** in drier areas.

Histosols: These soils develop from accumulations of organic materials on top of **lava** flows. They occur in cooler, moist conditions where anaerobic (low oxygen) environments are common. In areas of higher rainfall, they can become very acidic. The typical types of vegetation found on this soil order are Ohiʻa trees and ferns.

Inceptisols: These young, poorly developed soils are found on active slopes or in river valleys where material is constantly being deposited. They are most common on the older islands, and also occur in river valleys on the older volcanoes of the younger islands.

Mollisols: In other parts of the globe these rich, dark-colored soils are found on grasslands. In Hawaiʻi, however, the Mollisols are reddish in color, due to their high iron content, and they are found on the coastal plains and gentle slopes up to around 300 meters (1500 feet) above sea level in drier areas (65–130 centimeters [25–50 inches] of rain or less annually). In the past, these areas were extensively used for sugarcane crops.

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.*

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

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

Review

__kaolinite__ • a silicate clay mineral, also known as china clay.

Oxisols: These are highly weathered soils that are very low in fertility and develop in hot tropical climates. They are found on low-elevation dry areas, or in some of the very wet highland areas. They are very common on the older islands of Kauaʻi and Oʻahu, but they are not found on the younger islands.

Spodosols: These soils form in forests in moist to wet areas on some of the uplands in Kauaʻi and Molokaʻi. They are not used for any form of agriculture.

Ultisols: These weathered soils are rich in the clay mineral **kaolinite** and form in warm humid climates with distinctive wet-dry seasons. They zone into Oxisols on some islands when rainfall decreases. They are acidic and yet, with the proper use of fertilizers, have become highly productive agricultural soils in Hawaiʻi.

Vertisols: These are very dark soils, rich in swelling clays. Their distinguishing feature is that they form deeply cracked surfaces during dry periods, but they swell again in the wet season, which seals all the cracks. As a result, they are very difficult soils to build roads or other structures on.

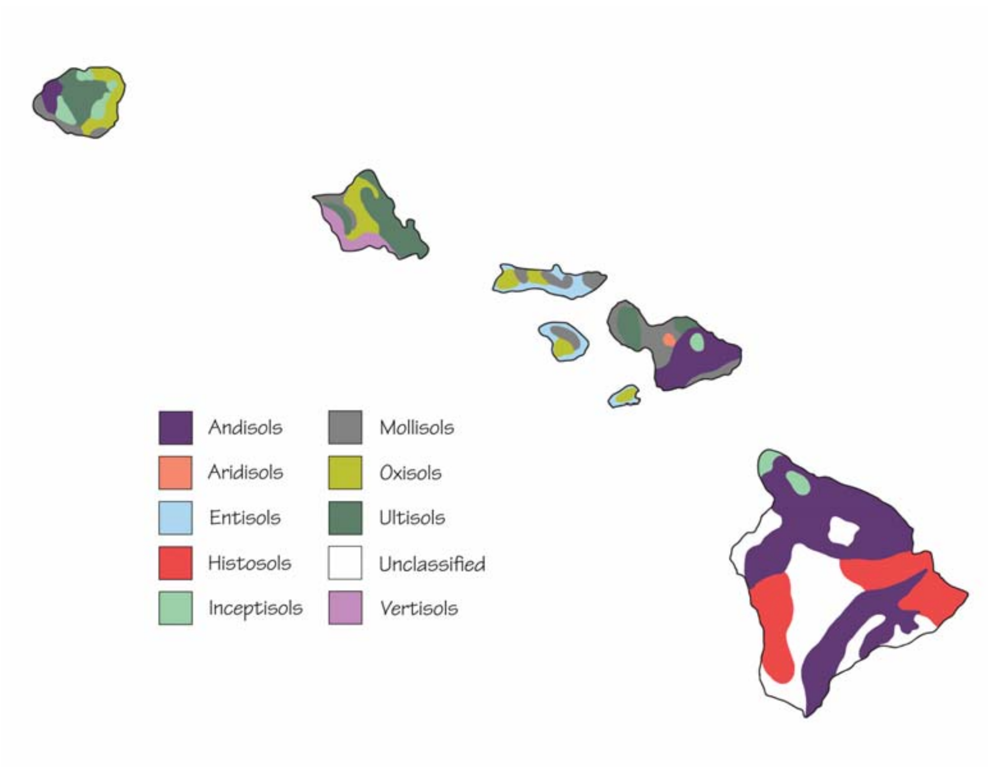

Figure 8.11: The dominant soil orders of Hawaiʻi.
(See TFG website for full-color version.)

Soils of the Basin and Range

Region 1

The Basin and Range is the vast expanse of land that runs along the eastern edge of the Cascades and Sierra Nevada, down through Nevada, and toward the nation's southwestern portions. It formed as the result of extreme tension on the continental **lithosphere** that underlies the Western US. A series of extensional **faults** led to the very prominent, zebra stripe-like pattern of sharp cliffs and wide valleys that make up the region's topography.

See Chapter 4: Topography for more information about the landscape of the Basin and Range.

The Basin and Range contains a vast **watershed** called the Great Basin (*Figure 8.12*), so named because it lacks an outlet for surface water. Although very little

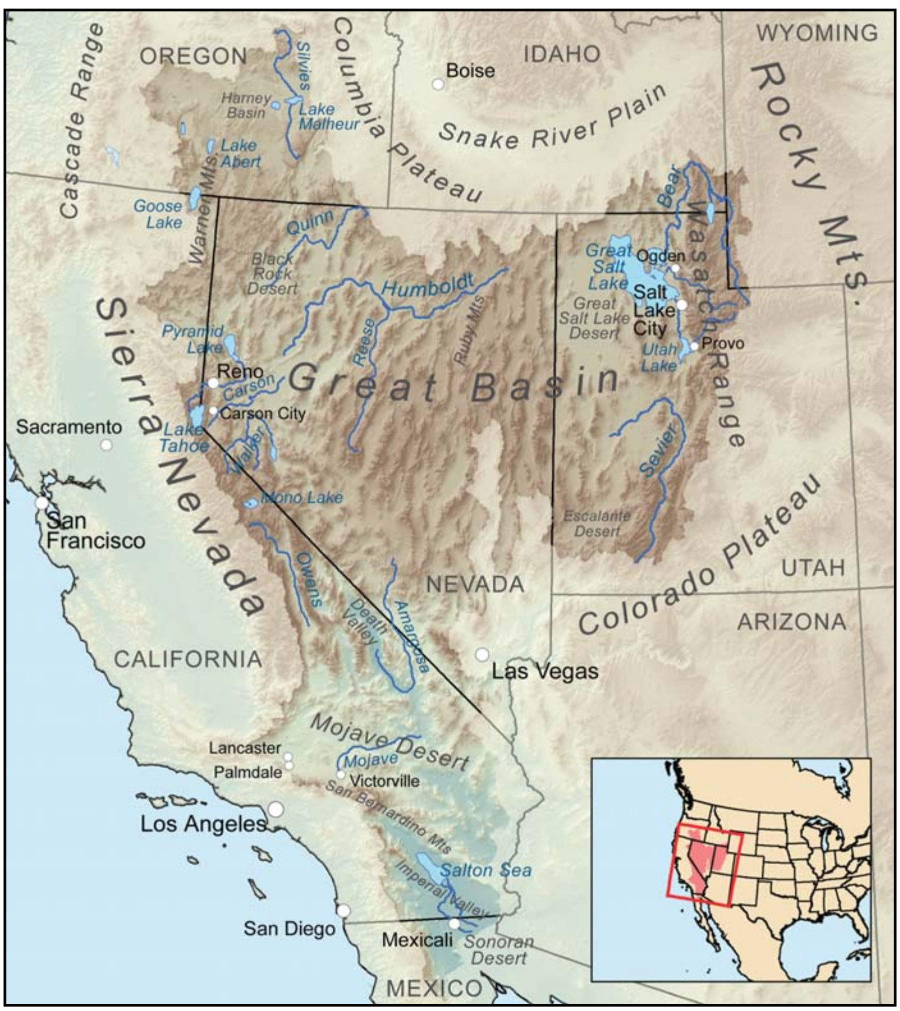

Figure 8.12: Extent of the Great Basin.

Region 1

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

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.*

watershed • *an area of land from which all water under or on it drains to the same location.*

playa lake • *ephemeral or dry lakebed that occasionally contains only a thin layer of quickly evaporating water.*

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

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

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

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

rain falls in this arid place, what does fall never reaches the ocean but instead drains into the valleys and collects in **playa lakes**, where it soon evaporates. This results in either dry soils or barren desert with sediment surfaces that have not become soil.

As a result of this harsh climate, Aridisols dominate the Basin and Range. One of the identifying characteristics of these soils is their inherent dryness. There is very little plant life in much of the region, so an organic soil horizon takes either a long time to form or does not form at all. Sediments that are introduced from weathered outcrops vary. More **calcium carbonate**-rich soils, called Calcids (a suborder of Aridisols), are common in the southern portions, while more silica-rich Argids (a suborder of Aridisols) are common in the northern areas. Traces of Mollisols and Entisols can be found around the edges of the region, and small amounts of Gelisols can be found in eastern Nevada.

Soils of the Columbia Plateau

Region 2

This region's geology, and therefore its soil, is dominated by the Columbia River Flood Basalts. Beginning in the **Miocene** (17 million years ago) and leading up to the **Pleistocene**, flood basalts erupted in numerous locations throughout the region and flowed over the landscape, leaving few places untouched. These **effusive** lavas resulted from a **hot spot**. This hot spot now rests under Yellowstone National Park, the site of considerable **hydrothermal** activity. Wind-transported sediments known as loess are also important to the region. The Palouse Loess, for example, is famous for supporting productive agricultural lands.

See Chapter 2: Rocks to learn more about the Columbia River Flood Basalts.

The Columbia Plateau is mostly covered by grasslands and some forests, and is composed primarily of Mollisols. These soils tend to be dry in the summer and are later re-moistened by the fall and winter rains. They typically rest on top of gently sloped surfaces, in this case loess-covered flood basalts. **Mafic** minerals, a result of past volcanism, are common in the loess that these soils are derived from. This region experiences slower erosion than the more steeply sloped and continuously changing mountainous regions nearby. This allows the soils ample time to develop a rich and dark topsoil horizon, one that is perfect for supporting grasslands and farming. Agriculture is widespread in this region and is supported by irrigation from several rivers flowing through the area, which help to soak the summer-dried soils. Some of Washington's best apples are grown on the Columbia Plateau.

Some Aridisols can be found in the Channeled Scablands of eastern Washington (*Figure 8.13*)—a barren, eroded area scoured clean by the Missoula Floods—as well as in the southeast corner of this region.

See Chapter 4: Topography for more information about the Missoula Floods.

Figure 8.13: Aridisols in the Channeled Scablands near Wenatchee, Washington.

Soils of the Northern Rocky Mountains
Region 3

The Northern Rocky Mountains provide only a glimpse of the Rocky Mountains that nearly bisect the country. The Rockies formed as the result of both volcanism and **terrane accretion**. From the **Jurassic** to the **Cenozoic**, oceanic lithosphere was **subducted** under the continent at a very shallow angle, driving volcanism farther inland than is typical. The subducting **plate** also brought terranes towards the continent, which accreted during events like the **Laramide Orogeny**. The coastline of the continent began to grow and move farther from the Rocky Mountains, also pushing the subduction zone farther away. With the lack of nearby subduction, volcanism ceased and the Rockies were left far from the coast, tectonically inactive and gradually eroding.

The mountainous terrain and past volcanism are equally responsible for the soil types present in the region. Inceptisols are common due to the steep slopes and wet conditions found in elevated areas. The rapid erosion and frequent washing away of soils means that soils in many areas are poorly developed. Although the bulk of Inceptisols occur on the East Coast, there are parts of the

Regions 2–3

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.*

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

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

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

Western US, like the Rockies, that are both humid and forested enough for them to form. The Northern Rockies are unique to the rest of the Rockies in that they also harbor Andisols, a relict of the region's volcanic past that are more dominant in the Cascade-Sierra region.

Soils of the Cascade-Sierra Mountains
Region 4

The Cascades and Sierra Nevada are each the result of distinct volcanic arcs that produced one long span of mountainous terrain. Stretching from Canada all the way down to northern California, the younger Cascade Range was produced by intense volcanism brought on by the continuing subduction of oceanic lithosphere under the North American plate. The frequent ejection of volcanic material contributed greatly to the sediments and minerals present in the area, and this set the stage for the formation of soils that are found almost exclusively in the Pacific Northwest.

See Chapter 1: Geologic History for more detail about subduction and accretion in the formation of the Western states.

Andisols compose most of the Washington area of the Cascades, while Inceptisols dominate the Oregon Cascades. Uniquely identified by the presence of volcanic glass and minerals derived from igneous rocks, many of these soils formed under dense coniferous forests. As in the Rocky Mountains, erosion is frequent in this terrain, making prolonged and deeper soil development difficult.

The Sierra Nevada are located in California, directly south of the Cascades. The Sierra's distinctive **granite** originally formed from ancient **magma intrusions** that have long since cooled and are now heavily weathered (*Figure 8.14*). Even without active volcanism, the range was able to grow due to **exhumation** and **uplift**, and its **relief** became more pronounced with the formation of the lower Basin and Range region to the east. The Sierra act as a transition zone between the arid climate in the east and the coastal climate to the west, and Alfisols tend to form in this type of zone. Although these soils form throughout the nation, and over a greater area east of the Mississippi River, the unique suborder of Xeralfs make up the majority of the Alfisols in the region. These soils can be forested, or even used as crop and grazing lands.

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

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

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

exhumation • *the erosional uncovering or exposing of a geological feature that had been previously covered by deposited sediments.*

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

Figure 8.14: The heavily weathered soils of Temple Crag in the Sierra Nevada consist of carbonate-rich Alfisols and Inceptisols.

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

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

Soils of the Pacific Border
Region 5

The Pacific Border Region has a notable range of soil orders because of its varied topography, nearby volcanism, coastal processes, and the past glaciation of its northern areas. High-energy beaches in the north and lower-energy beaches in the south provide a range of sediments for soil building. Soil material is also contributed by streams descending from the mountains, which create unique **fluvial** deposits. An amazing history of chaotic events, including repeated glaciations during the Pleistocene, the Missoula Floods, and the Columbia River Flood Basalts, have all left their mark on the coast. All of the dominant soil types previously discussed can be found in this region due to the variance in climate, vegetation, and geology that exists from north to south. Andisols are found mostly along the Washington coast, Inceptisols cover the coasts of Oregon and northern California, and Mollisols are scattered around the rest of California's coast.

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

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

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.*

patterned ground • *patterns and sorting in the soil caused by repeated freezing and thawing, which causes repeated heaving upwards and settling of the rocks and pebbles in the soil.*

Soils of Alaska

Region 6

Alaska's cool climate and rugged terrain limits the agricultural and forestry-related uses of its soil. Accordingly, less than a tenth of the state has been surveyed beyond the "exploratory" level. The United States federal government owns 65% of the state: a conglomeration of national parks, national forests, and national wildlife refuges.

Although Alaska's cooler climate limits the number of soil types present there, its diverse topography does allow for 7 of the 12 soil orders to occur. The state has two major mountain chains, a vast interior highland, remote stretches of frozen plains, and more coastline than the 49 other states combined. It is also home to the Aleutian Islands, a **volcanic island** chain built of basaltic lava and ash deposits that create prevalent Andisols. Of course, the frigid temperatures have an influence on soil regimes, particularly in the interior and on the Arctic coast. Cold temperatures also slow the rate of chemical reactions, while ice can increase erosion. Much more of the state was glaciated in the recent past, though extreme aridity seems to have kept significant swaths ice-free. **Ice sheets** were predominantly found in the south central and panhandle areas, grinding rock to produce sediment.

Precipitation in Alaska generally decreases to the north, varying from less than 18 centimeters (7 inches) per year on the Arctic coast, to more than 630 centimeters (250 inches) per year in parts of the southeast. This increased rainfall in Alaska's southern portion and panhandle contributes to the wetlands and peat bogs found there, where poor drainage and slow decomposition leads to the development of Histosols.

Approximately 332,000 square kilometers (128,000 square miles) of Alaska (nearly twice the size of Washington State) are mountainous, and 39,000 square kilometers (15,000 square miles) of that are glaciated. Other than in parts of the high Rockies, the only permafrost found in the United States is in Alaska. More than 80% of the state has some amount of permafrost—it is nearly ubiquitous north of the Brooks Range but thins to the south, where it is primarily found only in the mountains of the panhandle. Permafrost usually forms anywhere that the average annual air temperature is below -1°C (30°F). The longer the area remains frozen, the deeper the ice can reach, sometimes extending thousands of meters (yards) below the surface. In southern Alaska, where it is too warm to form today, there are still stretches of relict permafrost that remain frozen from the Pleistocene, when conditions were cold enough for it to form (*Figure 8.15*). Unsurprisingly, the permafrost-associated Gelisols are the most common soil type found here.

Subfreezing temperatures affect soil by altering erosional processes, decomposition, the movement of soil particles, and the types of organisms that live in and on the soil. Most permafrost is overlain by no more than a meter (3.3 feet) of annually thawed soil, known as the active layer. The active layer comprises the O and A soil layers, while the lower beds are frozen, effectively removing them from the soil profile. This is precisely why Gelisols are high in organic content and low in nutrients: minerals are prevented from reaching the surface, and organic materials accumulate above the frozen layers.

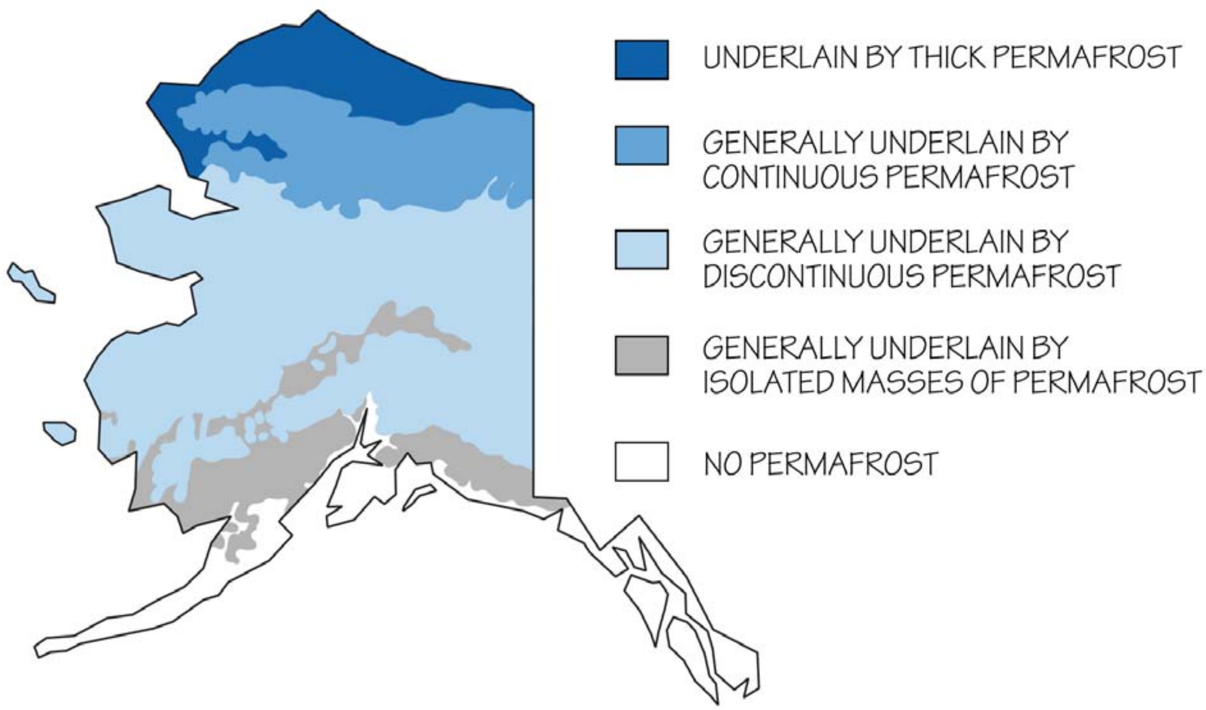

Figure 8.15: The location (and types) of permafrost in Alaska. (See TFG website for full-color version.)

As organic-rich Gelisols build up at the surface, older layers become deeply buried and eventually freeze. Once frozen, organic materials cease to decay, effectively sequestering the carbon they contain in the ground. When permafrost thaws, decay begins again, and carbon-based molecules—perhaps most significantly methane—are released. Methane is an extremely potent **greenhouse gas**, and climatologists believe permafrost thaw will be one of the most important feedbacks driving **global warming** in the coming decades. The buildup and explosive release of methane-rich gases has also been implicated in unusual landforms such as craters and hollows that can form suddenly in permafrost landscapes.

Thawing and freezing can cause soil to move and mix. For example, cold and dry conditions cause the surface to contract, creating cracks that may then fill with sediment. Warmer and wetter conditions cause the ground to expand, and the sediment in the cracks can be forced up. An area in which this process is repeated creates a network of landforms called **patterned ground**. (*Figure 8.16*)

Thawing permafrost can also cause the soil to shift and sink. In some parts of Alaska, these shifts have resulted in trees growing at unusual angles in order to compensate for their changing footing, a phenomenon known as “drunken trees.” (*Figure 8.17*)

Figure 8.16: An overhead view of patterned ground in Alaska.

Figure 8.17: A clear example of drunken trees.

Entisols represent the most productive agricultural soils of the state, and are found on **floodplains** and **outwash plains** where new sediment is deposited at frequent intervals. The Matanuska-Susitna area is also known as “Alaska’s breadbasket,” due to the fertile Entisols that produce over 75% of the state’s agricultural output.

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

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

Soils of Hawai‘i
Region 7

Hawai‘i’s climate, topography, and substrate age are all characterized by large gradients, and there is a similarly large variation in the types of soils found here, despite the somewhat uniform lithology of the underlying basaltic lavas. Of the 12 soil orders classified by the USDA, 10 are found in this state—Alfisols and Gelisols being the only orders not found on the island chain. As might be expected, fewer soil orders are found on the younger islands.

Unlike a continental system, each Hawaiian volcano begins as a blank slate—a barren basalt flow on which soil begins to develop only a few years after the eruption of the substrate. Soil development follows the arrival of early colonizing organisms, both plants and soil microbes, that begin to transform rock into soil. These early soils are relatively rich in nutrient elements derived from the parent material, but are relatively poor in nitrogen, a product of biological activity. Nitrogen-fixing lichens are among the first colonizers of lava flows, and they are critical to the creation of soils capable of supporting a young ecosystem (*Figure 8.18*).

Figure 8.18: Sword ferns and small gray dots of lichen colonize a lava flow on Kīlauea volcano. The lichen is a nitrogen fixer, and the fern contributes organic matter to the soil.

Soil development is rapid in the tropics, where high temperatures and locally abundant rainfall accelerate the process. Once soils are established, rainfall also dissolves and mobilizes compounds in the soil, mediating chemical reactions that alter pH and the availability of nutrients. The rate of soil development in Hawai‘i depends strongly on rainfall. Dry areas evolve in the same direction as wet areas do, but much more slowly. Soluble compounds such as sodium, magnesium, and calcium are leached from the soil, while insoluble compounds such as oxides of iron and aluminum are left behind.

As Hawaiian soils develop, nitrogen also becomes more abundant due to its addition by nitrogen-fixing bacteria. Phosphorous is gradually leached from the soil at a rate faster than it is replaced. In very old soils, where nearly all the phosphorous in the soil profile has been lost, it can only be replaced by deposition from the atmosphere. Interestingly, in Hawai‘i this input is principally via long-distance atmospheric transport of dust from Asia (*Figure 8.19*).

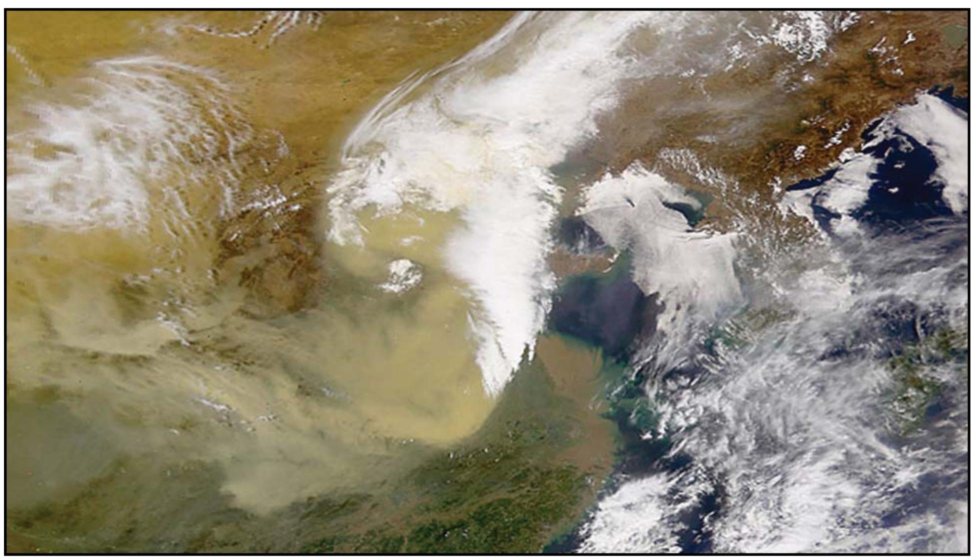

Figure 8.19: Satellite image of China, where continental dust (tan patch at center) blows off of the Gobi desert in a spring storm. Dust storms such as these are important for transporting nutrients to Hawaiian ecosystems. (See TFG website for full-color version.)

The youngest soils and the oldest soils in Hawai‘i are not well suited for agriculture. The youngest soils are thin, do not have much water-holding capacity, and are poor in nitrogen. In contrast, the oldest soils are acidic, have high levels of aluminum that can be toxic to plant roots, and are poor in phosphorous. But many soils in Hawai‘i are quite fertile, making the islands highly productive for both traditional and modern methods of cultivation. Harvesting crops tends to remove the most nutrient-rich parts of plants from the system, and this can lead to nutrient depletion over time. Crop rotation and fallow periods can help limit nutrient losses, as can fertilizer use. In traditional wet taro cultivation, where taro is grown in flooded paddies, new sediment brought in by streams provides nutrient-rich material to the taro patch each year, supporting high yields over time. Traditional dry land taro cultivation tended to focus on the “sweet spots”

where there was enough rain to support the crops but not so much that the soil had become too weathered, acidic, and nutrient poor.

In many parts of the world, certain types of soils were valued for the clays they contained that could be made into pots and vessels. Weathering processes in Hawai‘i tend to produce clays that are not well suited for pottery, and thus pottery was not an important traditional craft, unlike in some other Polynesian areas.

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.

Alaska

The Alaska state soil is a Gelisol called the Tanana series. These are important agricultural soils in Alaska, and when they are developed for agriculture, they can be used for hay, pasture, grains, and vegetables.

California

California's state soil is the San Joaquin series, which covers more than 200,000 **hectares** (500,000 acres) of the Great Central Valley. Grapes, oranges, figs, and almonds are just a few of the crops grown on this Alfisol. This soil is also a favorite for urban development due to the presence of **hardpan**, roughly a meter (3.3 feet) below the surface, which restricts water percolation.

Hawai‘i

Given Hawai‘i's volcanic history, it should be no surprise that its state soil is an Andisol. The Hilo series covers more than 5,900 hectares (14,500 acres) and is a highly productive agricultural soil formed principally from weathered volcanic ash.

Nevada

The Orovada series is the state soil of Nevada. An Aridisol, this soil is deep and well drained, having formed in loess that is high in volcanic ash. The presence of ash reduces the amount of water needed for irrigation, making this a valuable agricultural soil. It is primarily used to grow crops such as barley, winter wheat, alfalfa, and grass (for hay and pasture). Located mainly in the Great Basin portion of the Basin and Range, it covers more than 150,000 hectares (360,000 acres) of northern Nevada.

fossil • *preserved evidence of ancient life.*

hectare • *a metric unit of area defined as 10,000 square meters.*

hardpan • *a dense layer of soil, generally found below the topsoil layer, that is generally impervious to water.*

Soils

State Soils

Oregon

An Ultisol known as the Jory series is the state soil of Oregon. This series can be found on more than 120,000 hectares (300,000 acres) of land in the western part of the state. It is a very productive agricultural soil that is a favorite of the local wine industry. The name comes from Jory Hill in Marion County, which owes its name to a family that settled in the area in 1852.

Washington

The state soil of Washington is the Tokul series, an Andisol that formed in volcanic ash and loess over a dense glacial till containing high concentrations of manganese and iron. The name comes from a small community and creek located in King County. The state has more than 400,000 hectares (1,000,000 acres) of Tokul soils, the majority of which are located on the western side of the Cascade Range.

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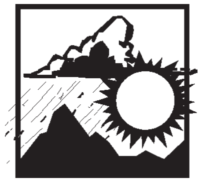

Chapter 9: Climate of the Western US

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—for example, San Francisco—has a different climate from one that has a large variation, such as Buffalo. Scientists have settled on 30 years as the shortest amount of time over which climate can be defined, but of course it can also refer to millions of years.

You cannot go outside and observe climate. **Weather**, on the other hand, can be observed instantly—it is 57 degrees and raining *right now*. Weather varies with the time of day, the season, multi-year cycles, etc., while climate encompasses those variations. Our choice of clothing in the morning is based on the weather, while the wardrobe in our closet is a reflection of climate. Due to its great variety of environments, from the **boreal** areas of Alaska to the subtropics of Hawai‘i, residents of the West generally have a diverse wardrobe. The most variable climates, however, are in the interior areas and mountains of the western continental US. These areas can vary from frigid in the winter to scorching in the summer. By contrast, coastal climates have only moderate seasonal variation, while Alaska is always cool and Hawai‘i is always warm. The West’s climate is also extremely variable with respect to moisture, from the arid deserts of Nevada to the rainforests of western Washington.

Past Climates

Climate, like other parts of the Earth system, is not static but changes over time, on 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. What is now the West has been tropical or temperate through most of its history, but it has also ranged from very wet to very dry.

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

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.*

boreal • *a cold temperate region relating to or characteristic of the sub-Arctic climatic zone.*

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.*

fossil • *preserved evidence of ancient life.*

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

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

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

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

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

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

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

history of the Earth's climate, and that of the West. Unfortunately, we do not have as clear an understanding of climate 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, 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 will never be repeated. These torrential rains were constant for *millions* of years, absorbing **salt** and other **minerals** from the earth as the rainwater coursed to the lowest areas, forming Earth's oceans and seas.

At this time, the sun produced significantly less **energy** than it does today, so one might expect that once the oceans formed, they would continue to cool and eventually freeze. Yet temperatures stabilized, perhaps because there was a greater concentration of potent **greenhouse gases** in the atmosphere and less land surface to reflect light, so temperatures remained high enough for liquid water to exist. Indirectly, the ocean was responsible for the final ingredient of the modern atmosphere because it was home to the first life on Earth. Photosynthetic bacteria appeared perhaps as early as 3.5 billion years ago, but the abundant **iron** and organic matter quickly absorbed the oxygen they produced. After hundreds of millions of years, these sinks were exhausted, and free oxygen could finally build up in the atmosphere. With this addition, the modern atmosphere was complete, though the relative amounts of the gases composing it would, and still continue to, shift. *The composition of the atmosphere and the huge volume of water on Earth are two of the most important factors affecting climate.*

Much of the light from the sun passes unimpeded through the atmosphere and hits the Earth. Approximately 70% of that light is absorbed and retransmitted from the surface as heat. The transmitted heat, which has a longer wavelength than light, is trapped by gases in the atmosphere including water vapor, carbon dioxide, and methane. The similarity between this process and that which warms a greenhouse earned these "*greenhouse gases*" their moniker.

While the atmosphere was forming 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**

Past

constantly wells up from deep fissures and solidifies into relatively dense rock, 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 rearranging of the continents, and the amount and types of minerals exposed to the atmosphere play a huge role in the climate. Not only do the continents and oceans move through different climate zones, but the continents also affect climate based on their size, and the **weathering** of rock on the continents plays a large role in the composition of the atmosphere. For example, rock that is enriched in organic matter will release abundant amounts of carbon dioxide as it weathers, while rock rich in **feldspar** and **mica** will take up carbon dioxide.

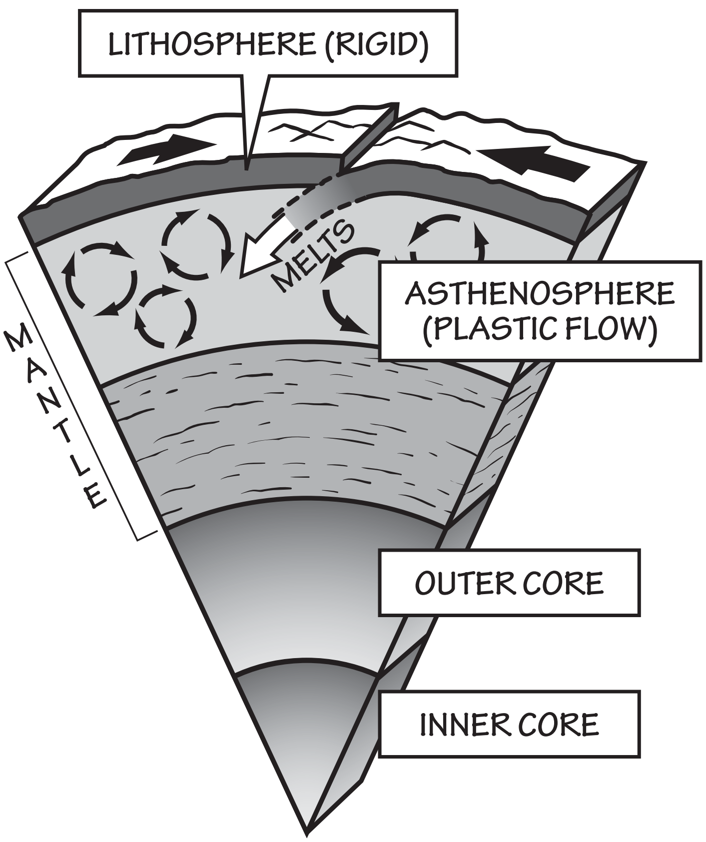


Figure 9.1: The layers of the Earth include the rigid crust of the lithosphere, which is constantly moving over the plastically flowing asthenosphere.

Nearly one billion years ago, the Earth began fluctuating between warm and cool periods lasting roughly 150 million years each. During the cool periods, there is usually persistent ice at the poles; during the warm periods there is little or no glaciation anywhere on Earth. Today, we are still in a cool period—although the world has been cooler than it is at present, it has been much hotter for much of its history (*Figure 9.2*). Through the shifting global climate and the movement of the tectonic plates, parts of what is now the West have at times been at the bottom of a shallow sea, a collection of islands scattered across a

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

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

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.*

Past

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

tropical ocean, a coastal plain with swamps and rivers, covered with ice, and wracked by great floods.

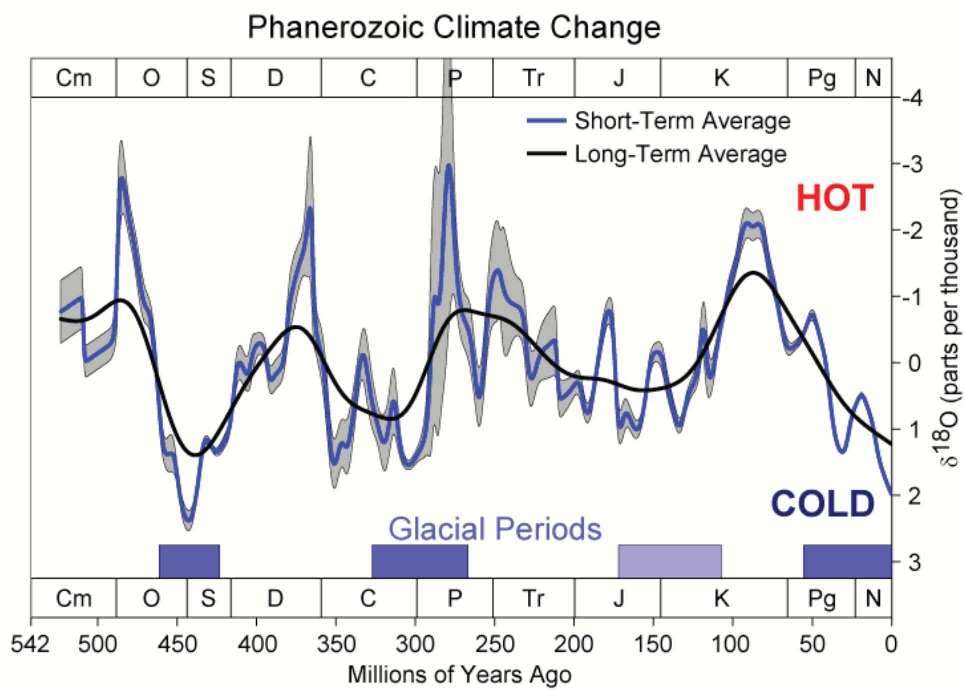


Figure 9.2: Changing global climate throughout the last 542 million years. These data were compiled using the ratios of stable oxygen isotopes found in ice cores and the carbonate skeletons of fossil organisms. (See TFG website for full-color version.)

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 towards a series of cooling feedbacks and caused ice to spread from pole to pole.

See Chapter 6: Glaciers to find out more about glaciations.

An ice-covered planet would remain that way because almost all of the sun's energy would be reflected back into space, but 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. These gases

Past

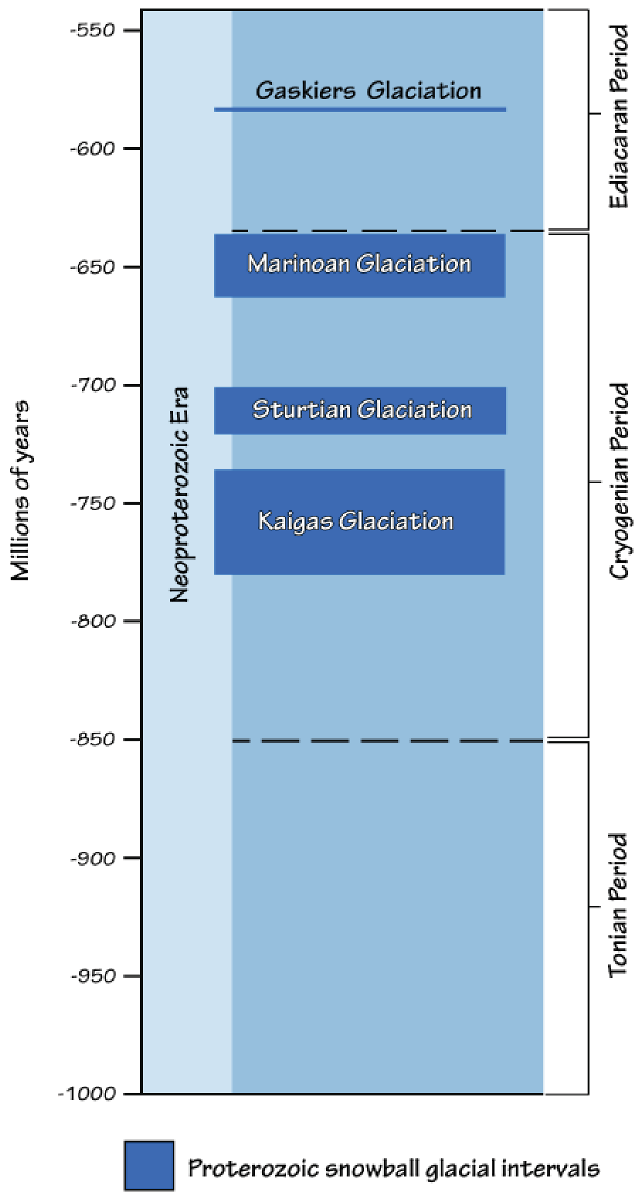


Figure 9.3: Snowball Earth periods during the Proterozoic.

are usually removed from the atmosphere by organisms and the weathering of rocks, but this was not possible through miles of ice! After millions of years, the concentrations of methane and carbon dioxide increased to the point that greenhouse warming began to melt the **ice sheets**. Once the melting started, more of the sun's energy was absorbed by the surface, and the warming feedbacks began. Because the oceans had been covered, nutrients from volcanic gases and chemical changes in the rocks accumulated in the waters. Once they were re-exposed to light, a population explosion of **cyanobacteria** produced more and more oxygen capable of combining with freshly thawed carbon sources to make more carbon dioxide, further enhancing the warming.

For the next 1.5 billion years, the continental crust that was to become North America, including some of the West, drifted around the surface of the Earth.

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).*

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

9 Climate

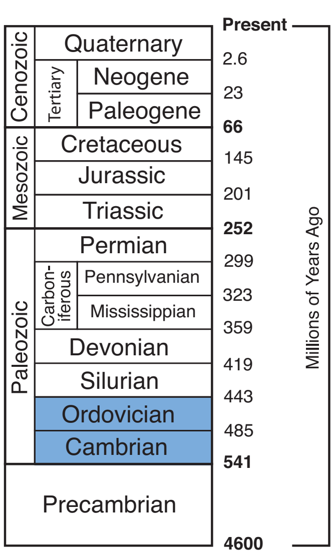
Past

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

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

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

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



A new supercontinent—**Rodinia**—formed, and the part that is now North America was stable, forming what is known as a **craton**, or continental interior relatively free of the folding and **faulting** that characterizes continental margins that are subjected to mountain building and other plate tectonic processes. About 850 million years ago, during the **Cryogenian**, the Earth entered a 200-million-year **ice age**. The North American portion of Rodinia was near the equator, and there were two more Snowball Earths during this time. The fact that North America was at such a low latitude, yet had **glaciers**, is strong evidence that the Earth really did freeze over completely. There is no direct evidence for these events in the West, although some evidence can be found in the rocks of Idaho.

Life and Climate

By 635 million years ago, the Earth had warmed again, and the North American continent moved towards the equator. Throughout much of the **Paleozoic**, North America's terrestrial margin ran through Idaho, Arizona, and easternmost Utah, with the continental shelf extending out through California, Oregon, and Washington (*Figure 9.4*). The West had a warm climate, and fossils such as **trilobites**, **brachiopods**, and **archaeocyathids**--**extinct reef** formers—found

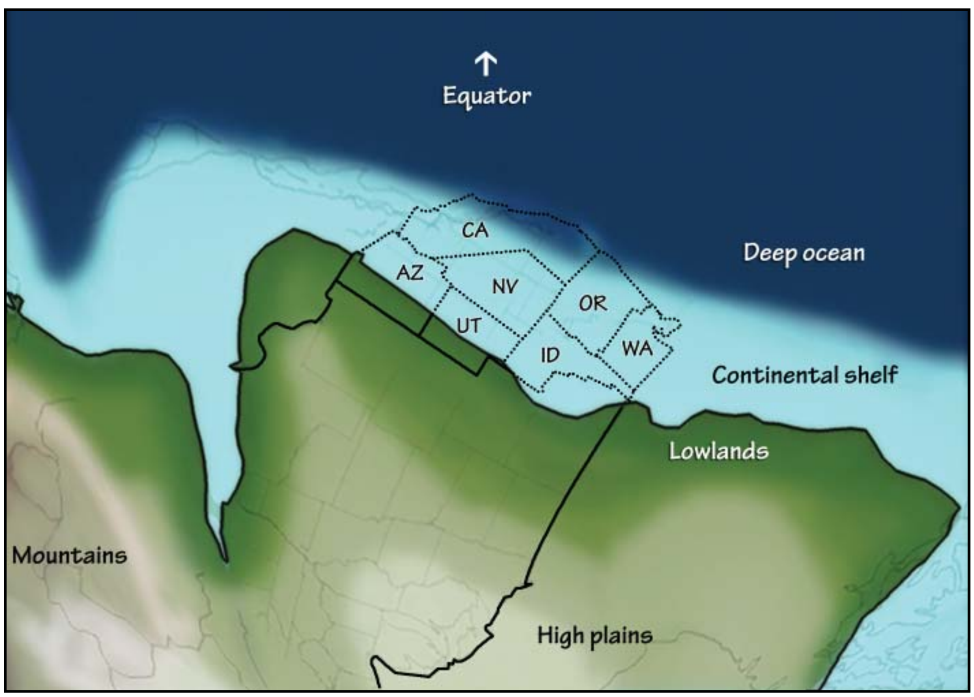


Figure 9.4: The Western United States at 600 million years ago. The entire continent is located in the southern hemisphere, near the equator.

in eastern California and Nevada provide evidence of warm, shallow seas. Sea level rose in the **Ordovician**, and both deep- and shallow-water marine deposits are known from that time. **Conodonts** and **graptolites** are found in deep-water deposits from northeastern Washington and shallow-water marine rocks throughout Nevada and southeastern California, revealing that the climate remained warm during the Ordovician. At the end of the Ordovician, from 460 to 430 million years ago, the Earth fell into another ice age, but corals found in California indicate it remained warm enough for tropical seas to exist there. **Silurian**-age rocks tell us much the same story.

See Chapter 3: Fossils to learn more about fossils of the West's ancient seas.

Alaska is almost entirely composed of ancient **terranes** and **volcanic island** arcs that drifted together at different times during Earth's history and had not assembled into anything resembling modern Alaska until the **Jurassic**. Most of these terranes appear to have experienced warm, wet climates, and geologists have concluded that they all originated in tropical areas of what is now the Pacific Ocean. Alaska's **Cambrian**- through Silurian-age rocks all formed on these tropical **microcontinents**. This is also true for much of central and western Washington, all of Oregon, and most of northwestern California, which formed in a similar manner as terranes and island arcs **accreted** onto the edge of the continent at its **subduction** zone.

From 430 to 300 million years ago, North America moved north across the equator, and the cycle of warming and cooling was repeated yet again. In the **Devonian**, sea level was higher than it had been earlier, but despite this, Devonian rocks are relatively scarce in the West, with small areas widely scattered across Nevada. The most extensive outcrops of Devonian rocks are located on the tropical accreted terranes, and include some very large reefs. Devonian rocks are also common in northern Alaska. These rocks include **carbonate** platforms, which are consistent with a low-latitude position and warm climate.

By the Early **Carboniferous**, ice capped the South Pole and began to expand northward. Although the Earth's temperature fell during this time and the frozen water far to the south caused sea levels to drop, the West still remained relatively warm because of North America's low-latitude position. Mountain building in Nevada raised the sea bottom, dividing the marine environment into shallow water to the east and deep water to the west. Nevada's shallow-water deposits contain reefs, indicating that the climate there was still warm. Later, in the **Permian**, these shallow areas became beaches and lagoons as sea level dropped. Carboniferous and Permian rocks in Oregon, northern California, western Washington, and Alaska originated on tropical terranes—some contain lush, tropical floras that are completely dissimilar to those on the main part of the continent, a testament to their continued isolation in the ocean far from the West (which had now become part of the supercontinent **Pangaea**). Carboniferous rocks in northern Alaska contain extensive carbonate platforms, which are indicative of a warm climate. Alaska's Permian rocks are also indicative of a marine environment.

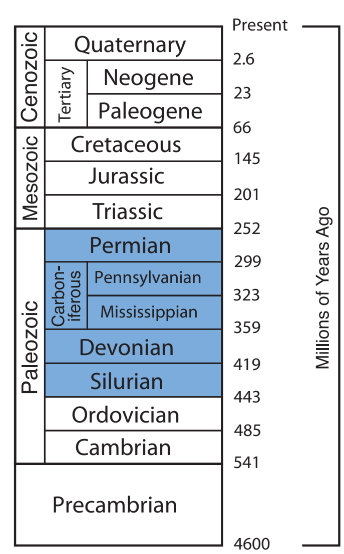
Around 220 million years ago, the West moved north from the equator. Pangaea, a supercontinent composed of nearly all the landmass on Earth, began breaking

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

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

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

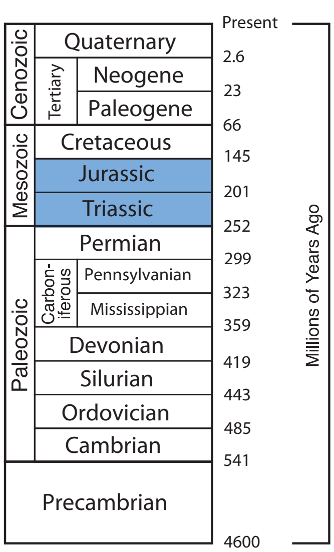
Pangaea *• supercontinent, meaning "all Earth," which formed over 250 million years ago and lasted for almost 100 million years.*



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

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

***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.*



up into continents that would drift toward their modern-day positions (*Figure 9.5*). The Earth remained warm until worldwide temperatures began to dip again, around 150 million years ago. At this time, the West was still largely underwater, but the Sierra Nevada Mountains had begun to form as a volcanic island arc close to the edge of the continent. Nevada's **Triassic** rocks contain both deep-water marine and terrestrial deposits—its Triassic seas were rich with **ichthyosaurs** and other marine reptiles, while its terrestrial rocks reflect the aridity and seasonality of the climate farther inland. As mountain building continued into the Jurassic, the seas became shallower, while terrestrial deposits expanded. By this time, terranes were beginning to collide with the continent—some of these collisions included volcanic islands ringed with corals, indicating that the climate remained warm. Similar island arcs formed close to what is now southern Alaska, where a very productive sea flooded the Triassic continental margin. The organic-rich rocks that formed in this sea are some of the most prolific source rocks for **oil** on Alaska's North Slope.

See Chapter 7: Energy for more information about the production and use of oil in Alaska.

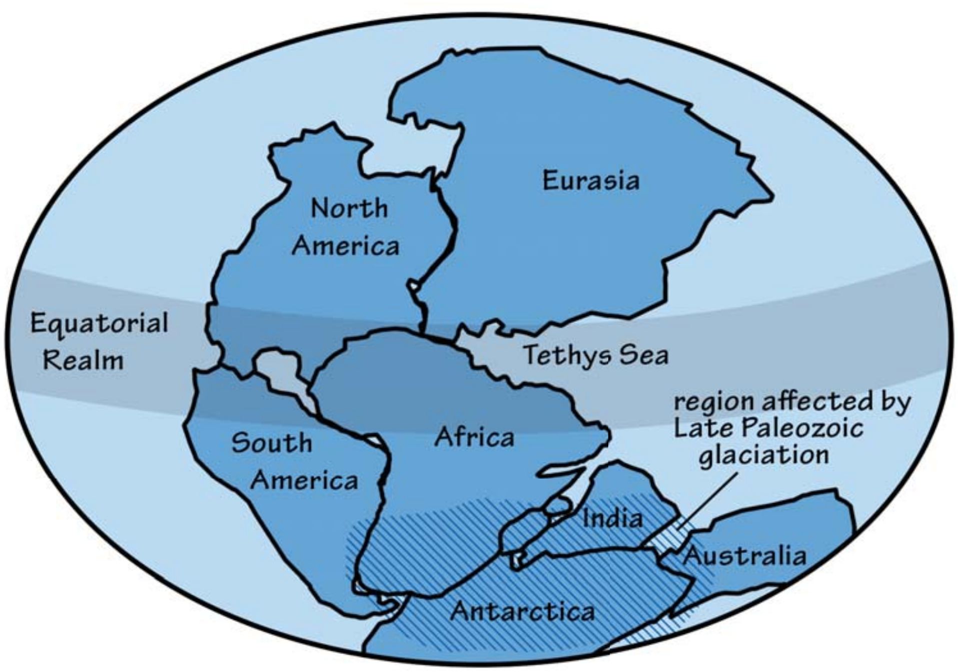


Figure 9.5: The break up of Pangea began around 220 million years ago.

Jurassic rocks are widely scattered through Oregon and Washington, where they contain coral-ringed volcanic arcs with associated deeper marine sediments. Jurassic rocks in California reflect both shallow-water marine and terrestrial environments. A large area of shallow-water marine deposits was laid down just off of the rising Sierra Nevada, in what is now the eastern Central Valley. The

Past

terrestrial rocks of southeastern California contain **ginkgos** and **cycads** that indicate a warm, moderately wet climate. Terrestrial Jurassic rocks in southern Nevada, however, show that the climate on land was still arid. Meanwhile, much of southern Alaska was assembled during the Jurassic as a series of island arcs and terranes collided with northern Alaska, which had now drifted into its current position and existed as a broad, flat shelf of shallow marine rocks.

The Earth warmed near the beginning of the **Cretaceous**, and sea level rose. Mountain building continued throughout the West with the formation of both the Sierra Nevada and the Rocky Mountains. **Erosion** predominated, and Nevada and Oregon have a very sparse record of Cretaceous sedimentation and climate; the few outcrops from this time period show that Nevada was terrestrial and Oregon was still largely marine. Washington has a slightly better record, showing that it too was still principally marine. Global climate was warm, but reefs did not form, probably due to the intense mountain building and erosion that shed a great amount of sediment into the interior embayments and the Pacific Ocean. Even though Alaska was closer to the North Pole than it is at present, fossil vegetation indicates that its climate was very similar to that of western Oregon today. Lush swamps and forests occupied lowland areas, and some swamps had become rich **coal** beds.

The climate cooled again at the end of the Cretaceous, 65 million years ago. This cooling had the greatest impact on northern Alaska, where fossilized forests resemble those found near Anchorage today. But after the end of the Cretaceous, the climate warmed once more—by around 50 million years ago, the West's climate was actually hot, with palm trees growing in southern Alaska! Alaska's northern forests once again grew to resemble those of modern forests much farther south. The sea withdrew from most of Oregon and Washington, and plant fossils are abundant throughout these states. One of the best records of the West's Cretaceous climate is found in Oregon's John Day fossil beds. Here, plant and animal fossils indicate that from 50 to 35 million years ago this area was home to a subtropical rainforest with banana and citrus trees. Fossil floras in western and north-central Washington tell a similar story, and palm trees were abundant. Between 35 and 20 million years ago, however, the climate became cooler and drier, and prairies and deciduous trees such as oak, maple, and alder flourished. This coincided with the initial **uplift** of the Cascade Range (37–7 million years ago), which began to create a rain shadow (*Figure 9.6*) to the east. The final uplift of the Cascades and Sierra Nevada created the intense rain shadow that is responsible for the aridity of eastern Washington, eastern Oregon, and Nevada today. Moist Pacific Ocean air moves eastward with the prevailing **winds**, and it 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 it warms as it moves down the eastern side of the mountain range, promoting evaporation.

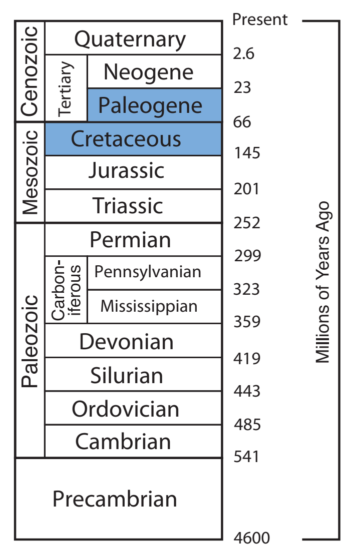
See chapter 3: Fossils for more about plants of the prehistoric West.

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.*

erosion *• the transport of weathered materials.*

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

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



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

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

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

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

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.*

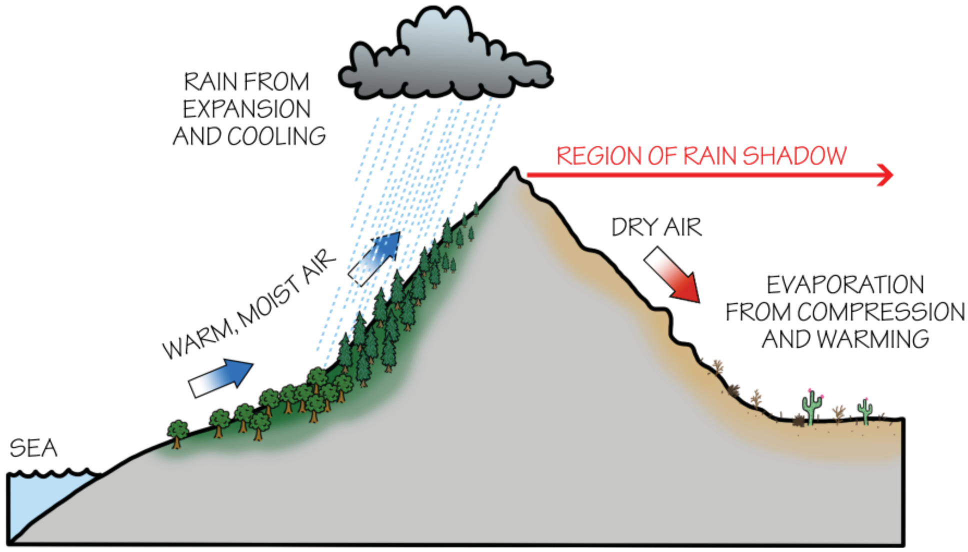


Figure 9.6: The key characteristics of a rain shadow.

Late in the **Cenozoic**, eruptions in eastern Oregon produced enormous amounts of **basalt** that flowed north and west, filling the Columbia River basin. These are some of the largest such eruptions in the history of the Earth, and they took place several times over a span of about 11 million years. While evidence that these eruptions influenced global climate is ambiguous, climatic changes are recorded in **soils** that formed atop some of the **lava** flows. These soils indicate a decrease in temperature after a period known as the Middle **Miocene** Climatic Optimum, a brief warming episode that occurred around 16 million years ago.

See Chapter 2: Rocks to learn more about the Columbia Flood Basalts.

Since 800,000 years ago, an equilibrium appears to have been reached between warming and cooling, with Earth's **ice caps** growing and retreating primarily due to the influence of astronomical forces. During the **last glacial maximum**, ice covered the northern part of Washington State (*Figure 9.7*). The ice sheet did not extend into central or northern Alaska since the local climate was very dry, though an ice cap covered the Brooks Range. During periods of ice advance, the West was colder than it is today, with extensive mountain glaciers occurring throughout the region; in fact, Yosemite Valley was carved out at this time. Microfossil evidence from the Rancho La Brea Tar Pits in Los Angeles tells us that southern California's climate around 40,000 years ago was similar to San Francisco's today.

See Chapter 3: Fossils for more on the Rancho La Brea Tar Pits.

Around 12,000 years ago, all of Washington east of the Cascades was inundated and scoured by numerous enormous, violent floods. These occurred when an ice sheet alternately blocked and retreated from what is now the Clark Fork River in northwestern Montana and northern Idaho. When the river was

Past

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

windward • *upwind; facing into the prevailing winds, and thus subject to orographic precipitation.*

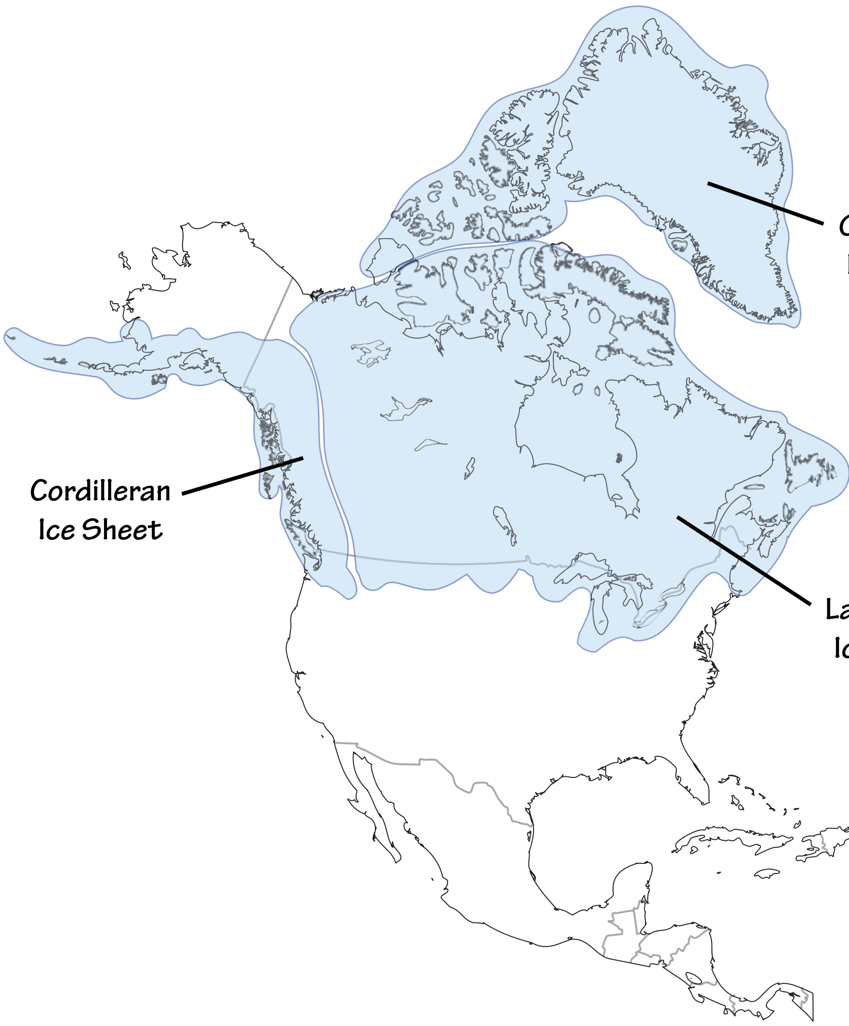


Figure 9.7: The maximum extent of the Cordilleran and Laurentide ice sheets across western North America and Alaska.

blocked, an enormous lake—Glacial Lake Missoula—built up behind the ice dam. When the ice dam later failed, the water was released catastrophically. These floods cut through the dust deposits and basalt that covered much of the region, leaving islands, escarpments, and channels so large that ground-based geologists did not at first recognize their origins.

The Hawaiian Islands began to form 11 million years ago, although most are younger than 7.5 million years. These islands formed from volcanoes erupting from the sea floor over what geologists call a **hot spot**. Hawai‘i has a poorly preserved paleoclimate record, probably because the landscape has been so active, with continuous volcanic eruptions and new lava flows covering the landscape as well as intense erosion occurring on the wetter, **windward** sides of the islands. Because of the

See Chapter 8: Soils to learn more about the soils of Hawai‘i.

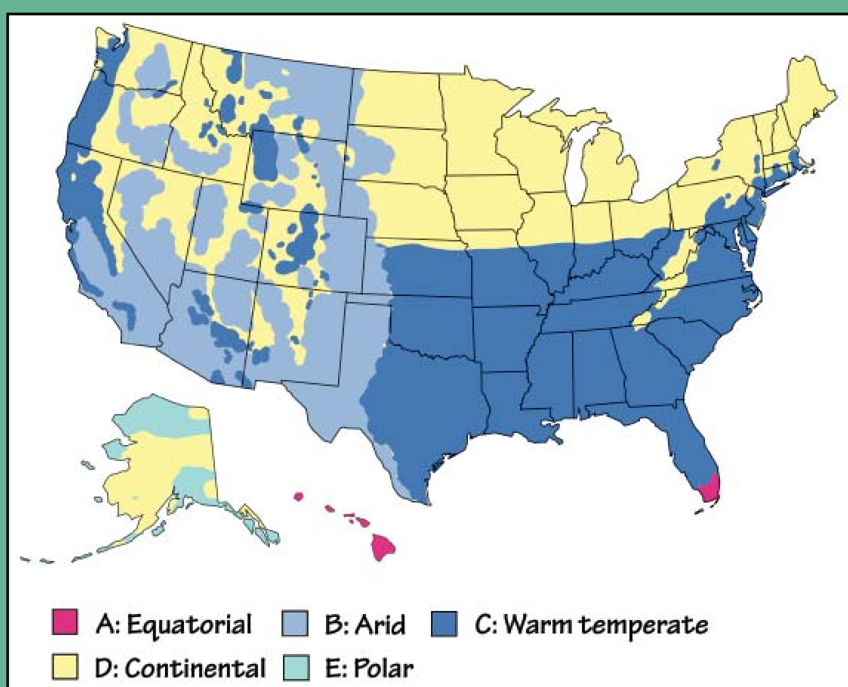
islands' latitudinal position, geological records found in the nearby deep sea, and the nature and depth of the soils formed on the long-exposed lava, we know that Hawai'i's climate has always been tropical to subtropical.

Present Climate of the Contiguous Western States

Because of its wide latitudinal range, the proximity of the Pacific Ocean, and the presence of long, north-south mountain ranges, the Western States have an enormous variety of climatic areas. These include hot, dry deserts in the Basin and Range, a Mediterranean climate along the southern Pacific Border,

The Köppen Climate Map

Wladimir Köppen developed a commonly used system of climate categorization based on the kinds of vegetation that 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.)

rainforests in the northern Pacific Border and Alaska, and tundra in Alaska's far north. Even individual states can have tremendous diversity—depending on which of the many **Köppen system** maps you refer to, the state of Washington alone contains as many as eight different climate types.

With such diverse climate types, a wide range of temperatures can be experienced throughout the West (*Figure 9.8*). Generally, temperatures tend to decrease northward (and also from west to east), with cooler temperatures at higher elevations and across the West's north-south mountain ranges. Temperatures in coastal areas are moderated by the Pacific Ocean and, in the northwest, by the Rocky Mountains, which prevent cold Arctic air from reaching the coast. Average lows and highs in Southern California range from 3° to 46°C

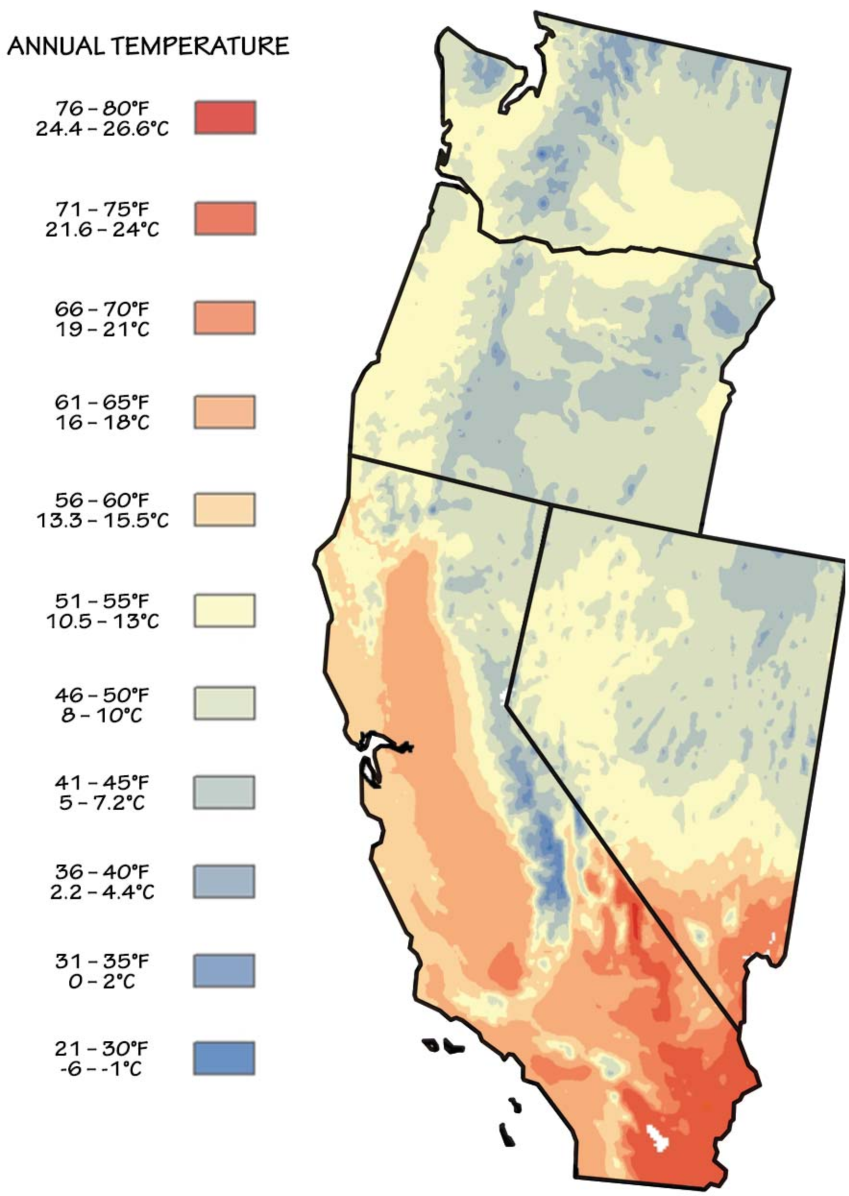


Figure 9.8: Mean annual temperature for the contiguous Western states. (See TFG website for full-color version.)

Present

__jet stream__ • a fast-flowing, narrow air current found in the atmosphere.

(37° to 114°F) inland in Death Valley and 9° to 24°C (49° to 76°F) on the coast in San Diego. Statewide average lows and highs in Oregon run from -3° to 28°C (26° to 82°F), while in Washington, temperature ranges from -1° to 32°C (29° to 89°F). Nevada experiences average temperatures spanning from 4° to 40°C (39° to 104°F)

The West's spectacular mountain ranges (apart from those in Alaska) run from north to south. These ranges—the Coastal Range, the Cascades, the Rockies, and the Sierra Nevada—create a pronounced east-west precipitation gradient across the Western states. The overall effect is to produce dry rain shadows on the eastern sides of the West's mountain ranges, and wet areas on the western sides (*See Figure 9.6*). This effect is most pronounced from Northern California up through Washington, since the **jet stream** is often located over this area—especially in winter—and brings moist ocean air inland. As an example of how extreme this precipitation gradient can be, Olympic National

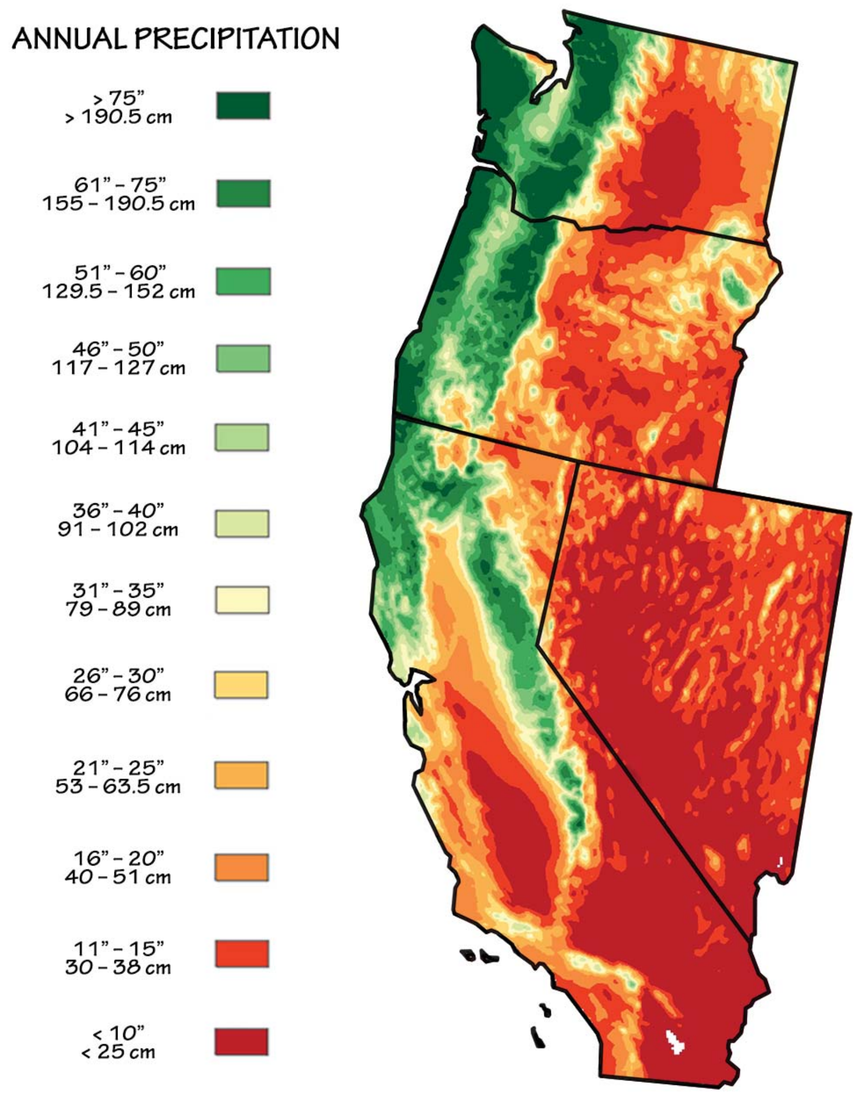


Figure 9.9: Mean annual precipitation for the West Coast. (See TFG website for full-color version.)

Park in Washington receives over 190 centimeters (75 inches) of rain annually on average, whereas communities only 400 kilometers (250 miles) to the east in Washington receive only 18 to 20 centimeters (7 to 8 inches) annually. As the most arid state in the US, Nevada receives only about 24 centimeters (9.5 inches) of rainfall a year (*Figure 9.9*).

Present Climate of Alaska

Alaska's climate, like that of other parts of the West, is influenced by its mountain ranges and its proximity to the ocean. Statewide averages range from a low of -20°C (-4°F) in January to a high of 11°C (52°F) in July (*Figure 9.10*). North of

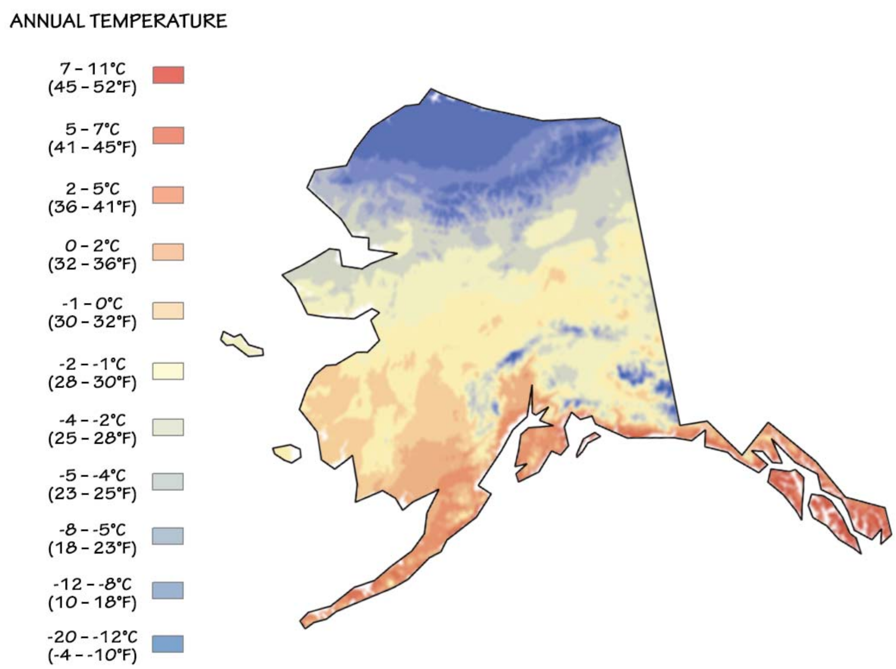


Figure 9.10: Mean annual temperature for Alaska. (See TFG website for full-color version.)

the Brooks Range, Alaska has a cold, dry, polar climate with frequent winter blizzards. Temperatures on the coast are moderated somewhat by the Arctic Ocean. Central Alaska has a dry continental climate, with a large variation between summer and winter temperatures. For example, the town of Takotna in Alaska's interior has an average low temperature of -27°C (-17°F) in January and an average high of 22°C (72°F) in July.

A third climate area exists in the Alaskan southeast, south coast, and southwestern islands, and in west-central Alaska in the summer. These areas have moderate temperatures—an average annual temperature of about 7°C

(45°F)—and high precipitation. Some areas are home to lush rainforests and receive around 500 centimeters (200 inches) of rain a year (*Figure 9.11*). The climate in west-central Alaska is influenced by a phenomenon that is unique in

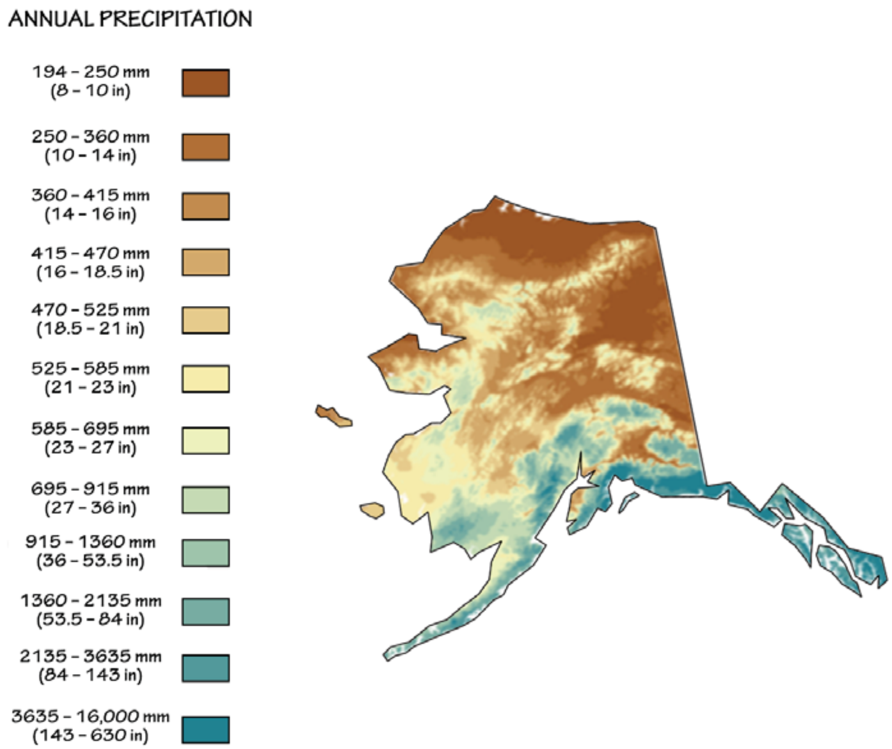


Figure 9.11: Mean annual precipitation for Alaska. (See TFG website for full-color version.)

the United States: the seasonal presence of sea ice. In the winter when sea ice covers the Bering Sea, this area loses the moderating effect of open water and has a continental climate. When the sea ice melts in summer, the climate returns to a warmer, more humid maritime state.

Figure 9.12: Melting permafrost has caused a house in Shishmaref, Alaska to topple; on the Alaska Highway, permafrost subsidence caused the road to collapse under the weight of a pickup truck.

Climate 9

Hawaiʻi

The lives of the West's residents are tied to climate in critical ways. People in Southern California's coastal area and Central Valley enjoy a pleasant climate, but they depend on water from elsewhere—mostly from snowmelt—for their everyday needs and for agricultural irrigation. At the time of this writing in 2014, California is in the midst of an extreme drought, and 10% of the state is in exceptional drought, the most severe possible. In Alaska, infrastructure such as roads, buildings, and oil pipelines built on **permafrost** is vulnerable to a warming climate, since the land surface develops bumps and pits when permafrost melts (*Figure 9.12*). Climate is also linked to energy resources—in the Pacific Northwest, the combination of **topographical** variation and abundant precipitation creates an ideal environment for hydropower.

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.*

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

trade winds • *a major tropical wind system, involving the flow of high-pressure subtropical air to the low-pressure equatorial zone.*

Present Climate of Hawaiʻi

The eight main Hawaiian Islands stretch between 19° and 22° north latitude. This places them within the tropics, and also within the belt of persistent northeast **trade winds** (*Figure 9.13*). This geography, combined with the high topography of many Hawaiian peaks, gives rise to large variations in climate across the islands—Hawaiʻi Island alone has some of the most extreme climate gradients of any place on earth.. Additionally, as half of the land area of Hawaiʻi lies within eight kilometers (five miles) of the ocean, the ocean is an important control on climate.

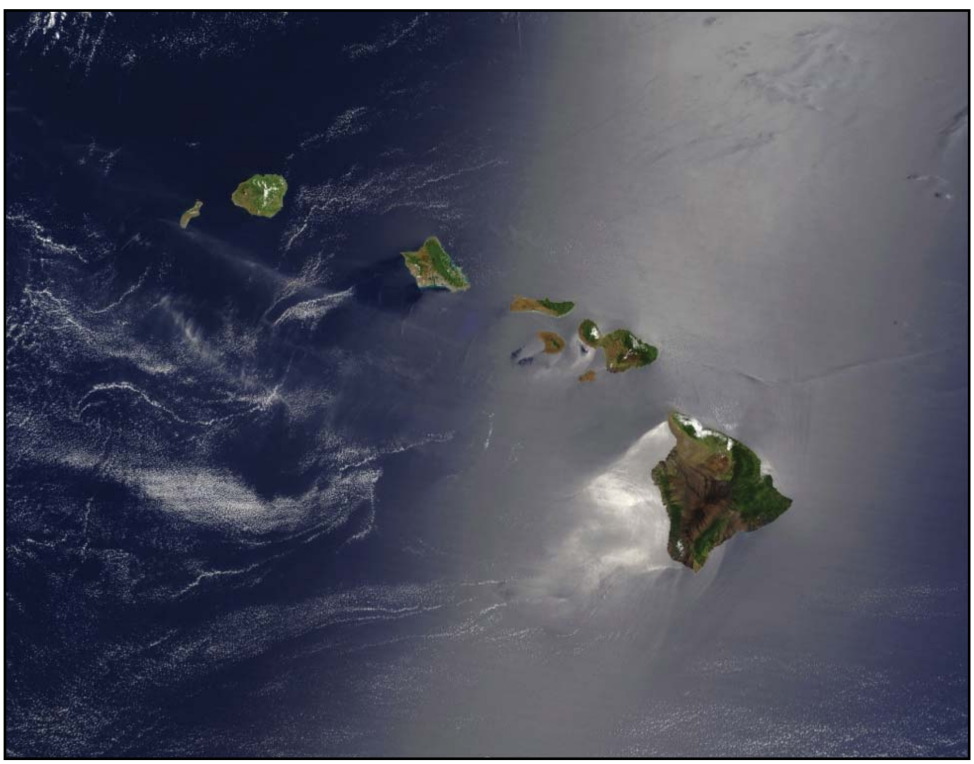


Figure 9.13: The effect of the northeast trade winds is seen in the shiny, highly reflective, calm water southwest of Hawaiʻi Island, where the ocean lies in the lee of the island's big volcanoes.

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

Effect of the Ocean

Hawai‘i is a small archipelago in the center of the world’s largest ocean. Water has a very high **heat** capacity (i.e., a lot of energy is required to raise the temperature of water). This means that the annual temperature variation of the ocean is small. Around the Hawaiian Islands the ocean surface temperature falls between 24°C (75°F) in winter and 27°C (81°F) in summer. The seasonal variation in land surface temperature for coastal Hawai‘i is similar, about 5°C (9°F) from winter to summer. In a continental setting the seasonal land temperature variation would be much larger; for example, in Chicago the seasonal variation is 25°C (45°F). Thus the ocean dominates climate in Hawai‘i’s coastal areas.

Effect of Latitude

As mentioned earlier, Hawai‘i lies between 19° and 22° north latitude, just south of the Tropic of Cancer. At this latitude, the global circulation of the atmosphere plays a significant role in climate. Incoming sunlight warms the Earth’s surface, and it does so year-round at equatorial latitudes. The air directly above the surface is warmed and rises. The rising air expands and then cools, allowing water vapor to condense and fall as rain; worldwide equatorial latitudes are therefore characterized by meteorological low pressures and high rainfall (*Figure 9.14*). The rising air also flows poleward when it reaches neutral buoyancy with

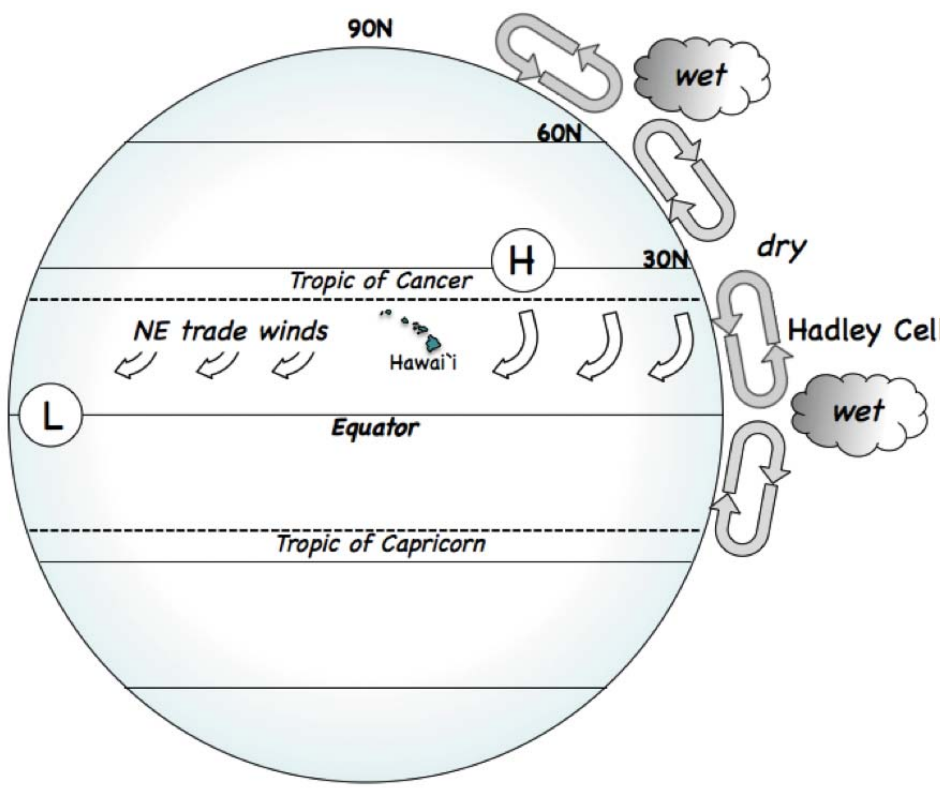


Figure 9.14: Aspects of general atmospheric circulation important for Hawai‘i’s climate. The islands lie within the tropics, in a belt of persistent northeast trade winds, and beneath the descending limb of the Hadley circulation cell. A stable high-pressure system—the North Pacific Anticyclone (H)—remains north-northeast of the islands throughout the year.

its surroundings, where it continues to cool and eventually becomes denser and sinks. This occurs at a latitude of ~30° in both hemispheres. The sinking air is **compressed** and consequently warmed, and so it becomes strongly undersaturated with water vapor and has a low relative humidity. Near the latitudes of 30°N and 30°S are zones of high pressure and exceptionally dry climate, Earth's "desert" latitudes. At the surface, the air completes its circuit by flowing back toward the equator. The surface airflow is deflected westward by the Earth's rotation, creating the trade winds. This circulation pattern is known as a **Hadley cell**—named after 17th century meteorologist George Hadley—and is an important part of atmospheric circulation.

Hawai‘i, in the northern tropics, is located beneath the descending limb of the Hadley cell. Thus, the air above the islands warms as it approaches the surface, with a temperature gradient running from warm to cool air with increasing altitude. At the same time, the air heated by contact with the warm earth surface also cools with increasing altitude. Most of the time (80–90% of days) these two cooling trends are not continuous, and there is instead a temperature discontinuity located at an altitude of about 2000 meters (6000 feet). This arises from the more rapid cooling rate of the moist lower air relative to the cooling rate of the dry upper air. This discontinuity is called the **trade wind inversion** (*Figure 9.15*). The inversion is easily seen from any vantage point in the islands, as it creates a ceiling for cloud formation (*Figure 9.16*). Because of this control on cloud position, the inversion also functions as a control on the distribution of rainfall across the islands.

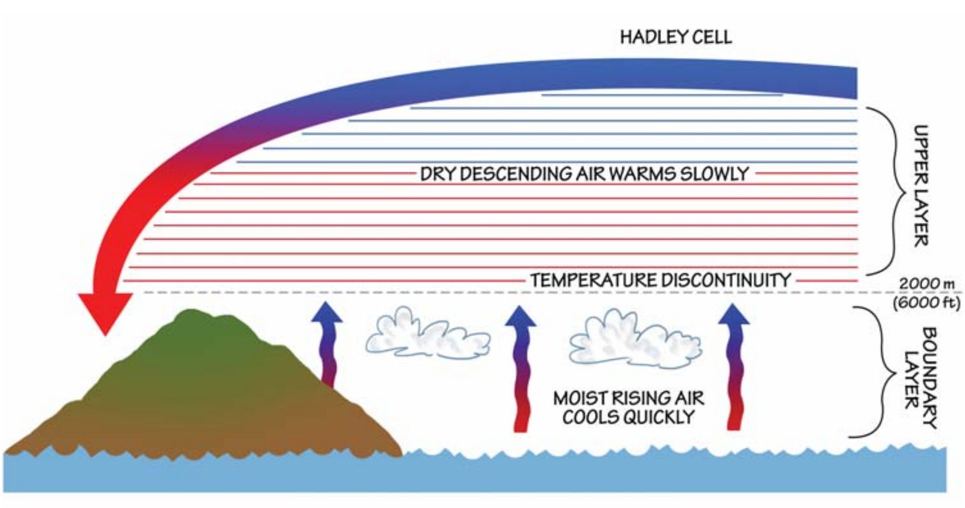


Figure 9.15: The rate of cooling of moist boundary layer air is faster than the rate of warming of dry descending Hadley cell air. The temperature (density) discontinuity prevents boundary layer air from mixing with upper layer air, and so it creates an upper ceiling for cloud formation.
(See TFG website for full-color version.)

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

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

boundary layer *• the atmospheric layer closest to the surface of the Earth, which has a high relative humidity and is affected by the Earth’s heat and moisture.*

leeward *• downwind; facing away from the wind.*

orographic precipitation *• rainfall caused when wind pushes a mass of humid air up the side of an elevated land formation like a mountain.*

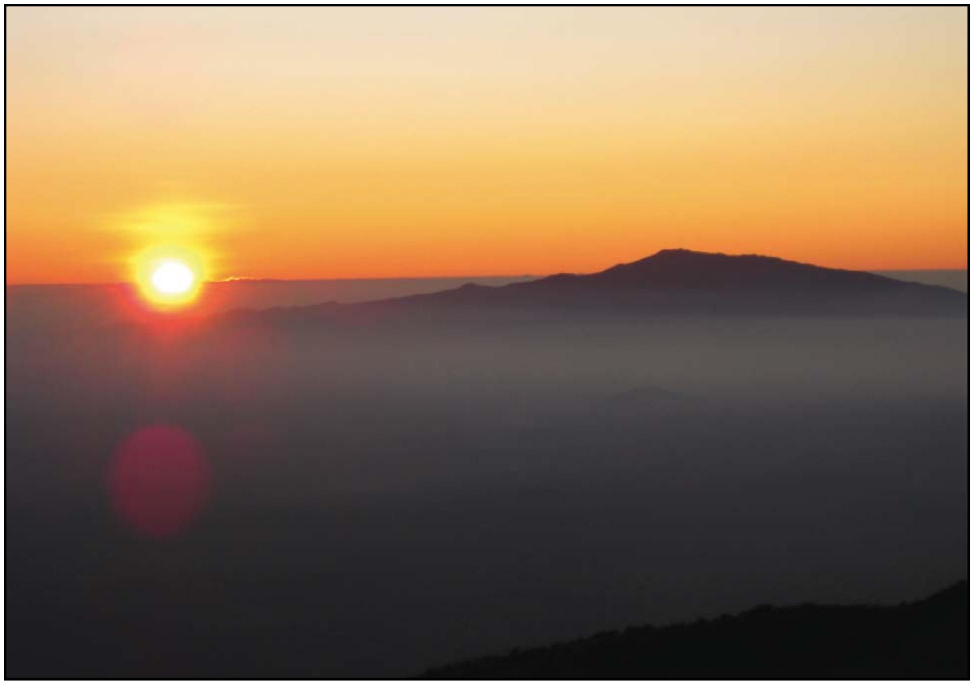


Figure 9.16: Trade wind inversion. The summit of Hualālai, at sunset, rises above the inversion layer while hazy and humid boundary layer air remains below. The Hualālai summit is 2521 meters (8271 feet), and here the inversion is ~1980 meters (~6500 feet).
(See TFG website for full-color version.)

Effect of Topography

The most interesting control on the climate of Hawai‘i is the high topographic **relief** of the islands. The islands of Hawai‘i, Maui, Kaua‘i, Moloka‘i, and O‘ahu all have summits that are above 1200 meters (4000 feet) in elevation. On Hawai‘i Island the peaks of Mauna Kea and Mauna Loa are each above 4180 meters (13,700 feet). Without these summits, Hawai‘i would be a warm and humid place with relatively low rainfall. However, the presence of these huge mountains changes the local climate dramatically, which, in turn, leads to the great diversity of climate zones found in Hawai‘i (*Figure 9.17*).

The air above the ocean—the **boundary layer**—has a high relative humidity because it is in contact with the warm tropical ocean. Northeast trade winds carry this moisture-laden air to the Hawaiian Islands. The mountainous islands divert the airflow both around and over the topographic obstructions. Air that rises over the mountains expands and cools, and the moisture acquired from the ocean condenses and rains out. The windward sides of each island are therefore places with frequent and abundant precipitation (*Figure 9.18*). As the air continues down the **leeward** slopes it is at first compressed, and subsequently warms, and no additional moisture condenses; the leeward island shores are therefore very dry. This topography-induced upward airflow creates **orographic precipitation** on windward slopes and a rain shadow on the leeward side. On most of the Hawaiian Islands, the maximum rainfall occurs at 610–910 meters (2000–3000 feet) above sea level, although the two wettest spots in the islands are slightly higher in elevation. Wai‘ale‘ale on Kaua‘i (1570 meters [5150 feet]) and Big Bog on Maui (1650 meters [5400 feet]) vie with each other for the title

of wettest spot in the US, and indeed at ~1000 centimeters (~400 inches) of annual rainfall they are two of the wettest spots on Earth.

Areas of high topography are dry, as the trade wind inversion prevents clouds from rising high enough for orographic precipitation to occur there. The high summits and leeward slopes receive most of their annual precipitation during winter storms, when high-altitude, low pressure systems develop in the subtropics. These *kona* (Hawaiian for leeward) storms bring extended periods of rain and even snow (the latter on the summits of Mauna Kea, Mauna Loa, and Haleakalā).

Climate Gradients

Ocean, atmosphere, and topography interact in Hawaiʻi to make the islands a land of diverse climate with extreme climate gradients. The maps of rainfall and temperature distribution in Hawaiʻi (s*ee Figures 9.17* and *9.18*) clearly show the range and proximity of these variations. On Maui, the distance is only 32 kilometers (20 miles) from Big Bog (the wettest location, with 1029 centimeters [405 inches] per year) to Kihei (the driest, at 28 centimeters [11 inches] per year). On Kauaʻi the distance from the wettest spot, Wai'ale'ale

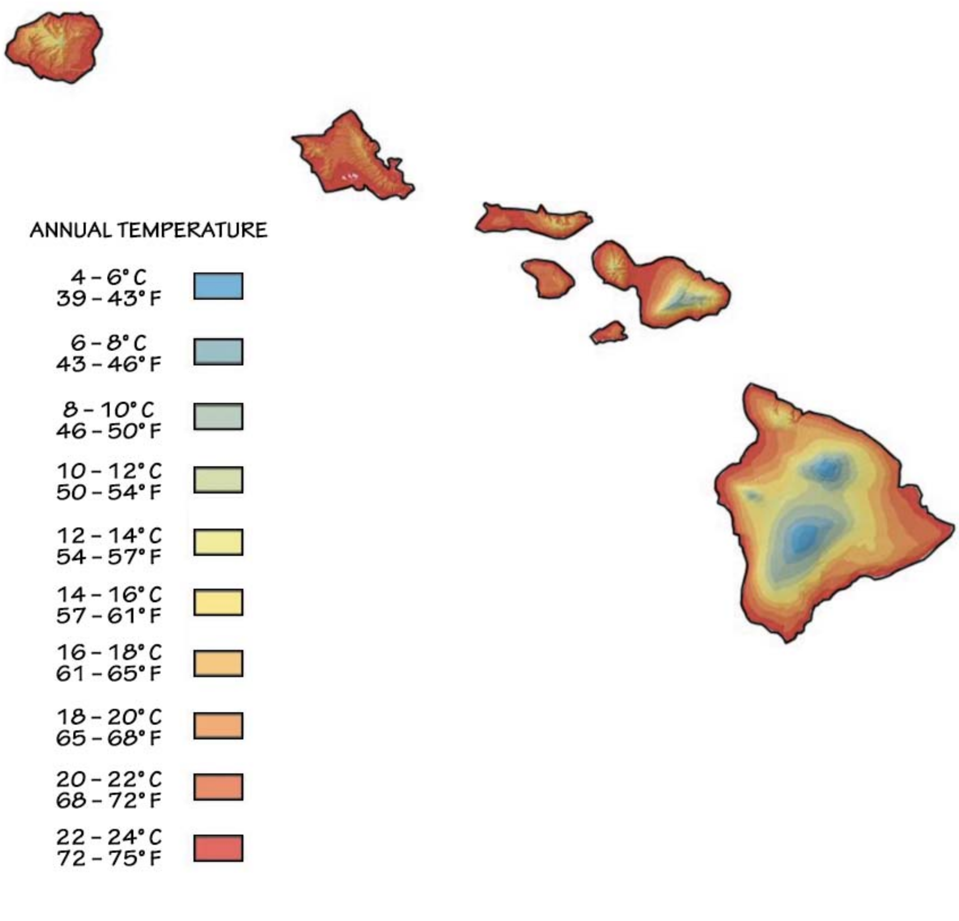


Figure 9.17: Mean annual air temperature in Hawaiʻi. Air temperature is inversely related to elevation. Thus the temperature variations map large-scale topographic features as well. (See TFG website for full-color version.)

(1143 centimeters [450 inches] per year) to the driest spot, Polihale Beach (46 centimeters [18 inches] per year), is only 26 kilometers (16 miles). This gives Kaua‘i a rainfall gradient of 38 centimeters per year per kilometer (24 inches per year per mile). Superimpose this gradient onto New York City, with its rainfall level of 127 centimeters (50 inches) per year: could we imagine a desert just three kilometers (two miles) west of Central Park?

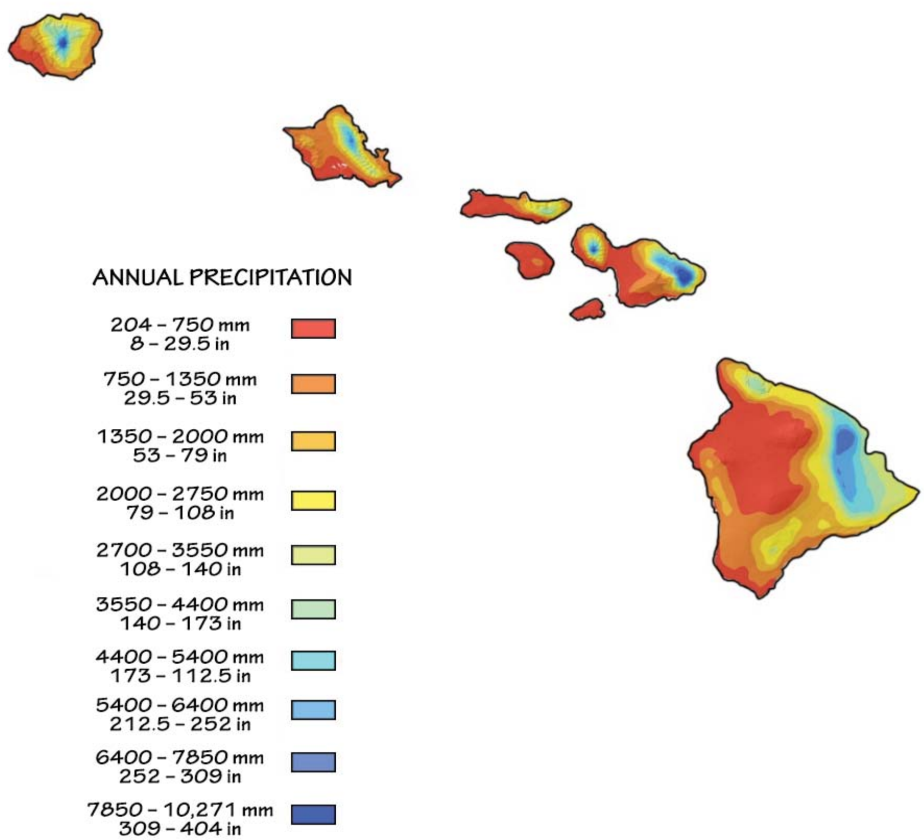


Figure 9.18: Mean annual rainfall in the Hawaiian Islands. Northeast trade winds combine with topography to create a strongly asymmetrical rainfall distribution. Leeward (west) areas receive little rainfall while windward (east) slopes are some of the wettest places on Earth. (See TFG website for full-color version.)

Large changes over short distances characterize the Hawaiian Islands and drive natural processes as well as human activity. Rates of weathering and erosion are much higher in areas of high rainfall. Therefore the islands' windward slopes are more deeply incised by stream erosion. In dry areas erosion rates are lower; however, episodic winter storms can lead to large sediment loads discharged to the ocean from arid areas with little vegetative cover. Sedimentation events have a negative impact on coral reefs, as the corals require clear, sediment-free water for optimal growth. The proximity of different climate regimes gives Hawai‘i a highly diverse set of ecosystems. As colonizing organisms move into

parent material *• the original geologic material from which soil formed.*

endemic *• native to a particular geographic area or range.*

sustainable *• able to be maintained at a steady level without exhausting natural resources or causing severe ecological damage, as in a behavior or practice.*

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

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

the numerous different ecological niches, they undergo an **adaptive radiation** of species, resulting in one of the most highly **endemic** and unique groups of organisms on the planet. Rates of soil formation are also dependent on climate. Sufficient weathering is required to break down **parent material**, yet too much weathering will remove nutrients, ultimately rendering soils infertile. Native ecosystems, as well as agricultural systems, function best in conditions of optimal rainfall and soil fertility, yet these parameters can and do change over very short distances.

See Chapter 8: Soils to learn more about the effect of weathering on the soils of Hawai‘i.

Climatic diversity and steep climate gradients make Hawai‘i a unique natural laboratory for basic scientific research and applied agricultural research. The high-altitude, cloud-free summits of Mauna Kea and Mauna Loa are ideal sites for astronomical and atmospheric research, respectively. These same climatic features draw tourists from around the world and influence the development of human communities in the islands. Not surprisingly, most development occurs on the sunny leeward sides of the islands, but, unfortunately, most water resources are found on the windward sides. This paradox is both a problem and an opportunity for **sustainable** resource management, both now and in the future.

Climate Change

Hawai‘i’s steep climate gradients also provide a unique opportunity to study the effects of **climate change**. When global temperatures rise or fall, Hawai‘i’s ecosystems migrate up or down the mountainsides. This phenomenon can be observed for past climates through the analyses of fossil pollen grains. During glacial epochs, the summits of Mauna Kea, Mauna Loa, and Haleakalā were covered by ice caps. Clear evidence of glaciation is seen on the slopes of Mauna Kea today, where terminal **moraines** mark the maximum extent of ice, 18,000 years ago. Additionally, ancient **sand** dunes—now **lithified** to calcareous **sandstone**—mark the position of sea level highstands during **interglacial** periods.

Climate scientists have long identified the summits of Hawaiian volcanoes as ideal sites for atmospheric study. In 1956, NOAA established the Mauna Loa Observatory (MLO) at an elevation of 3500 meters (11,500 feet) on the north flank of Mauna Loa. MLO is well above the trade wind inversion, and it is located more than 3200 kilometers (2000 miles) from any continental landmass. Instrumentation at MLO therefore samples very clean air in the upper atmosphere, and MLO is the oldest and most important baseline station for analysis of atmospheric composition.

Atmospheric carbon dioxide is among the many parameters measured at MLO. The CO_2 record extends from 1958 to present, and it shows the influence of both natural and **anthropogenic** processes (*Figure 9.19*). 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, while CO_2 accumulates in the atmosphere during

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

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

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

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

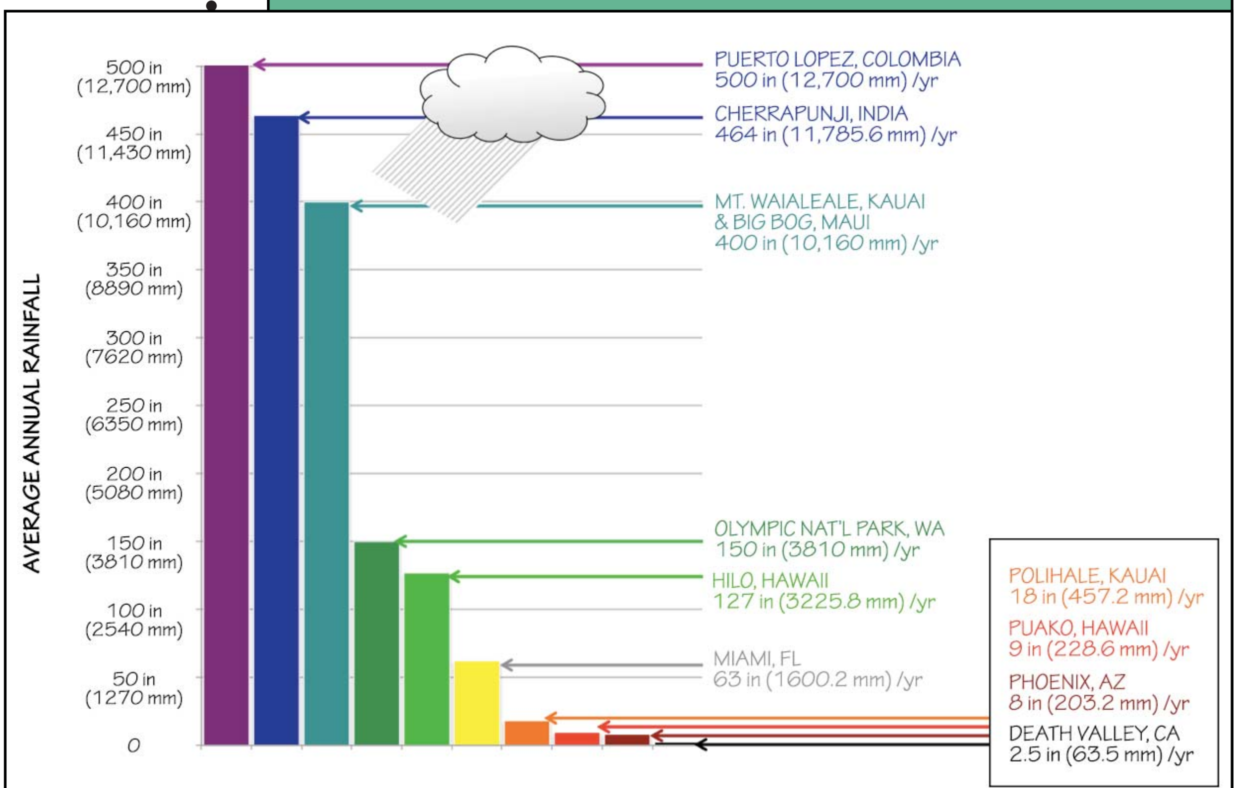
anthropogenic • *caused or created by human activity.*

9 Climate

Hawai‘i

Rainfall Extremes

Two locations in Hawai‘i—Mt. Wai‘ale‘ale on Kaua‘i and the more recently monitored Big Bog on Haleakalā, Maui—average 1029 cm (405 inches) of annual rainfall. Many areas on the islands' leeward coasts receive less than 50 cm (20 inches) of annual rainfall. The village of Puakō on Hawai‘i's *kona* coast averages 23 cm (9 inches) per year and is the driest inhabited spot in the islands, while the summit of Mauna Kea receives only 20 centimeters (8 inches) per year—the driest place in the state, with the same rainfall as Phoenix, Arizona.



(See TFG website for full-color version.)

The truly remarkable aspect of this large variation in rainfall is the short distance that separates rainy and dry areas in Hawai‘i. The wettest (Big Bog) and driest (Mauna Kea) places in Hawai‘i are only 121 kilometers (75 miles) apart. On the continental US, Olympic National Park in

Washington is the rainiest spot (380 centimeters [150 inches] per year) while Death Valley, California, is the driest (6.4 centimeters [2.5 inches] per year). This variation in rainfall is not nearly as large as that measured in Hawaiʻi, and the two locations are 1450 kilometers (900 miles) apart.

Globally, the rainiest places on Earth are on the windward slopes of the world's largest mountain ranges. Puerto Lopez de Micay, Colombia, is in the Andean foothills, while Cherrapunji, India, receives orographic rainfall from moist air flowing during the monsoon season from the Indian Ocean to the Himalayas. Cherrapunji has only recently had its title as the "Rainiest Spot on Earth" washed away by Puerto Lopez, but it still holds the record for most rainfall in a single year: 2647 centimeters (1042 inches) in 1961.

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

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 CO_2 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 MLO data from Hawaiʻi are our oldest and most reliable direct measurements of anthropogenic atmospheric change.

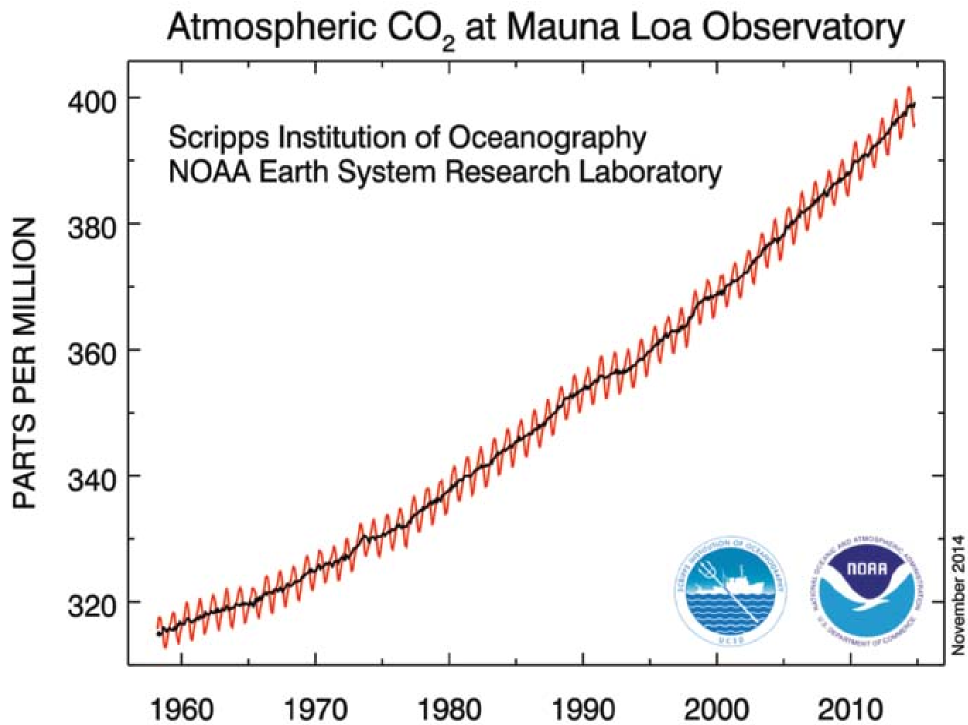


Figure 9.19: Measured concentration of atmospheric carbon dioxide (1958 to present) at MLO.

Future Climate of the West

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 towards 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.

See Chapter 6: Glaciers for more about interglacial periods.

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. The burning of fossil fuels and removal of forests are the main human activities that alter the composition of the atmosphere. Most dramatically, we are adding huge amounts of carbon dioxide and other greenhouse gases, which trap heat radiated by the Earth. Since plants remove CO_2 from the atmosphere, deforestation compounds the issue.

It is extremely difficult to predict the outcome of putting increasing amounts of carbon (as CO_2) into the atmosphere, but there are several important reinforcing effects already being observed. The increasing heat is causing glaciers and sea ice around the globe to melt, and as the ground and ocean they covered is exposed, these darker surfaces absorb and re-radiate increasing amounts of heat.

As permafrost in high latitudes melts, the carbon in the soils will become free to enter the atmosphere and, worse, to be converted by bacteria into the even more potent greenhouse gas, methane. Less directly, higher temperatures lead to more frequent and severe droughts, which, in turn, lead to more wildfires that release carbon and **aerosols** into the atmosphere. Aerosols can have a cooling effect as they reflect away radiation from the sun, but they can also pose a public health hazard.

Water is extremely good at absorbing heat: water vapor is 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 linger in the atmosphere for years.

The West contributes significantly to climate change. The population of any industrialized and particularly wealthy country produces pollution. The more than 54 million residents of the West 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 Western states, California emits by far the most greenhouse gases. In 2011 California was the second highest greenhouse gas emitter in the nation, behind only Texas, and the majority of its emissions came from transportation.

On the other hand, Western states are making changes to reduce human impact on the climate. The city of Seattle was an early adopter of 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, Washington, California, and Oregon are the top three producers of **renewable** electric energy in the nation.

aerosol • *tiny solid or liquid particles in the air.*

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.*

hectare • *a metric unit of area defined as 10,000 square meters.*

Trends and Predictions

Studies show that the West's climate is changing right now, and that change has accelerated in the latter part of the 20th century. These changes include the following:

- Temperatures in the West have increased in the last 25 years during all seasons.
- Nighttime temperatures in the Southwest have increased by almost 1.7°C (3°F) since 1900.
- The average annual number of wildfires of over 400 **hectares** (1000 acres) has doubled in California since the 1970s.
- The freeze-free season in the Northwest is on average 11 days longer for the period of 1991–2010, compared with that of 1961–1990.
- Heavy downpours have increased by 18% in the Northwest from 1948 to 2006.
- Statewide average temperatures in Alaska have increased, with winter temperatures increasing the most: up 3.2°C (5.8°F) from 1949 to 2011.

Climate models predict that the West's climate will continue to warm, and that the average annual temperature will rise by 2° to 6°C (3° to 10°F) by the end of the 21st century. In Alaska, temperatures are expected to rise more rapidly, by 2° to 4°C (3.5° to 7°F) by the *middle* of the 21st century. These increased temperatures lead to a whole host of other effects, including drier soils from more evaporation, the increased likelihood of drought and fires, and more rain (rather than snow) in the winter.

Water supply is a critical issue in the West, and communities will need to adapt to changes in precipitation, snowmelt, and runoff as the climate changes. Models predict that winter and spring storms in Nevada will shift northward, dropping less rain and snow in already arid areas. California will likely be faced with less water flowing in its rivers, declining high elevation forests, and expanding grasslands, along with increased pressure on the water supply for agriculture and cities (*Figure 9.20*).

The Northwest is expected to see less summer precipitation and more winter precipitation, and more of the winter precipitation falling as rain rather than snow. Over the past 40 to 70 years, the Cascade Range has experienced a 25% decline in snowpack measured on April 1, a trend that is expected to continue. This means less water from snowmelt in the warm season. Spring runoff in Northwestern streams is expected to occur nearly 20 to 40 days earlier during the 21st century. Sea level rise from melting glaciers and the thermal expansion of a warmer ocean will be a concern for cities such as Seattle, Tacoma, and Olympia (*Figure 9.21*).

Figure 9.20: This lake near San Luis Obispo, California contains barely any water following a several-year drought.

Climate models project that Alaska will receive more precipitation, but that soils will actually become drier due to increased evaporation from warmer air temperatures. Summers are expected to support a longer growing season, and also to see more drought and wildfires. Invasive insects that damage Alaskan

Future

trees will be better able to survive warmer winters, and will therefore increase and spread. Sea ice will cover the ocean for shorter portions of the year, possibly changing the distribution of plankton blooms, a part of the marine food chain upon which Alaska's fisheries depend.

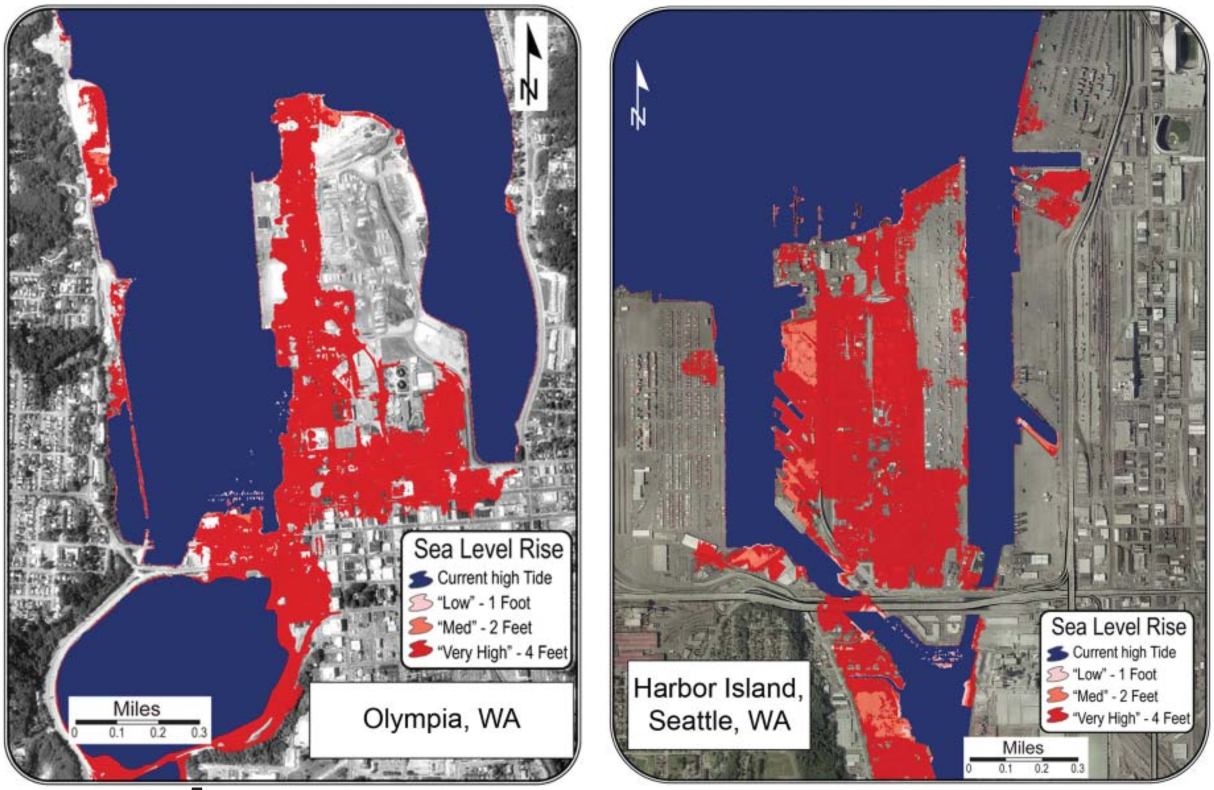


Figure 9.21: Maps showing portions of the cities of Olympia and Seattle, Washingrton that will be inundated if sea level rises by one, two, or four feet. (See TFG website for full-color version.)

Hawai'i stands to be significantly impacted by climate change, with serious potential effects on both its ecosystems and economy. Rising temperatures could disrupt the pattern of trade winds, changing rainfall patterns across the islands and creating periods of flooding or drought. Higher temperatures will also place more stress on native plants and animals, enabling the proliferation of invasive species that are better able to withstand temperature extremes. Warming oceans and increased ocean acidity could trigger massive coral die-offs as well as affecting ocean circulation. Finally, sea level rise could inundate much of Hawai'i's coastline—the worst case scenario of a 2-meter (6-foot) sea level rise would bring Hawai'i's coast 1.6 kilometers (1 mile) inland in some places, submerging or eroding important economic locations like Waikiki Beach and parts of Honolulu.

Resources

Books

Allmon, W. D., T. A. Smrecak, & R. M. Ross, 2010, *Climate Change—Past Present & Future: A Very Short Guide*, Paleontological Research Institution, Ithaca, NY, 200 pp.

Committee on the Importance of Deep-Time Geologic Records for Understanding Climate Change Impacts, 2011, Understanding Earth's deep past lessons for our climate future, National Academies Press, Washington, DC, http://www.nap.edu/download.php?record_id=13111.

Karl, T. R., J. M. Melillo, & T. C. Peterson (eds.), 2009, *Global Climate Change Impacts in the United States*, Cambridge University Press, Cambridge, NY, 188 pp, http://downloads.globalchange.gov/usimpacts/pdfs/climate-impacts-report.pdf.

Melillo, J. M., T. C. Richmond, & G. W. Yohe (eds.), 2014, *Climate Change Impacts in the United States: The Third National Climate Assessment*, US Global Change Research Program, 841 pp, http://www.globalchange.gov/nca3-downloads-materials.

Ruddiman, W. F., 2014, *Earth's Climate: Past and Future, 3rd edition*, W. H. Freeman, New York, 445 pp.

Websites: General Resources on Climate

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, & S. Kluge, SERC Earth Exploration Toolkit, http://serc.carleton.edu/eet/envisioningclimatechange/index.html.

Global Climate Change: Vital Signs of the Planet, NASA, http://climate.nasa.gov. (Climate data particularly from satellite-based remote sensing.)

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 Warming and Hurricanes, Geophysical Fluid Dynamics Laboratory, 2013, http://www.gfdl.noaa.gov/gloval-warming-and-hurricanes.

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 Hurricane Data Center, National Oceanographic and Atmospheric Administration, http://www.nhc.noaa.gov. (News on current hurricane forecasts.)

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/.

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

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.

U.S. 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.)

Websites on State- or Region-specific Climate Resources

The Age of Western Wildfires, Climate Central Sept. 18, 2012, http://www.climatecentral.org/news/report-the-age-of-western-wildfires-14873.

Alaska PaleoAtlas Glacier: A Geospatial Compilation of Pleistocene Glacier Extents, by W. Manley & D. Kaufman, Institute of Arctic and Alpine Research (INSTAAR), University of Colorado, Boulder, http://instaar.colorado.edu/groups/QGISL/ak_paleoglacier_atlas/.

Burt, C. C., 2012, New wettest location for the U.S.A. discovered? Wunderground May 15, 2012, http://www.wunderground.com/blog/weatherhistorian/new-wettest-location-for-the-usa-discovered.

Climate and Topography [of California] by E. Kauffman, Atlas of the Biodiversity of California, http://www.dfg.ca.gov/biogeodata/atlas/pdf/Clim_12b_web.pdf.

Climate change impacts, the Northwest (WA, OR, ID), http://climatenexus.org/wp-content/uploads/2013/06/ClimateChangeImpactsNW.pdf.

Climate impacts in Alaska, Climate Change Impacts and Adapting to Change, Environmental Protection Agency, http://www.epa.gov/climatechange/impacts-adaptation/alaska.html.

Climate impacts in the Northwest [includes Oregon, Washington], Climate Change Impacts and Adapting to Change, Environmental Protection Agency, http://www.epa.gov/climatechange/impacts-adaptation/northwest.html.

Climate impacts in the Southwest [includes California], Climate Change Impacts and Adapting to Change, Environmental Protection Agency, http://www.epa.gov/climatechange/impacts-adaptation/southwest.html.

Climate impacts in the U.S. Tropical Islands, Climate Change Impacts and Adapting to Change, Environmental Protection Agency, http://www.epa.gov/climatechange/impacts-adaptation/islands.html.

Giambelluca, T. W., Q. Chen, A. G. Frazier, J. P. Price, Y.-L. Chen, P.-S. Chu, J. K. Eischeid, & D. M. Delparte, 2013, Online rainfall atlas of Hawai‘i, *Bulletin of the American Meteorological Society,* 94: 313–316, doi: 10.1175/BAMS-D-11-00228.1.

Western Regional Climate Center, http://www.wrcc.dri.edu/. (A wide variety of weather and climate data and state-by-state climate narratives.)

Chapter 10: Earth Hazards of the Western US

Natural hazards are events that result from natural processes and that have significant impacts on human beings. Extreme **weather** conditions or geologic activity can cause substantial short-term or long-term changes to our environment. These changes can influence crops, homes, infrastructure, and the **atmosphere**. The 4.6-billion-year-old Earth has experienced many of these natural changes, and it has always adjusted accordingly.

The Western United States is located at the junction of three tectonic **plates**: the Pacific, the Juan de Fuca, and the North American. The movement of these plates, even though it occurs on the scale of millimeters per year, makes the Western US a dynamic landscape. The dramatic result is a dizzying assortment of natural hazards such as **earthquakes**, **tsunamis**, landslides, and volcanoes. The Pacific plate is **subducting** under Alaska, creating the volcanoes of the Aleutian Islands. The Juan de Fuca plate is subducting under Washington, Oregon, and Northern California, creating the Cascade volcanoes, and the Pacific plate is grinding past the North American plate along the famous San Andreas Fault. At the same time, the Basin and Range province, which includes nearly the entire state of Nevada, is being stretched and **faulted** by plate movement. While the motion of all tectonic plates can cause earthquakes, the movement of a subducting plate can cause the world's largest earthquakes and tsunamis. Tectonic activity lifts the landscape high above sea level, and because uplifted land is subject to the force of gravity, **mass wasting** processes such as landslides are the inevitable result. These events can be triggered by rain, earthquakes, and coastal or river **erosion**. The Western US contains rugged landscapes and breathtaking vistas, but with that beauty comes a cost: there are more earthquakes, tsunamis, landslides, and volcanoes in the Western states than in all the other states combined. (While many of these same hazards affect the Hawaiian Islands, there are enough significant differences to warrant discussing Hawai'i separately.)

See Chapter 4: Topography to learn more about the landforms of the Western states.

Plate Tectonics

All tectonic plates move relative to other plates, and the Pacific plate is moving at a rate of roughly 50 millimeters/year (2 inches/year) relative to the North American plate. Most, but not all, of this motion occurs along the San Andreas Fault. The Sierra Nevada, whose **granite plutons** were created by

weather • *the measure of short-term conditions of the atmosphere such as temperature, wind speed, and humidity.*

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

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

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.*

mass wasting • *a process in which soil and rock move down a slope in a large mass.*

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

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the subduction of an ancient plate known as the Farallon plate, are located on the North American plate, but they are being pulled along by the Pacific plate. The Juan de Fuca plate, which is all that remains of the Farallon, is moving towards North America at an average rate of 36 millimeters/year (1.4 inches/year), creating the Cascade Range's volcanoes. As the Pacific plate continues to move northwest, it is causing the Basin and Range to pull apart. As a result, Nevada is full of sinking valleys and tilted mountains, and is growing wider in the process (*Figure 10.1*). Although this diagram does not show Alaska, the Pacific plate is subducting underneath the North American plate, creating the volcanic Aleutian Island Arc.

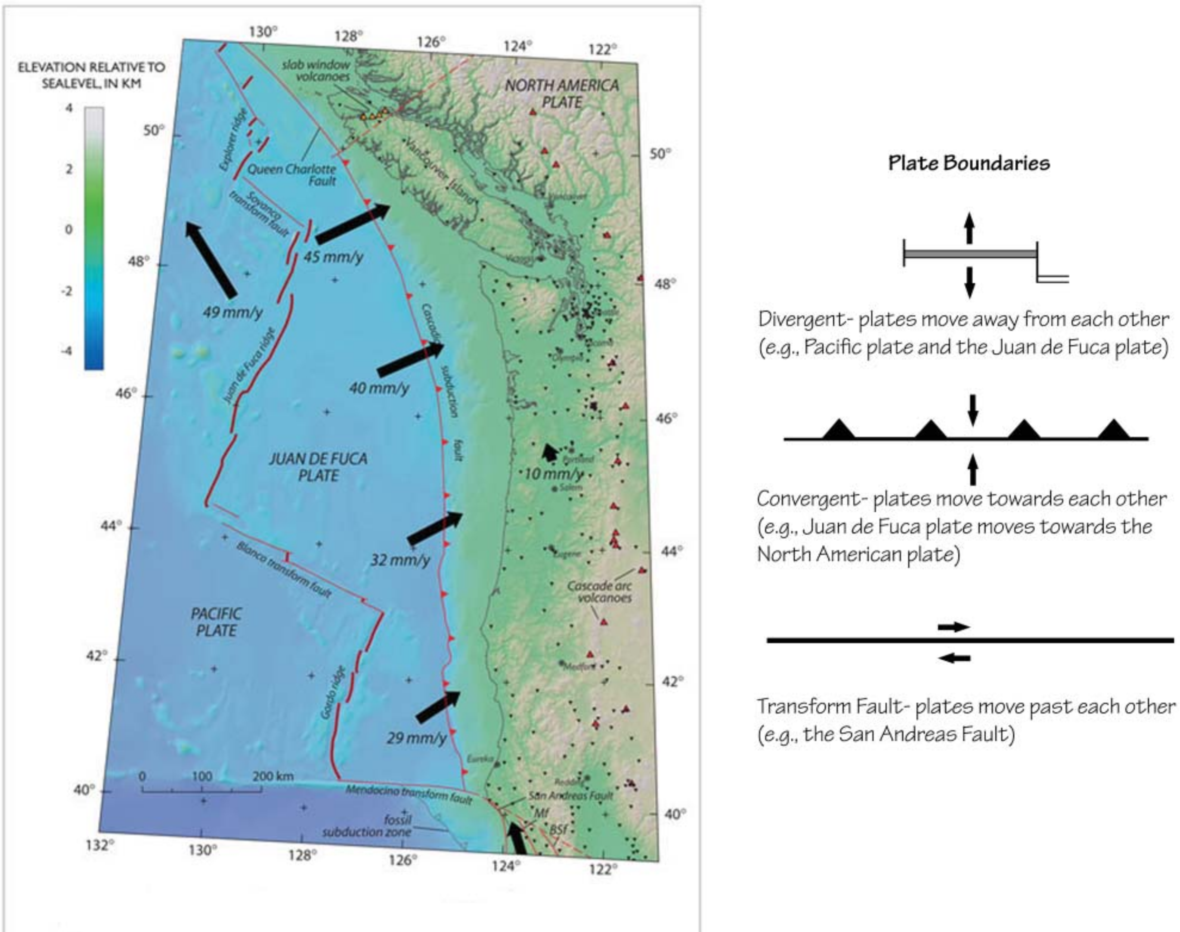

Figure 10.1: The general tectonic setting of the West Coast.
(See TFG website for full-color version.)

Convergent Boundaries

Where two plates collide, the denser plate (usually oceanic) subducts under the lighter one (either a younger oceanic plate or a continental plate) and creates a subduction zone. Subduction zones produce the largest and deepest earthquakes in the world. The water in the subducting plate is carried deep into the **mantle** and causes the melting of the overlying mantle rock. The resulting **magma** is hot and buoyant, so it rises to the surface and creates volcanoes. In the Western US, the Aleutian Island Arc and the Cascade volcanoes provide surface evidence of **convergent boundaries**.

Divergent Boundaries

Divergent plate boundaries exist where tectonic plates are under tension—essentially being pulled apart. This tension leads to the upwelling of magma, which forces its way through the separating **crust** onto the surface. In oceanic settings, such as the Juan de Fuca Ridge, new oceanic crust is created, and shallow, minor earthquakes occur. In continental settings, such as the Basin and Range of Nevada, the result of the tension is faulting and shallow earthquakes. As the faults pull apart and thin the crust, the decrease in overlying pressure can result in the formation of **basaltic** magma, which, in turn, can lead to the formation of small volcanoes called **cinder** cones. The faulting also creates the down-dropped basins and tilted mountain ranges of the Basin and Range.

Transform Boundaries

Transform boundaries exist where adjacent tectonic plates are moving alongside each other, causing a transform fault to develop. Most transform fault boundaries can be found in the ocean, where they connect divergent boundaries. One exception is the San Andreas Fault, which is mainly located on land. It separates the small divergent boundaries in Mexico (between the mainland and the Baja Peninsula) from the Juan de Fuca Ridge, and runs through continental crust for the majority of its length. The San Andreas Fault produces earthquakes when the plates slip, but it can also create ridges parallel to the fault, as well as mountains and valleys when the fault changes direction.

Earthquakes

Earthquakes occur when a critical amount of stress is applied to the crust. 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 10.2*). The plane defined by the rupture is known as a fault, and the rock layers become offset along it. An excellent example of this kind of offset can be found along the San Andreas Fault at Point Reyes National Seashore. The Earthquake Trail, which begins at the Bear Valley Visitor Center, follows the trace of the 1906 San Francisco earthquake to a picket fence along the fault (*Figure 10.3*). The fence was once connected, but today it is separated by a 6-meter (20-foot) gap. Looking at the photo, one can visualize how the foreground moved to the left, while the background moved to the right. Although the San Francisco earthquake was quite large, most of the damage to the city was actually caused by a fire, which is a common secondary hazard of earthquakes.

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

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

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

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

cinder • *a type of pyroclastic particle in the form of gas-rich lava droplets that cool as they fall.*

seismic waves • *the shock waves or vibrations radiating in all directions from the center of an earthquake or other tectonic event.*

10 Earth Hazards

Earthquakes

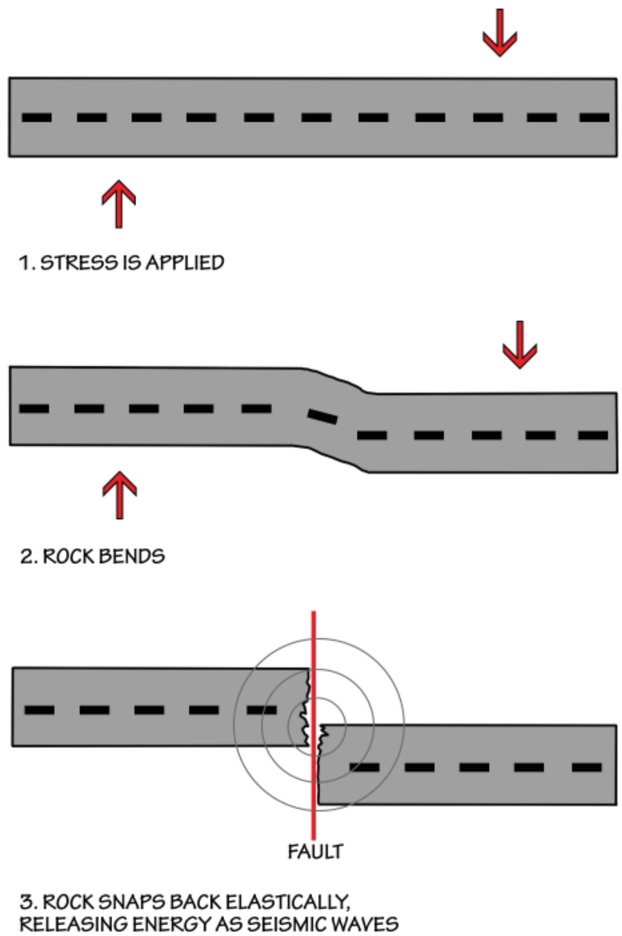

Figure 10.2: Elastic rebound.

There are two ways to measure 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, which measures the amplitude of a seismic wave at a defined distance from the earthquake. The Richter scale is somewhat limited, however, because it cannot accurately measure or compare large earthquakes. In 1979 Thomas C. Hanks and Hiroo Kanamori developed the Moment Magnitude scale, abbreviated M_w. Both the Richter scale and the Moment Magnitude scale use the numbers 1–10 to measure the amount of energy released. Although it is possible to have a magnitude smaller than 1, and there is technically no upper limit, this is the range commonly used when reporting earthquakes to the public. 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). These scales are logarithmic, meaning that a M9.0 earthquake would have 10 times the amplitude, and release 32 times the energy of a M8.0 earthquake. Accordingly, an M9.0 quake would have 100 times the amplitude and 1024 times the energy of a M7.0 earthquake. The largest earthquake in US history was the 1964 Alaskan Earthquake, which had an M_w of 9.2.

Figure 10.3: The picket fence provides clear visual proof of the potential significance of this type of offset.

Notable Earthquakes of the Western States		
Date	**Location**	**M_w**
3-28-1964	Prince William Sound, AK	M9.2
1-26-1700	Cascadia subduction zone, OR, WA, CA	M9.0
2-4-1965	Rat Islands, AK	M8.7
3-9-1957	Andreanof Islands, AK	M8.6
11-10-1938	Shumagin Islands, AK	M8.2
4-1-1946	Unimak Island, AK	M8.1
9-11-1899	Yakutat Bay, AK	M8.0
11-3-2002	Denali Fault, AK	M7.9
1-9-1857	Fort Tejon, CA	M7.9
4-18-1906	San Francisco, CA	M7.8
2-24-1892	Imperial Valley, CA	M7.2
6-28-1992	Landers, CA	M7.3
1-17-1994	Northridge, CA	M6.7

Earthquakes

The magnitude of an earthquake does not tell us how much damage is done by the waves in a particular area. 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*." The MMI scale is a subjective gauge compared to the Moment Magnitude scale. The USGS has attempted to improve the accuracy of MMI shake maps by soliciting data from the public. *Figure 10.4* shows the intensities felt by the 1964 Great Alaskan Earthquake (when data were collected through mail questionnaires). Today, after experiencing an earthquake, anyone may go to the USGS earthquake website and describe the effects at the "Did You Feel It?" page.

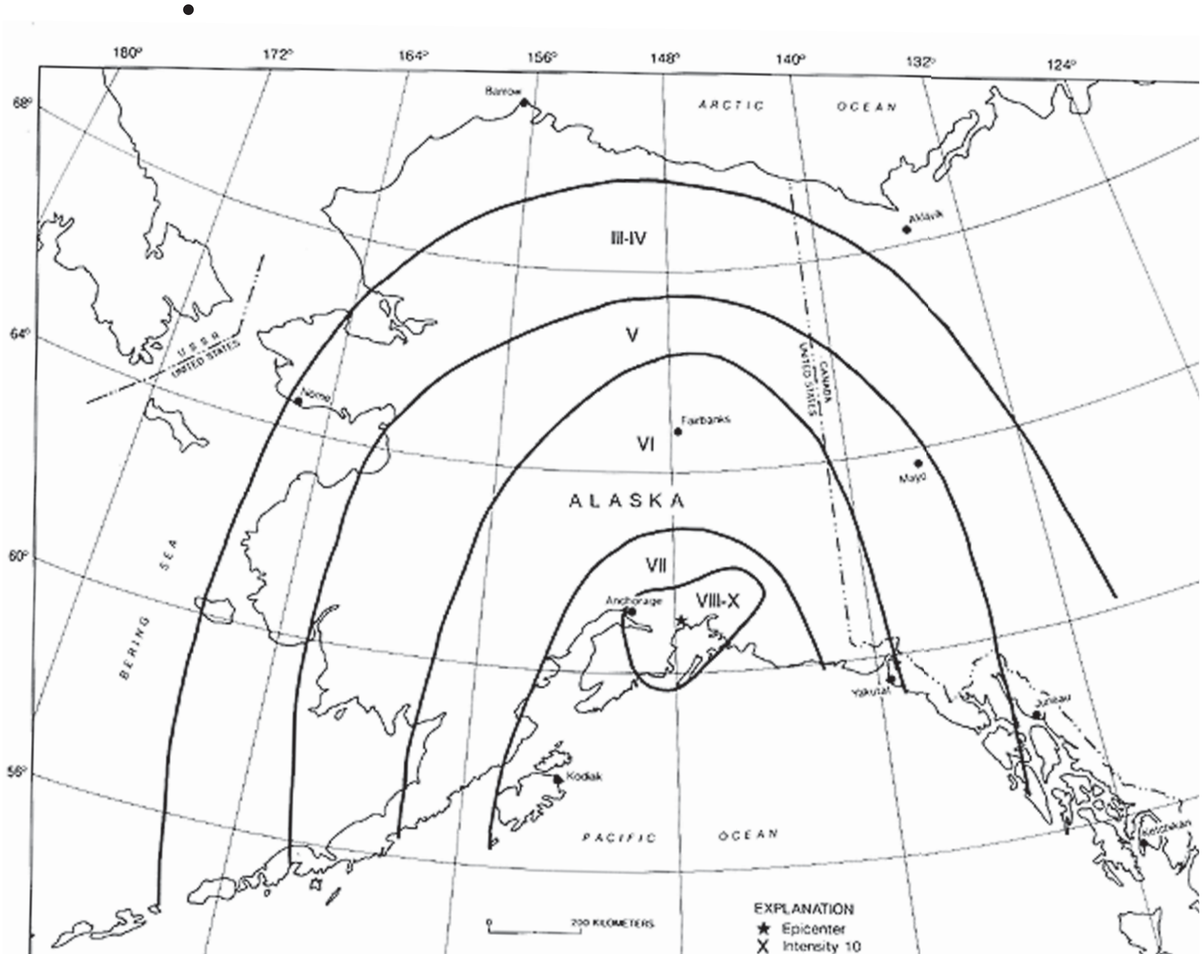

Figure 10.4: Intensity map of the 1964 Great Alaskan Earthquake.

Alaska has more earthquakes than all of the other states combined. California is second, with only about half as many as Alaska. The following table lists the number of earthquakes of M3.5 or greater from 1974 to 2003, according to the USGS Earthquake Hazards Program.

Alaska	12,053
California	4895
Hawai‘i	1533
Nevada	778
Washington	424
Idaho	404
Wyoming	217
Montana	186
Utah	139
Oregon	73

Cascadia

Although Washington and Oregon have not experienced many major earthquakes in the recent past, they are located above the Cascadia subduction zone (*Figure 10.5*). Since the Cascadia subduction zone is as large as the subduction zone that created the 2004 Sumatra Earthquake and subsequent

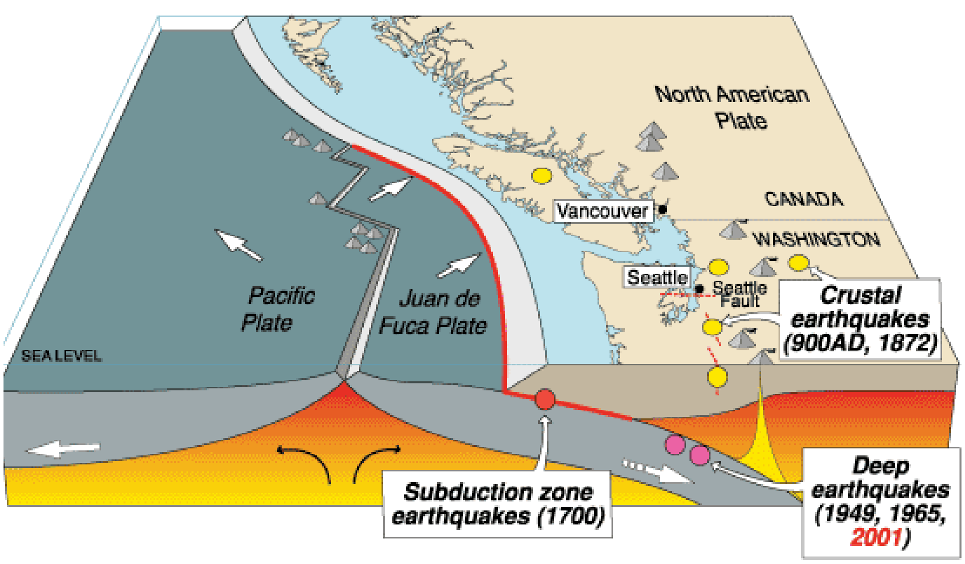

Figure 10.5: The Cascadia subduction zone and its related seismic occurrences.

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.*

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

tsunami, it could potentially generate an M8.0 or higher earthquake. It did just that in the year 1700, when the tip of the overriding plate (North America), which had been buckling upward under the stress of the ongoing collision, flattened out when the plates suddenly slipped past one another. The resulting earthquake caused the submergence of coastal land and the drowning of cedar forests along 965 kilometers (600 miles) of California, Oregon, Washington, and southern British Columbia. Places formerly above sea level dropped down, pushing enormous waves all the way across the ocean, and creating a tsunami that struck Japan. Written records of the damage to Japan's coastal villages allow us to pinpoint the day and time this earthquake occurred—the evening of January 26, 1700.

If the Cascadia subduction zone were to partially rupture today, it could create an M8.2 earthquake, and if it were to rupture along its entire length, it could generate an M9.0 earthquake. Geologists have recently forecast a 37% chance of an M8.2 or higher event within 50 years, and a 10–15% chance of an event of M9.0 or higher. Unlike Alaska, which had a population of only 763,000 in 2013, Washington and Oregon have a combined population of over 10 million people, most of whom live near the coast. Needless to say, Cascadia inhabitants would benefit greatly by preparing for a large earthquake and tsunami.

San Andreas

The San Andreas Fault, a 1304-kilometer (810-mile) long plate boundary (*Figure 10.6*), is not a single fault but a fault zone because it does not move all at once. Instead, great lengths of the fault rupture while other sections remain locked. Some sections do neither, but instead creep along without generating significant earthquakes.

Southern California is particularly susceptible to a devastating earthquake, in part because it has been so long since a major or great quake has occurred. Over 150 years ago, the M7.9 Fort Tejon earthquake caused 360 kilometers (225 miles) of the San Andreas Fault to rupture. The southernmost section of the San Andreas has not ruptured in the last 300 years. In response to this growing hazard, geologists have created a "Great ShakeOut" earthquake scenario. This scenario models the effects of a M7.8 earthquake on a 300-kilometer (180-mile) rupture from Bombay Beach at the Salton Sea to Lake Hughes north of Los Angeles. Both the Fort Tejon segment and the southernmost segment of the San Andreas fault zone are considered at risk for a major earthquake at any time, and either one could generate an earthquake that would wreak havoc on the lives of the 23 million inhabitants of Southern California. Earthquake preparedness drills based on this scenario have been taking place in southern California since 2008, and they attract millions of participants every year.

Tsunamis

A tsunami is a series of ocean waves that are generated by the sudden displacement of water. Although earthquakes are the most common cause, tsunamis may also be generated by **landslides**, **volcanic** explosions, meteor

Tsunamis

nuclear • *a reaction, as in fission, fusion, or radioactive decay, that alters the energy, composition, or structure of an atomic nucleus.*

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

calving • *when ice breaks off from the end of a glacier.*

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

Figure 10.6: San Andreas Fault and associated seismic zones. (See TFG website for full-color version.)

impacts, **nuclear** explosions, and **glacier calving**. Unlike a **wind**-generated sea wave, a tsunami wave has an extremely long wavelength. A very large wind-generated wave might have a wavelength of 200 meters (650 feet), but a typical tsunami has a wavelength of 200 kilometers (120 miles). Incredibly, tsunamis can travel at 800 kilometers per hour or kph (500 miles per hour or mph) in the open ocean.

Although tsunamis have extremely long wavelengths, while at sea they have only minimal height. In fact, ships in the open ocean may never notice the passing of a tsunami wave. As the wave approaches shore, however, the wavelength decreases and the wave height (amplitude) increases (*Figure 10.7*) as the water "piles up" upon reaching shallower depths. Even a tsunami with a moderate wave height can do great damage, however, because the great wavelength means it may take a single wave 20 to 30 minutes to sweep up the shore. Such waves resemble a wall of water more than a simple breaking wave (*Figure 10.8*).

Tsunamis

The tallest wave ever recorded occurred in Lituya Bay, located along the Alaskan Panhandle. On the night of July 9, 1958, a M8.5 earthquake initiated a landslide. Thirty million cubic meters (forty million cubic yards) of rock plunged into the bay, creating a local tsunami that destroyed all **trees** and vegetation up to a height of 524 meters (1720 feet) above the bay. Unusually high tsunamis

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

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

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.*

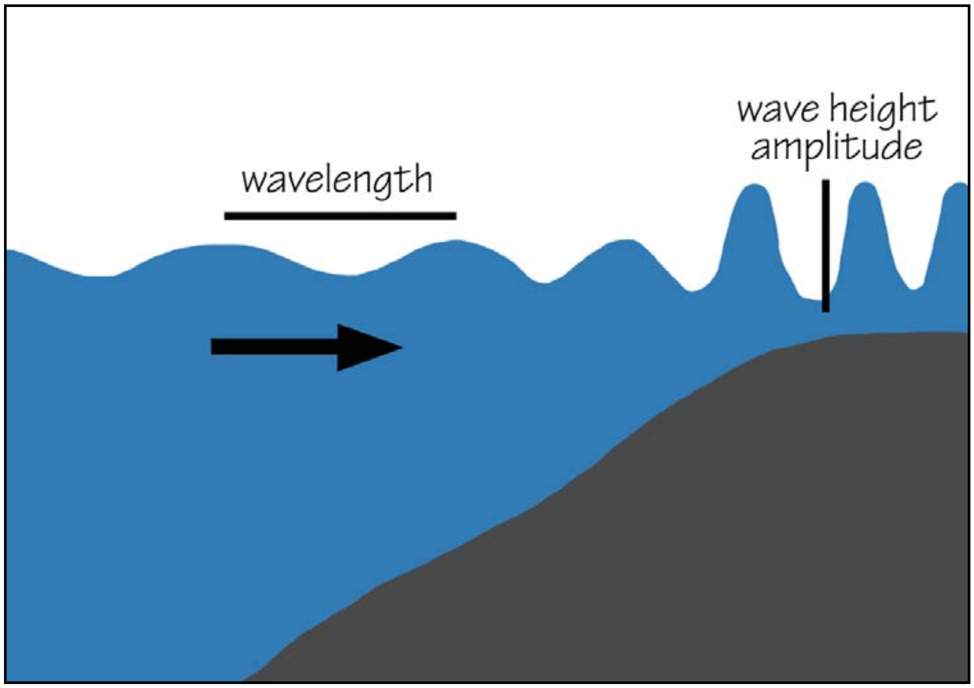

Figure 10.7: Changes to a tsunami wave as it approaches the shore.

are referred to as *megatsunamis*. This category includes landslide-generated tsunamis as well as tsunamis generated by a meteor impact, such as the meteor that struck 66 million years ago, causing the **extinction** of the **dinosaurs**. The height of the wave caused by that impact is estimated to have been as much as 5 kilometers (3 miles) high!

Often the trough of a wave will arrive before the crest, making it appear as if the sea is retreating. This strange sight might give residents time to escape before the crest arrives, if they recognize that the drawdown is a warning sign and not just the tide going out very quickly. The shape of a bay or harbor can accentuate the effects of a tsunami, funneling the wave's energy inland—such was the case in Crescent City, California, after the Great Alaskan Earthquake of 1964. The earthquake created a tsunami that arrived at Crescent City four hours later. Although the first three waves did only minor damage, the fourth wave, approximately 6 meters (20 feet) tall, inundated the town, killing 12 residents and injuring over 100, and destroying hundreds of buildings. Forty-seven years later, Crescent City was once again struck by a tsunami, this time from the 2011 M9.0 Tohoku-Oki Japan earthquake. Fortunately, there was only

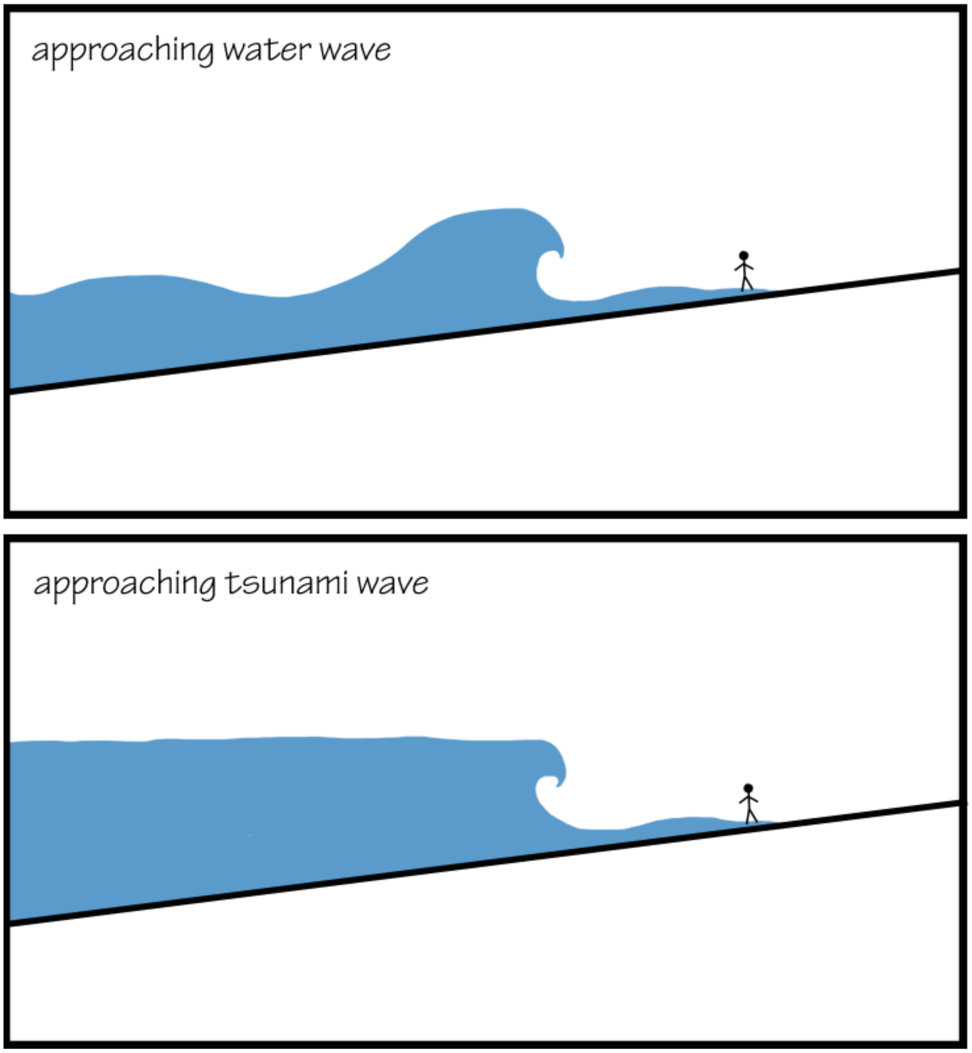

Figure 10.8: The difference between normal water waves and tsunami waves as they approach the shore.

one death because at-risk areas of the city were evacuated before the arrival of the first wave.

The West Coast of North America is prone to tsunamis because of the seismically active “Ring of Fire” around the Pacific Ocean. The National Oceanic and Atmospheric Association’s (NOAA’s) Pacific Tsunami Warning Center has created a tsunami warning system based upon earthquake data and real-time tsunami detectors in the deep ocean. If a tsunami is generated at a distance, residents of coastal communities can be warned so that they can follow established tsunami evacuation routes to high ground (*Figure 10.9*). If, however, a tsunami is generated just offshore, there is not enough time for a warning, as was the case for coastal Japan with the 2011 M9.0 earthquake and associated tsunami.

Landslides

megathrust *• powerful earthquakes occurring at subduction zones, where one plate is forced beneath another.*

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

creep *• the tendency of a material to move slowly or deform under the influence of pressure or stress.*

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.*

permeability *• a capacity for fluids and gas to move through fractures within a rock, or the spaces between its grains.*

terrace *• a flat or gently sloped embankment or ridge occurring on a hillside, and often along the margin of (or slightly above) a body of water, representing a previous water level.*

Figure 10.9: A typical tsunami evacuation route sign.

The Japan 2011 and Alaskan 1964 earthquakes are good examples of **megathrust** earthquakes that are likely to create tsunamis. As one tectonic plate tries to subduct below another, the two plates can become stuck together. The pressure from the subducting plate builds up and deforms the overlying plate by causing it to buckle (*Figure 10.10*). When the subducting plate finally moves, the overlying plate snaps back, **uplifting** the ocean and creating a tsunami. Not only could this happen along the Aleutian Island Arc's trench, it could happen again along the Cascadia subduction zone. The location of the trench, just offshore of northern California, Oregon, and Washington, is likely to give coastal residents little time for evacuation.

Landslides

The generic term "landslide" refers to a wide range of mass wasting events during which rock material moves downhill. The rugged **topography** of the Western US makes landslides a common problem. Landslides are usually triggered by high rainfall, but they can also be triggered by earthquakes, erosion, deforestation, groundwater pumping, and volcanic eruptions. Not all mass wasting events are rapid—slow land movement, known as **soil creep** (*Figure 10.11*), usually does not cause loss of life, but it can still destroy roads and buildings. Mud and **debris flows** are very fast landslides that are likely to kill anyone unfortunate enough to be caught in their path, as they can reach speeds that exceed 32 kph (20 mph).

Landslides

The slowest kind of landslide is known as **creep**. When **clay** in the **soil** on a hillside absorbs water, it will expand, causing the soil to swell. As the clay dries and contracts, the particles settle slightly in the downhill direction. The process causes fences and telephone poles to lean downhill, while trees adjust by bending uphill (*Figure 10.11*).

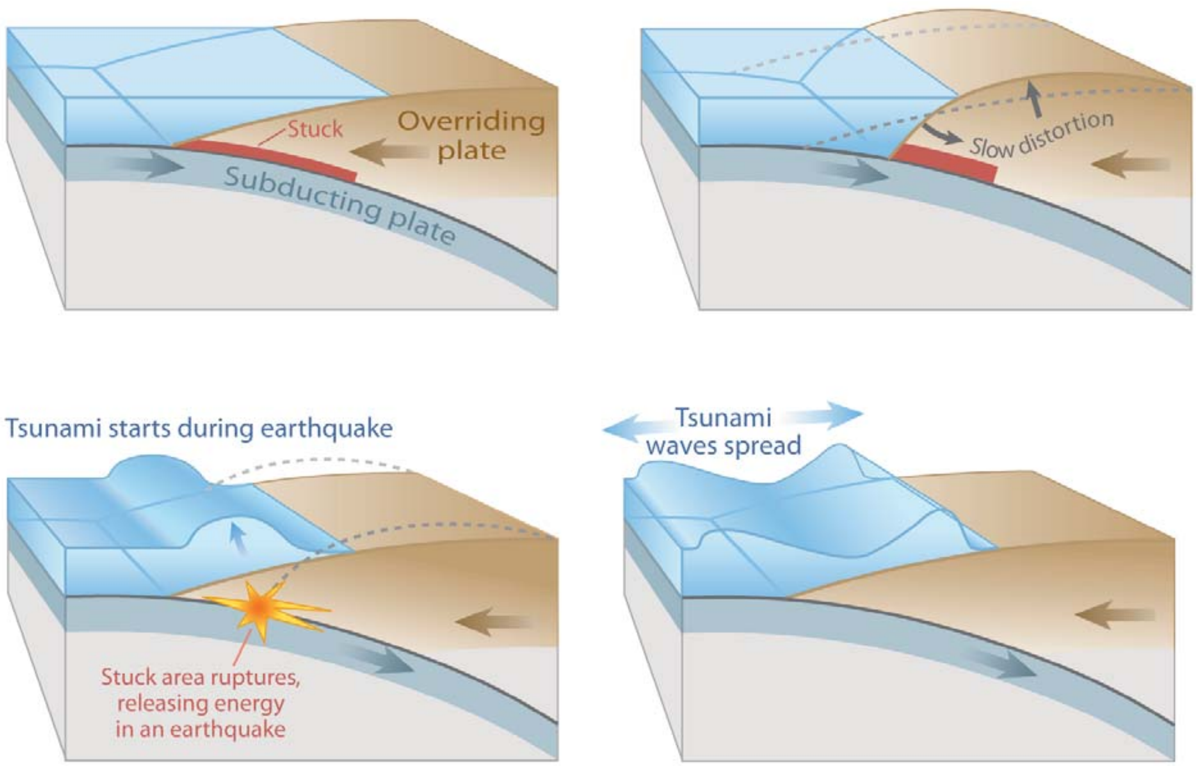

Figure 10.10: The steps involved in a megathrust earthquake and tsunami.

The Arctic tundra of Alaska is experiencing an unusual form of creep called **solifluction**. During the summer, rain passes through the thawed upper layer of the soil but cannot penetrate the **permafrost** below. Instead, the water builds up against the **impermeable** permafrost. As a result, the water and soil move slowly downhill like thick porridge.

The Pacific Northwest is particularly prone to landslides because of its high levels of rainfall. The most damaging landslide in recent history was the March 22, 2014 Hazel mudslide in Oso, Washington. The Hazel landslide has been active for over 60 years, causing numerous smaller slides—the March 22 slide came from a high **terrace** made of a poorly **cemented** layer of glacial **sand** and **gravel**. After a period of extremely high rainfall, a section of the terrace collapsed into a fast-moving mudflow that engulfed 49 homes and took 41 lives. Incredibly, most of the homes were located across a river from the terrace, on a bluff nine meters (30 feet) above the river.

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

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

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

Landslides

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

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).

lahar • a pyroclastic debris flow or mudflow that typically flows down river valleys after a volcanic eruption.

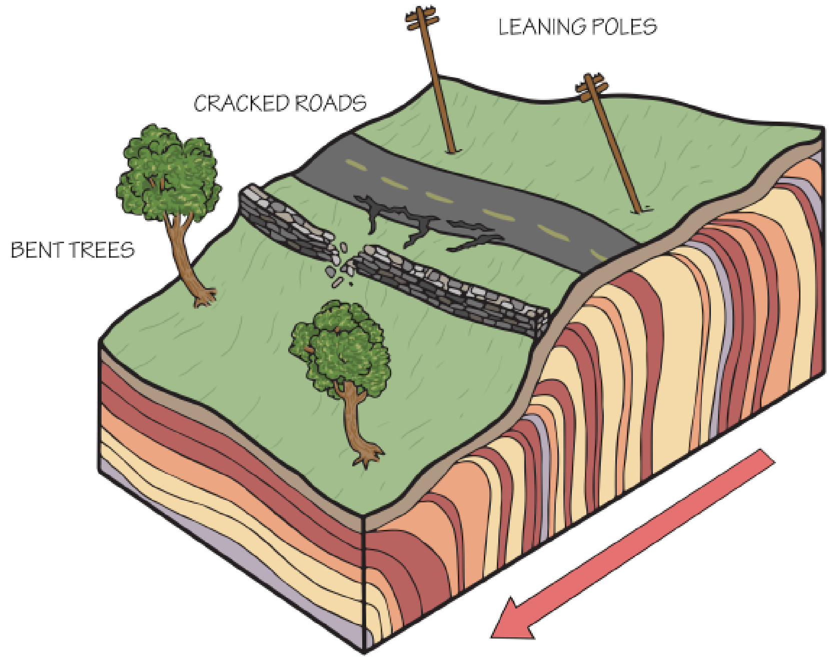

Figure 10.11: The effects of soil creep.

The coastal erosion of hillsides often results in landslides. Portuguese Bend on California's Palos Verdes Peninsula contains layers of rock that slope towards the ocean. Among these layers is **bentonite**, a very slippery clay layer. In the 1950s, houses were built on an area that soon started to slide once the city, in the process of road construction, had added material to the top of the slope. Although homeowners successfully sued the city for initiating the slide that destroyed their homes, they were also partially responsible since they added water to the slide by irrigating their lawns and using septic tanks. The land is still moving, and no houses can be built there.

Debris flows are a dangerous mixture of water, mud, rocks, trees, and other debris that move quickly down valleys (*Figure 10.12*). The flows can result from sudden rainstorms or snowmelt that creates flash floods. Areas that have experienced a recent wildfire are particularly vulnerable to debris flows, since there is no vegetation to hold the soil. El Niño **climate** conditions, which bring high precipitation, also increase the danger of debris flows. In response to these dangerous slides, many communities have built debris basins across their canyons to protect houses downstream (*Figure 10.13*). The USGS and NOAA are in the process of instituting a flash flood and debris flow early-warning system.

One of the most dangerous kinds of debris flow is a **lahar,** which is composed of water and volcanic debris such as ash. An eruption is not necessary to trigger a lahar. A melting glacier, a debris dam being breached, or a crater lake's walls collapsing can all send water and ash down the volcano at speeds up to 100 kph (60 mph). Mt. Rainier in Washington is considered the most dangerous volcano

Figure 10.12: This debris flow occurred on February 6, 2010 in La Canada-Flintridge, California as a result of a flash flood generated in Mullally Canyon.

Figure 10.13: This debris basin in Los Angeles county is designed to capture the sediment, boulders, and other debris washed from the canyon during a storm.

in the United States because of its proximity to high populations and its potential for lahars (*Figure 10.14*). The Puyallup River valley, directly downstream of the mountain, is built upon 500-year-old lahar deposits. The town of Orting is at the junction of two river valleys that descend from Mt. Rainer, making them capable of delivering a lahar. Since lahars are predicted to flow through the valley every 500 to 1000 years, the USGS has set up a lahar warning system to give people enough time to evacuate in the event of a lahar racing down the flanks of Mt. Rainier.

Volcanoes

Located along the Pacific Ring of Fire, the Western US contains many volcanoes. As can be seen in the table below, Alaska has the most volcanoes, most of which are found along the Aleutian Island Arc as a result of Pacific plate subduction. California, Washington, and Oregon contain the Cascade Range's volcanoes, which result from the subduction of the Juan de Fuca plate. All of the Cascade and Aleutian volcanoes are considered to be either active or dormant, which means they are capable of becoming active. Volcanic eruptions in the Cascades have been occurring for over 500,000 years, and have taken place at an average rate of two eruptions per century for the past 4000 years (*Figure 10.15*)

State	# of volcanoes
Alaska	97
Oregon	43
California	23
Hawai'i	17
Washington	16
Idaho	10
New Mexico	10
Arizona	7
Nevada	5
Utah	5
Colorado	3
New Hampshire	2
Virginia	2
Wyoming	1
Texas	1
South Dakota	1
Missouri	1
Mississippi	1

Earth Hazards 10

Volcanoes

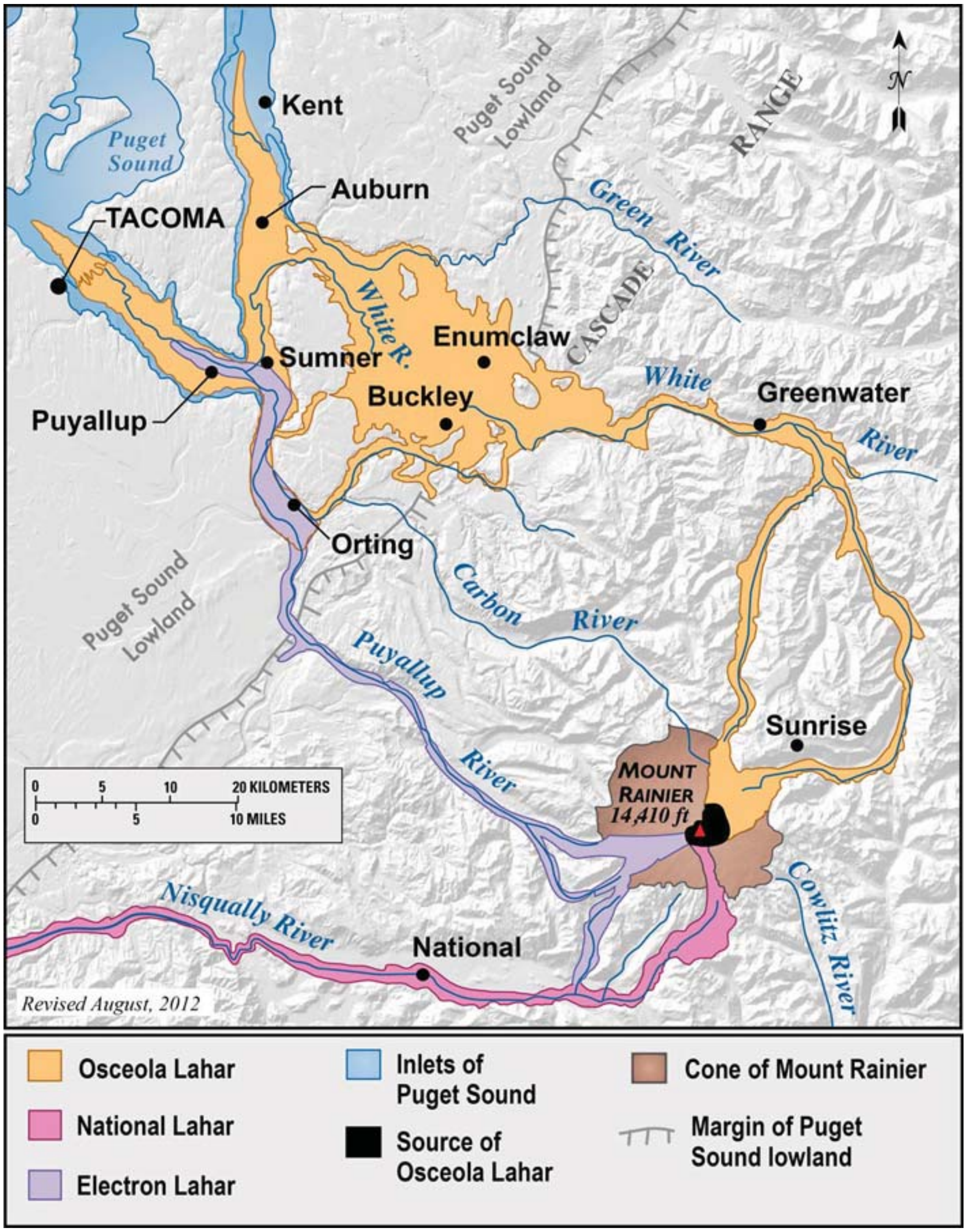

Figure 10.14: Lahar paths of Mt. Rainier. This map shows three major events that occurred in the last 10,000 years. Note how the lahars follow the river valleys.
(See TFG website for full-color version.)

stratovolcano *• a conical volcano made up of many lava flows as well as layers of ash and breccia from explosive eruptions.*

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

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

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

pyroclastic *• rocks that form during explosive volcanic eruptions, and are composed from a variety of different volcanic ejecta.*

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

The vast majority of volcanoes formed by subduction are **stratovolcanoes**, also known as composite volcanoes. Stratovolcanoes are built from the eruption of **andesitic** magma, which forms as the mantle above the subducting plate melts. This magma is viscous because of its high **silica** content, making it capable of trapping gasses and producing explosive eruptions. Stratovolcanoes eventually become layered with **lava** flows, **pyroclastics,** rock, and **volcanic ash** fragments ejected by an explosive eruption. They tend to be tall and cone-shaped, as can be seen in the picture of Augustine Volcano (*Figure 10.16*), located 300 kilometers

(186 miles) southwest of Anchorage, Alaska. When this volcano erupted in 1986, ash from an 11-kilometer (7-mile) high ash plume drifted over the Cook Inlet and grounded air traffic in Anchorage.

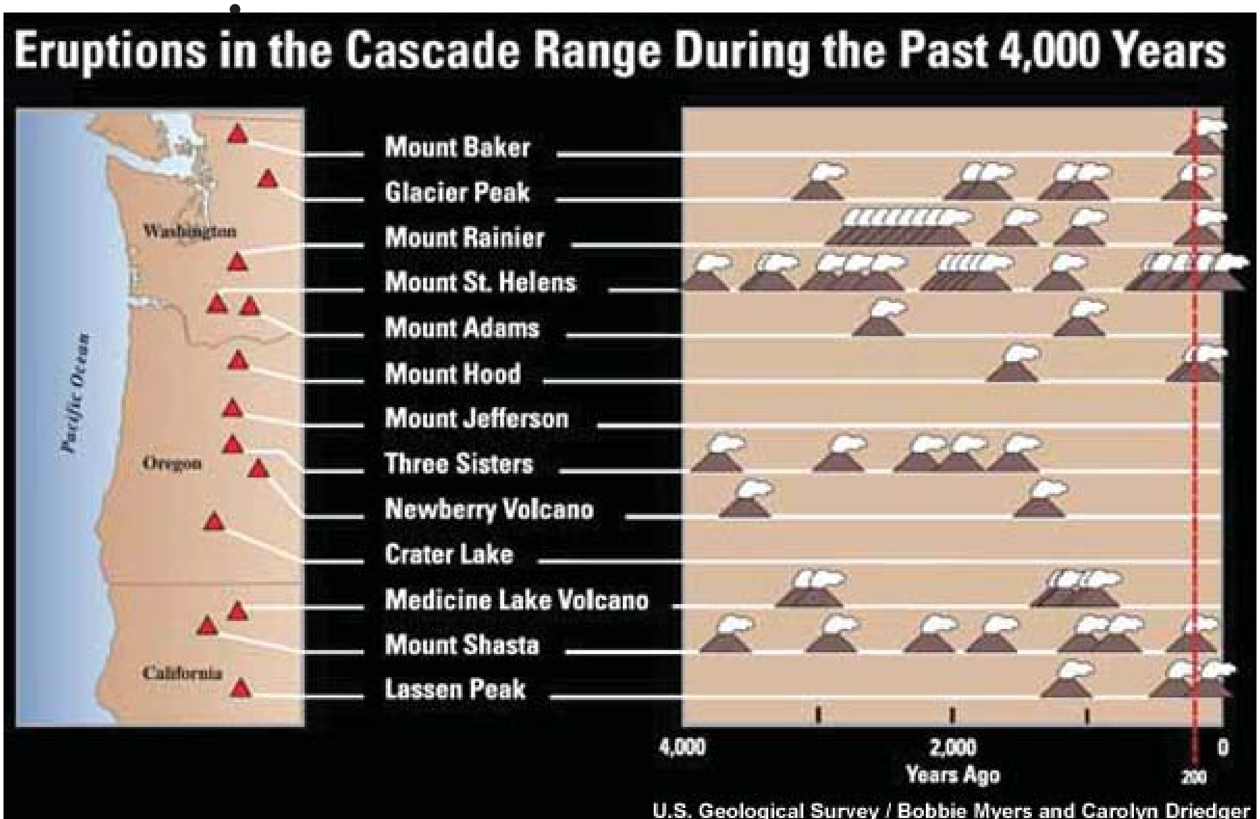

Figure 10.15: The eruptive history of the Cascade volcanoes.

Katmai National Park in Alaska is the site of the most powerful volcanic eruption in US history. In 1912, 13 cubic kilometers (3.1 cubic miles) of ash erupted from a vent on the side of Mt. Katmai. The ash completely filled a valley, which became known as the Valley of Ten Thousand Smokes for its many smoking fumaroles. The top of Mt. Katmai collapsed 1200 meters (3900 feet), creating an enormous **caldera**. After the explosive eruption, viscous **rhyolitic** lava pushed up from the vent, creating a volcanic dome, now known as Novarupta, which means "new volcano" (*Figure 10.17*).

Mt. Saint Helens is the most active volcano in the Cascade Range. Its most spectacular eruption occurred on May 18, 1980, when an earthquake shook the side of the mountain, triggering the largest landslide ever recorded. An explosive blast issued from the side of the mountain, reaching speeds up to 480 kph (300 mph) as it flattened forests in its path. Avalanches of hot ash and **pumice** called *pyroclastic flows* sped quickly down the side of the volcano and spread for miles. The volcano's rapidly melted glaciers created lahars that took

Volcanoes

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.

pumice • a pyroclastic rock that forms as frothing and sputtering magmatic foam cools and solidifies.

Figure 10.16: Augustine Volcano.

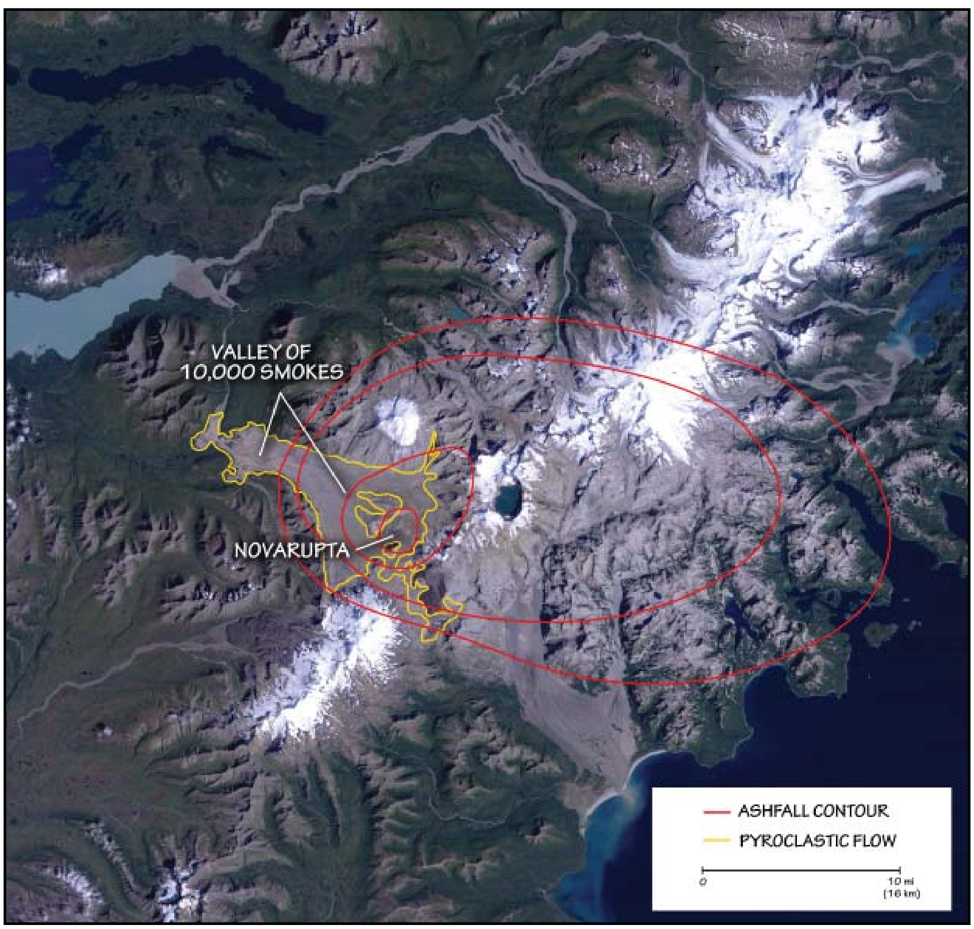

Figure 10.17: Novarupta and associated ashfalls. (See TFG website for full-color version.)

out 27 bridges and 200 homes. Despite evacuations in the weeks leading up to the eruption, 57 people died during the explosion. It was the deadliest and most costly volcanic event in US history. Mt. Saint Helens continues to be active, and it has built a lava dome inside its crater.

The Long Valley Caldera of California (*Figure 10.18*) was the site of a colossal eruption 760,000 years ago. The eruption created the Bishop Tuff ash layer (deposits of which cover an area nearly 2200 square kilometers [850 square miles] in size), and is estimated to have released 600 cubic kilometers (145 cubic miles) of ash, compared to the 1.2 cubic kilometers (0.3 cubic miles) of ash that was emitted by Mt. Saint Helens. There is still no good explanation for the basaltic and rhyolitic magmas that underlie the area, since there is no associated hotspot or subducting plate. There are many related volcanic features in the area, including Mammoth Mountain (a ski resort that sits atop a lava dome complex), Panum Crater (a rhyolitic lava dome), and numerous hot springs such as Hot Creek, which is located on a resurgent dome in the center of the caldera.

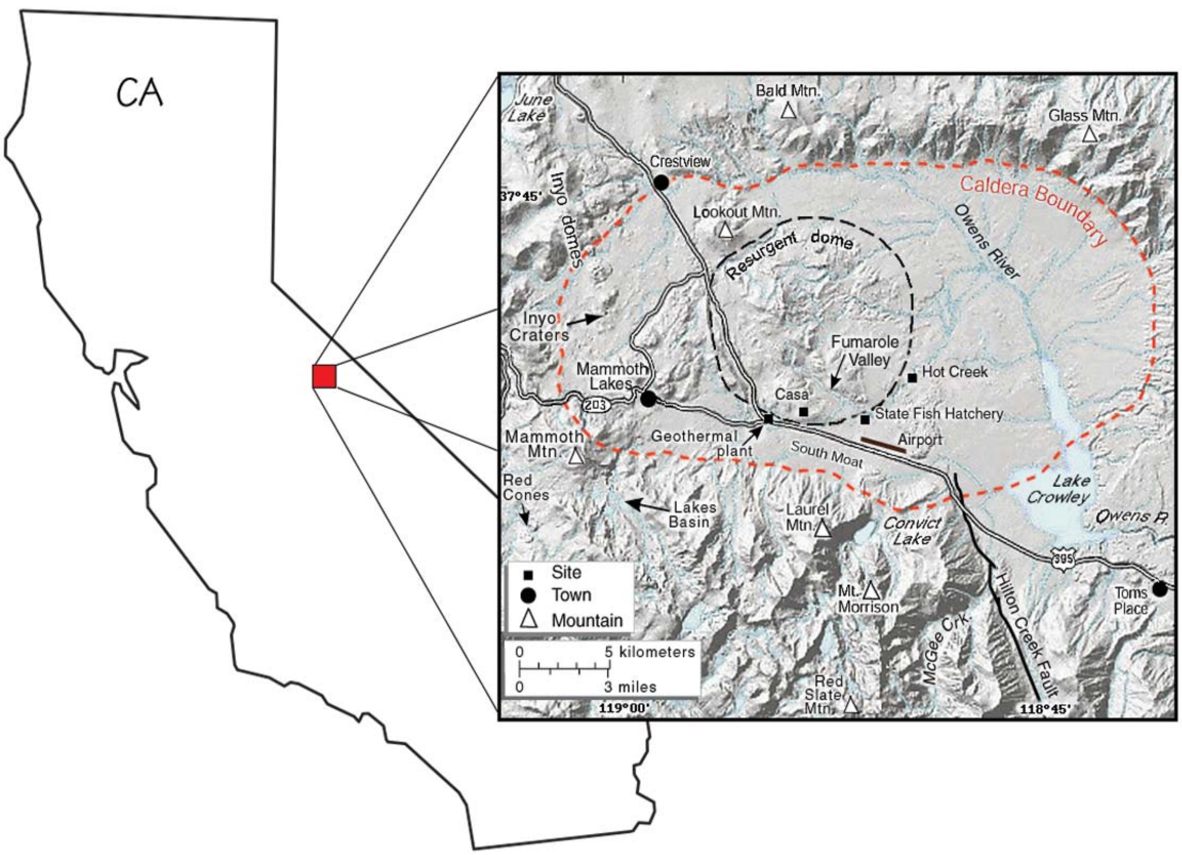

Figure 10.18: Extent and location of the Long Valley Caldera.
(See TFG website for full-color version.)

Volcanoes

The Mojave Desert is dotted with **scoria** cones and their associated basaltic lava flows. Scoria cones, also known as cinder cones, form as basaltic lava spews into the air and falls back onto the ejection site. The lava cools so quickly that volcanic gases become trapped in it as bubbles called **vesicles**. Scoria cones are small, steep, and short-lived. Amboy Crater and the Cima volcanic field of the Mojave National Preserve are excellent examples, among which the youngest scoria cone is only 10,000 years old. The Boring Lava Field, located near Portland, Oregon is an extinct lava field with 32 scoria cones (*Figure 10.19*). Scoria cone landscapes may appear ominous, but their effects are local, and they rarely cause a hazard to humans.

Figure 10.19: Beacon Rock is part of the Boring Lava Field in Oregon. It is the central core of a cinder cone whose outer layers were stripped away 57,000 years ago by the Missoula Floods.

The USGS constantly monitors volcanoes in Alaska, California, Hawai‘i, Oregon, and Washington, as well as the Yellowstone area in Wyoming. Although the exact timing of a volcanic eruption is difficult to predict, there are many signs that a volcano is becoming active. Volcanologists on the watch for eruptions look for earthquake swarms, changes in the level of the land, changes in **hydrothermal** activity, and changes in the gases emitted by the suspect volcano. Because ash plumes can destroy jet engines in less than a minute, the USGS also issues warnings for aviation. Luckily, the most active volcanoes in the United States are either in Alaska, far from population centers, or in Hawai‘i, where **shield volcanoes** erupt without significant explosions or loss of life.

scoria • *a highly vesicular form of basalt.*

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

shield volcano • *a volcano with a low profile and gradual slope, so named for its likeness to the profile of an ancient warrior's shield.*

10 Earth Hazards

hectare • *a metric unit of area defined as 10,000 square meters.*

water table • *the upper surface of groundwater.*

Natural Hazards in Hawai‘i

The Hawaiian Islands are vulnerable to many of the same environmental hazards that are a cause for concern anywhere on Earth, and also to a few that are particular to the residents of Hawai‘i. As both a coastal region and an active volcanic area, hazards associated with oceanic and volcanic processes and their related effects are of greatest concern.

Four main hazards characterize the Hawaiian Islands:

- Volcanic eruptions
- Earthquakes
- Tsunamis
- Floods and coastal hazards

Volcanic Eruptions

Volcanic hazards include lava and ash eruptions, and the emission of corrosive volcanic gasses. The Hawaiian volcanoes erupt basaltic magma, which is characterized by low-viscosity—and therefore highly fluid—lava flows. These flows are often channelized, allowing them to move over long distances at relatively high speed (10s of kph [mph]), but affecting a well-defined and narrow zone (*Figure 10.20*). Hawaiian lava flows pose little hazard to human life. However, structures or other immobile features (such as roads, agricultural areas, or other types of infrastructure) are often the victims of lava flows (*Figure 10.21*). As of 2011, the ongoing eruption of Kīlauea produced 3.5 cubic kilometers (1 cubic mile) of lava, covered 123 square kilometers (48 square miles) of land, added 206 **hectares** (509 acres) of land to Hawai‘i Island, destroyed 213 structures, and buried 14 kilometers (9 miles) of highway. Historically, Kīlauea's neighbors Mauna Loa and Hualālai have also experienced rapid, high-volume eruptions that would pose a hazard to the modern, more densely populated and urbanized flanks of these volcanoes today.

Occasionally, Hawaiian volcanoes erupt explosively. Kīlauea has had three explosive eruptive events in the last 100 years (1924, 2008, 2011) and six others in the last 1500 years. Although still gentle on the scale of global volcanism, these explosive eruptions are capable of blanketing large areas of Hawai‘i Island with ash and pyroclastic debris. When there is an unusual buildup of pressure within the magmatic plumbing system, an explosive eruption can result. Hawaiian volcanologists believe that the most common cause of explosive eruptions is the interaction of magma with groundwater. At Kīlauea this occurs when the floor of the summit caldera subsides to a depth near the **water table**: currently about 500 meters (1640 feet) below the surface. The most dangerous type of explosive behavior is a *pyroclastic surge*. Ash and volcanic gases race along the surface at extreme speed, with temperatures of several hundred degrees Celsius. The most recent pyroclastic surge from Kīlauea was in 1790, when a number of Hawaiians were overcome and killed. The estimated number of fatalities is between 80 and 5000; even the lower figure makes this the most deadly eruption in US history.

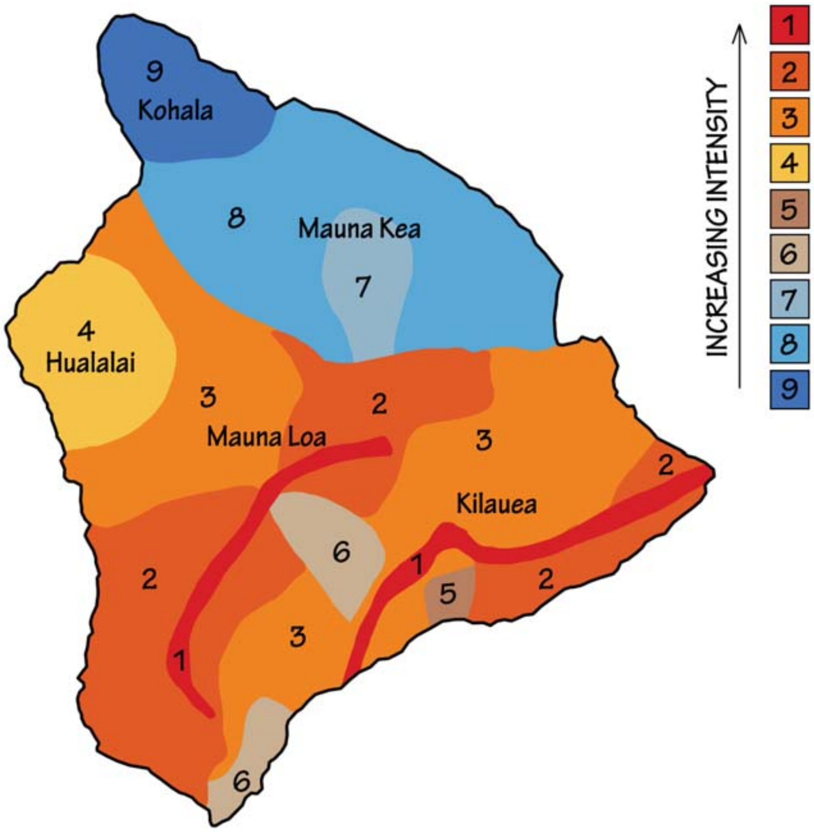

Figure 10.20: USGS Hawaiian Volcanoes Observatory map of Lava Flow Hazard Zones on Hawai‘i Island. (See TFG website for full-color version.)

Figure 10.21: Remains of Waha‘ula Visitor’s Center in Hawai‘i Volcanoes National Park.

10 Earth Hazards

Hawaiʻi

trade winds • *a major tropical wind system, involving the flow of high-pressure subtropical air to the low-pressure equatorial zone.*

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

aerosol • *tiny solid or liquid particles in the air.*

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

Some large explosions from Kīlauea's summit in the past have sent eruption clouds so high that they entered the west winds of the jetstream. As a result, their ash deposits were dispersed mainly in easterly directions. This is known to have occurred during explosive eruptions in 850–950 CE, about 1650 CE, and in 1790 CE. By contrast, the spectacular lava fountains of the 1959 eruption, the largest in the past 200 years, only sent material some hundreds of feet into the air, where it was dispersed to the southwest by the prevailing low-level *trade winds*. Although the on-land extent of the ash deposits is fairly well known, all the ash layers extend offshore for unknown distances.

Throughout a volcano's period of activity, it also emits a suite of volcanic gases. At Kīlauea and Mauna Loa—Hawaiʻi's two most active volcanoes—the main gas plume components are water vapor, carbon dioxide, and **sulfur** dioxide (SO_2). Of these, SO_2 is of the greatest concern. Sulfur dioxide can react with water in the atmosphere to form sulfuric acid, and it reacts with sunlight and **aerosols** to form volcanic smog, or "vog." Vog has been a problem throughout Kīlauea's eruption from 1983 to present, with especially elevated levels since activity returned to the summit in 2008 (*Figure 10.22*). In the post-2008 eruption period, emissions of SO_2 averaged 4000–6000 metric tons per day. This is a threat to people with respiratory ailments, and it also causes damage to agricultural crops in areas downwind of the summit eruption.

In order to understand volcanism and minimize volcanic hazards, the USGS has operated the Hawaiian Volcanoes Observatory on Kīlauea volcano since 1912. Volcanologists make visual observations and monitor ground deformation, seismicity, magma chemistry, and gas emissions in order to detect changes in volcanic behavior prior to an eruptive event. Hawaiian volcanoes commonly show clear precursors that signal the start of a new eruptive phase: most often an inflation of the volcano's summit and increased seismicity beneath the volcano. The state of Hawaiʻi has a robust civil defense warning system for volcanic (and other) hazards that alerts residents to potential threats.

Earthquakes

Hawaiʻi is seismically active; each year thousands of earthquakes occur in the Hawaiian Islands. Most earthquakes are linked to volcanism or the processes that form volcanoes. The seismicity map of Hawaiʻi shows that earthquakes occur most frequently near Hawaiʻi Island, the site of recent and active eruptions (*Figure 10.23*). From examination of the depth and distribution of seismicity, scientists recognize three types of earthquakes in Hawaiʻi. The deepest earthquakes (16–56 kilometers; 10–35 miles) occur within the **lithosphere** and are related to stresses created by flexure of the lithosphere in response to the

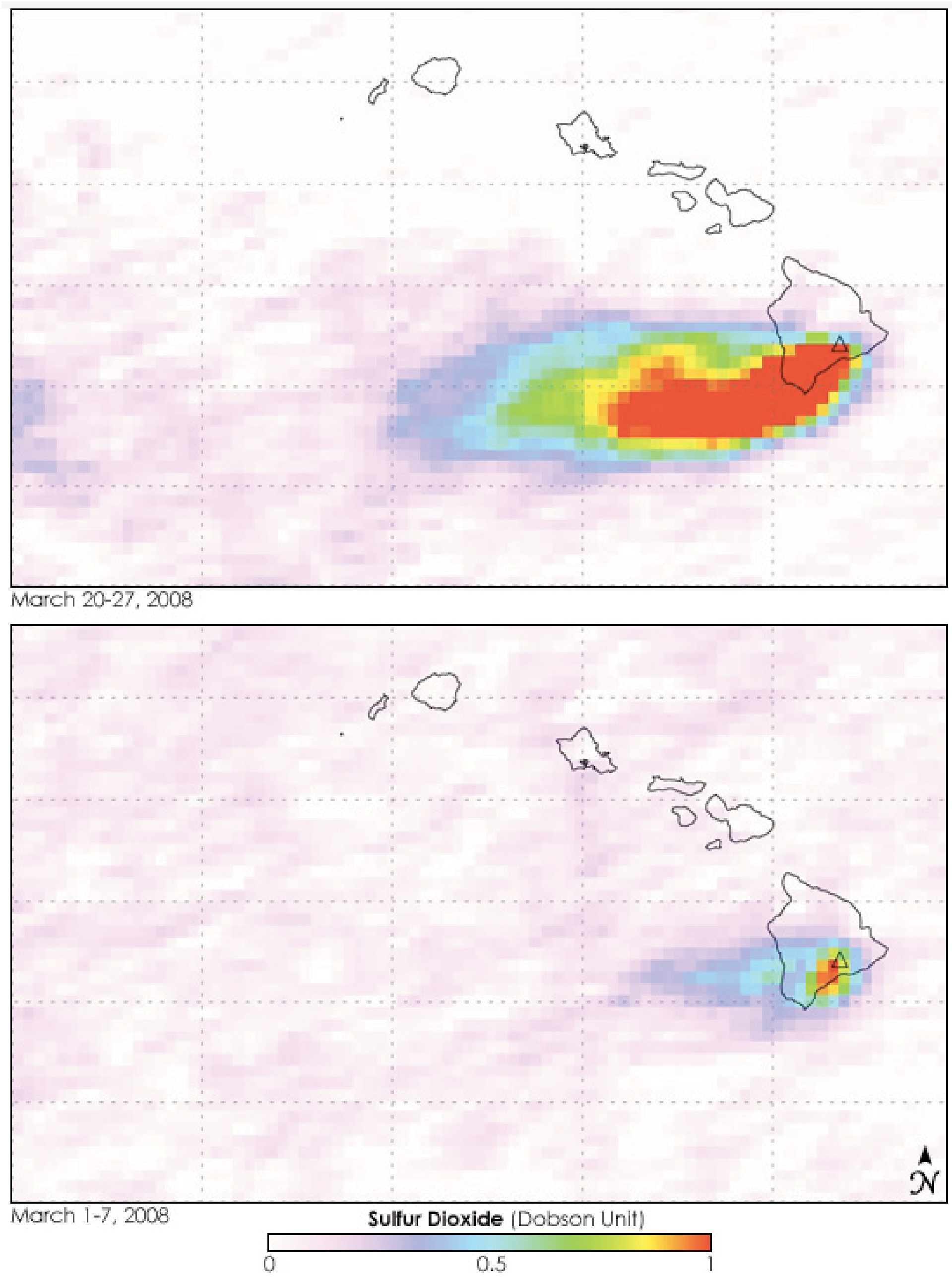

Figure 10.22: Sulfur dioxide plume after and before the Kīlauea summit eruption March 19, 2008. (See TFG website for full-color version.)

large mass load of the Hawaiian volcanoes. In 2006, an M6.7 earthquake of this type caused widespread damage across northern Hawai‘i Island (*Figure 10.24*).

A second group of earthquakes occurs along the boundary between the Hawaiian volcanoes and the older oceanic crust on which they sit. Under the influence of gravity, the flanks of the volcanoes tend to spread. This spreading motion causes earthquakes along a nearly horizontal fault between ancient oceanic crust and the overlying, much younger, volcanic edifice. An M7.2 earthquake of this type occurred in Kalapana on the south coast of Hawaiʻi Island in 1975. Similarly,

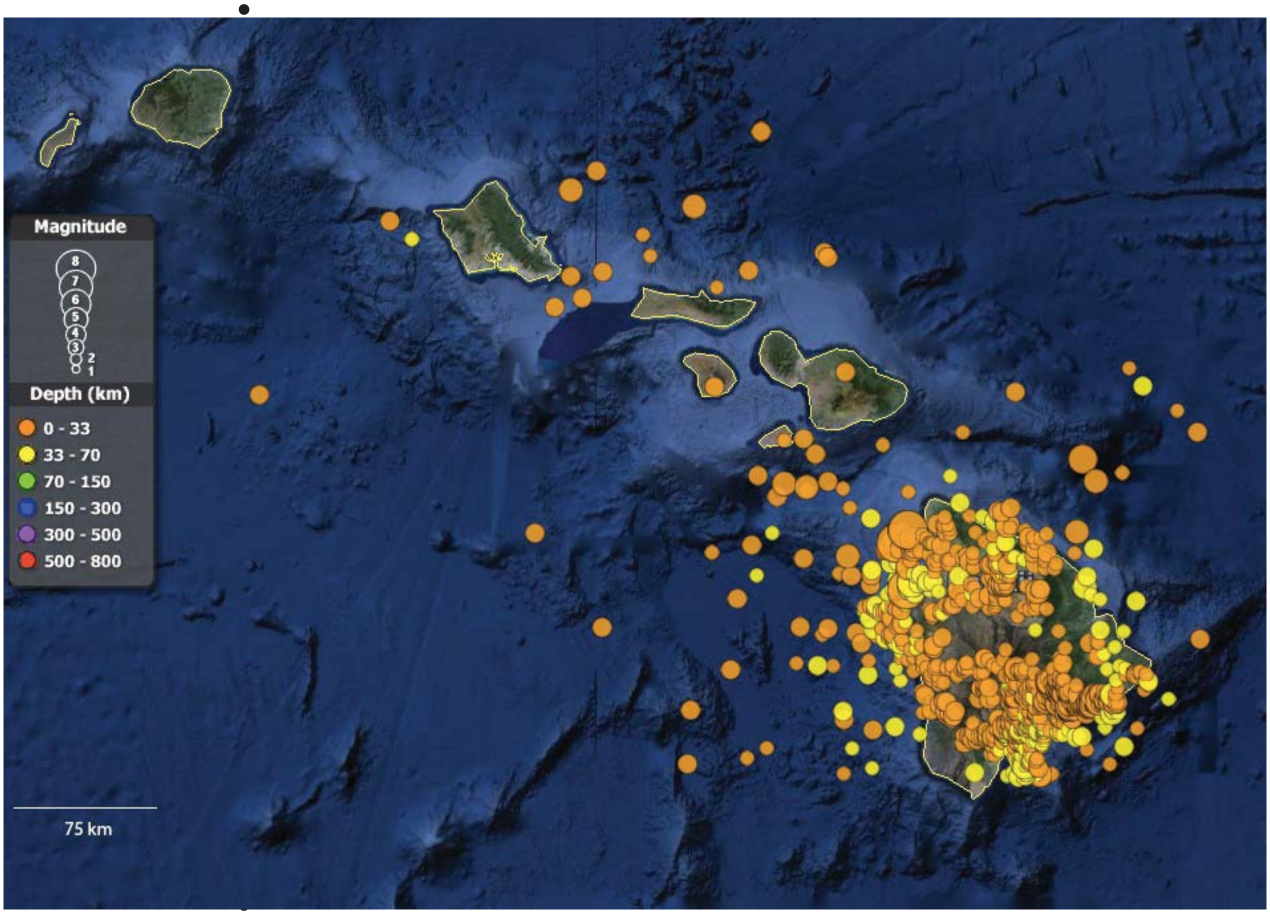

Figure 10.23: Ten years of M2+ earthquakes (2004–2014).
(See TFG website for full-color version.)

seismometer • *an instrument that measures seismic waves (movements) within the ground.*

faults visible on the surface appear to be related to this seaward motion of the volcanic flanks. In 1983, an M6.6 earthquake on Mauna Loa’s Kaʻoiki fault sent portions of Chain of Craters Road sliding into Kīlauea caldera.

The third suite of earthquakes are those caused by the migration of magma through volcanic conduits beneath the magma chamber. A common precursor to a volcanic eruption is an earthquake swarm known as *harmonic tremor*, which involves a set of early, continuous, low-magnitude vibrations (too small to be felt by people) that accompany the movement of magma toward the surface (*Figure 10.25*).

Although considered a hazard, earthquakes are also useful tools for probing the interior structure of Hawaiʻi’s volcanoes. An array of **seismometers** on Hawaiʻi Island detects small earthquakes that delineate fault zones dissecting

Figure 10.24: Kalāhikiola Church, Kapa‘au, Hawai‘i Island, 41 kilometers (25 miles) from the epicenter of the 2006 Kīholo (M6.7) earthquake.

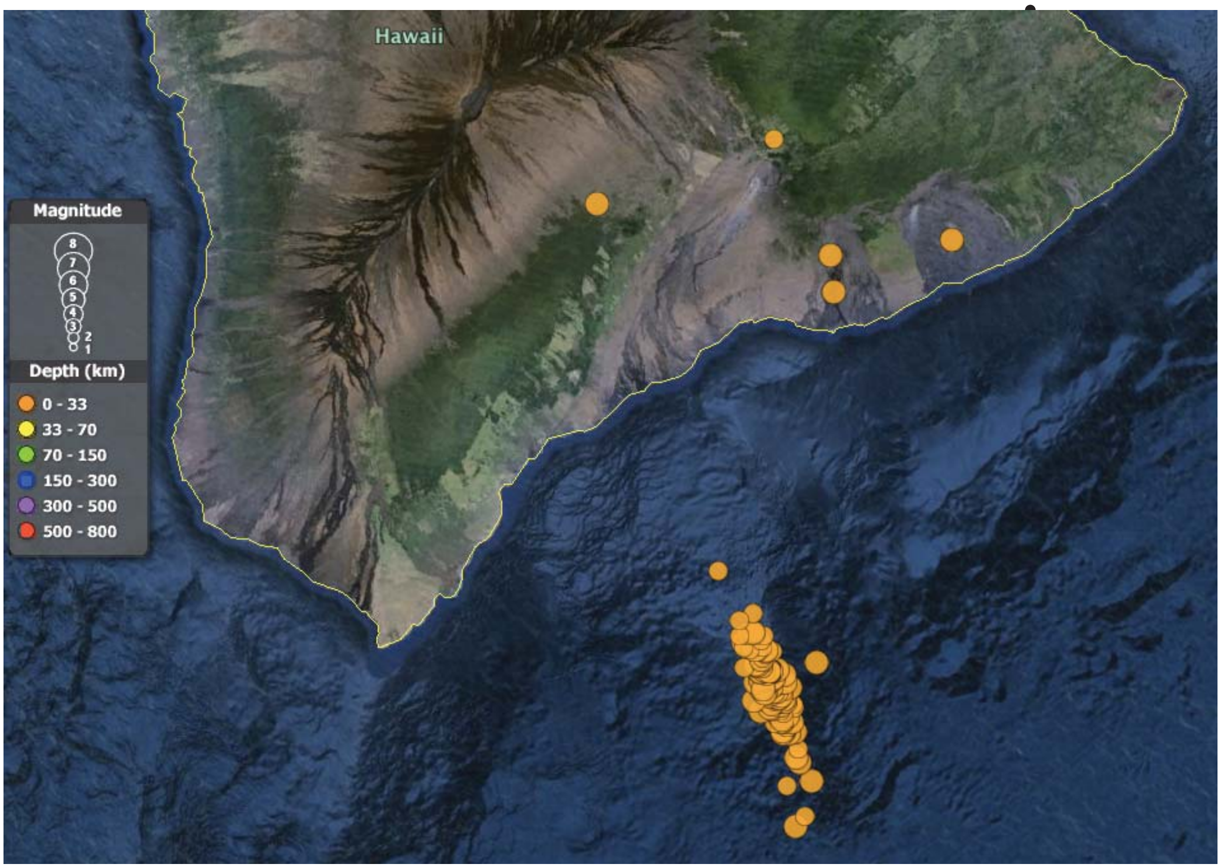

Figure 10.25: Earthquake swarm associated with the 1996 eruption of Lō‘ihi volcano. (See TFG website for full-color version.)

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

the volcanoes. These instruments also allow volcanologists to map magma chambers and **rift** zones.

There is an inverse relationship between the size of earthquakes and their frequency. Large earthquakes release large amounts of energy stored within the crust and lithosphere of the Earth, so they are infrequent. Smaller earthquakes occur all the time, releasing small amounts of energy. In Hawai‘i, microearthquakes occur every day. Fortunately, because Hawai‘i is not located on an active tectonic plate boundary there are no very large (M8.0+) earthquakes there.

Tsunamis

As mentioned previously, tsunamis are ocean surges usually caused by large earthquakes that displace the ocean floor. Displacements can also occur because of large landslides triggered by an earthquake. The sudden displacement generates a shock wave that in turn can generate a series of waves in the ocean. These waves travel at high speeds across the ocean basins, up to 800 kph (500 mph). They have long wavelengths (200 kilometers; 120 miles) but low amplitudes and are only 30 to 120 centimeters (1–4 feet) in height. When such a wave train reaches shallow water the wave velocity slows and the wavelength decreases, but the amplitude increases, sometimes dramatically (see *Figure 10.10*). The heights of tsunamis close to large earthquakes have exceeded 15 meters (50 feet) in Hawai‘i. Unfortunately, the use of the term “height” in tsunami reports can be confusing. In some cases it refers to the height of the oncoming surge of water above mean local sea level. In other cases it is used to describe the highest point reached by the wave, known as the “runup.” Runup heights are greater than wave heights, but descriptions do not always make the distinction clear.

Much of the Pacific Ocean is bordered by subduction zones, where many of the world’s largest earthquakes (and accompanying tsunamis) are generated. Because Hawai‘i is far from any subduction zone, there is usually ample warning time (5–15 hours) between the occurrence of a great earthquake and the arrival of a tsunami. Since earthquake waves travel through the solid earth ten times faster than tsunami waves cross the ocean, a large earthquake can be detected well before the arrival of a tsunami.

Historically, tsunamis have caused significant damage in Hawai‘i. For example, the great earthquake of 1946 in the Aleutian Islands (M8.1) generated tsunamis that caused substantial damage and loss of life in Hawai‘i. Wave heights reached more than 15 meters (50 feet) on Hawai‘i Island, and 159 people were killed in the state. This disaster led to the establishment of the first tsunami warning system, now known as the Pacific Tsunami Warning Center (PTWC). It monitors earthquake activity around the Pacific (*Figure 10.26*), and it also monitors pressure sensors deployed in the ocean that are sensitive to the passage of a tsunami wave (*Figure 10.27*). In 1960, the largest earthquake ever recorded (M9.5) occurred off the Chilean coast, and again the damage was severe on Hawai‘i. Although the PTWC issued a warning, many people were complacent because large earthquakes in Kamchatka in 1952 and the

Aleutians in 1957 had not produced significant tsunamis in Hawaiʻi. The 1960 wave heights were highest (10 meters; 35 feet) in Hilo Bay, killing 61 people. The Chilean Maule earthquake of 2010 (M8.8) and the Japanese Tōhoku earthquake (M9.0) both produced smaller tsunamis in Hawaiʻi, with wave heights of 1–3 meters (3–10 feet). Both were well predicted by the PTWC, and no fatalities occurred. Heightened public awareness after the 2004 Sumatran earthquake and tsunami in the Indian ocean may have played a role.

Figure 10.26: Tsunami alert map from the PTWC, generated on August 8 2014. Earthquakes with the potential to generate a tsunami are displayed and ranked by predicted tsunami severity. On this date the five events mapped each carried a low tsunami risk, including an M4.5 earthquake in Hawaiʻi.

There is no simple relationship between the magnitude of an earthquake and the magnitude of tsunamis it may generate. The direction of the tsunami wave's arrival and how it interacts with local sea floor topography can greatly influence the wave's height. Tsunami waves can "bend" or refract around topographic features, as occurred in the case of the 1960 Hilo Bay tsunami.

Local earthquakes in Hawaiʻi can also generate tsunamis, for which warning times will naturally be much shorter. In 1975, an M7.2 earthquake off the southeast coast of Hawaiʻi generated a pair of tsunami waves, the second of which reached a height of 8 meters (26 feet) at Halapē and caused two fatalities.

watershed • *an area of land from which all water under or on it drains to the same location.*

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.*

hurricane • *a rapidly rotating storm system with heavy winds, a low-pressure center, and a spiral arrangement of thunderstorms.*

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

tropical depression • *an organized, rotating system of clouds and thunderstorms.*

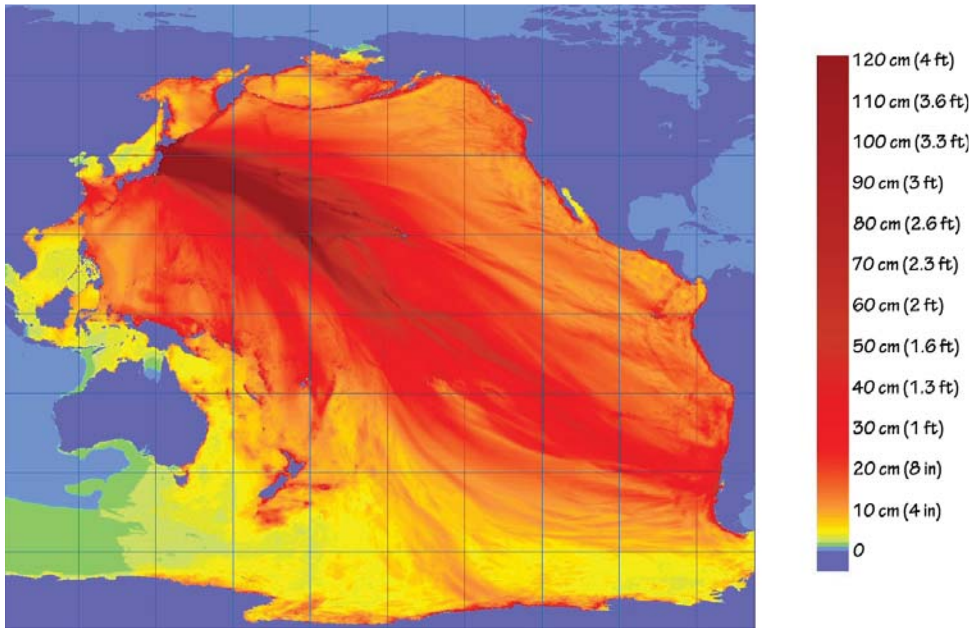

Figure 10.27: NOAA energy model and predicted wave height from the 2011 Tōhoku Japan tsunami. These are open-ocean wave heights; as the tsunami approaches a coastline the local landforms influence the wave height when it reaches shore.
(See TFG website for full-color version.)

Floods and Coastal Hazards

Hawai‘i is a mountainous tropical archipelago, thus floods are a frequent occurrence. Flash floods occur, on average, eight times a year in Hawai‘i, with the highest frequency seen during the rainy season from October to April (*Figure 10.28*). Hawai‘i’s **watersheds** are small and its streams are “flashy,” meaning that they can change quickly from dry to overflowing in a matter of minutes. Flood events cause landslides that can block roadways, or sometimes wash away a section of highway or infrastructure (e.g., water pipes, bridges, agricultural ditches). The rural nature of most of the Hawaiian Islands means that a washed-out road is a significant disruption, since few alternate routes exist. In addition, flash floods carry high sediment discharge, particularly in areas with degraded or highly modified terrestrial ecosystems. Hawai‘i’s fringing coral **reefs** are negatively impacted by pulses of flood-borne sediment, as corals require sunlight and clear water to maintain ecosystem health.

Like any coastal region, Hawai‘i is subject to **hurricanes** and storm surge. Hurricanes occur when a warm and moist tropical low-pressure air mass forms over portions of the ocean. These storms gather strength because the warm summer ocean water evaporates, creating very humid, low-pressure air. The air rises and condenses into water droplets that form clouds and release latent **heat**. The latent heat provides energy for even greater evaporation of warm ocean water, and thus the cycle continues until the low-pressure center moves over land. These storms are considered **tropical depressions** when wind

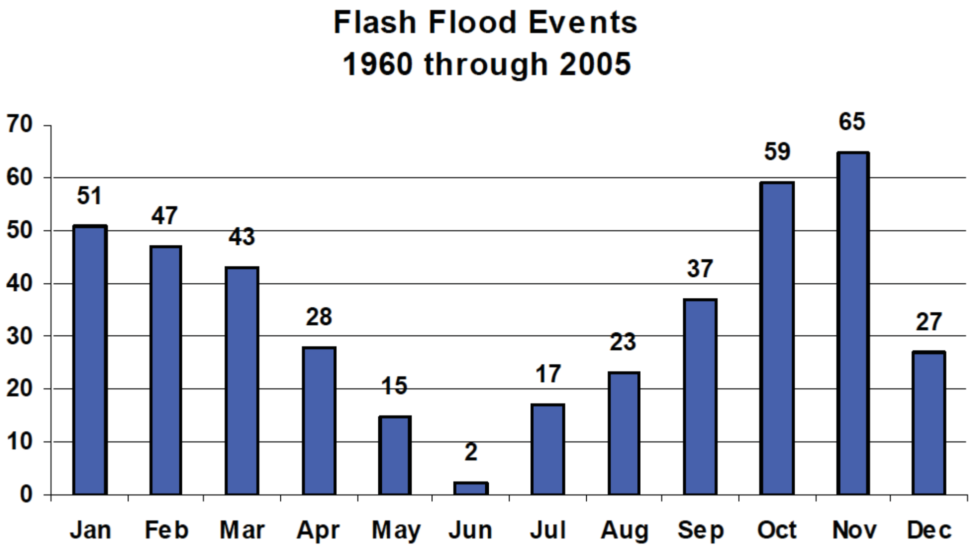

Figure 10.28: NOAA data on flash flood frequency in Hawai‘i.

speeds are below 63 kph (39 mph). As the storm develops a more organized structure, however, with more concentrated rising warm air in the center and bands of rain, it will officially become a tropical storm when its wind speeds reach the 63 to 117 kph (39 to 73 mph) range. Once winds have reached 119 kph (74 mph), the storm is classified as a hurricane. About four to five hurricanes occur in the central Pacific every year, but almost every storm system that reaches Hawai‘i has degraded to a tropical storm or tropical depression by the time it makes landfall. In terms of loss of human life, storm surge and high surf are the deadliest natural hazards in the Hawaiian Islands. Storms from any part of the Pacific can cause big swells and high surf on Hawaiian coasts. Hawai‘i’s north shores are famous for winter surf arising from storms in the north Pacific, while in summer, big waves strike south-facing shores.

Hazard Preparedness and Response

The historical record of natural disasters in Hawai‘i has prompted the creation of a robust system of warning and response for island communities. USGS seismometers, GPS, and associated instrumentation monitor earthquake and volcanic hazards, while NOAA buoys across the Pacific monitor marine conditions and NOAA/NASA satellites monitor the atmosphere and ocean (*Figure 10.29*). These inputs are networked with real-time response systems, including NOAA’s National Weather Service and PTWC, and Hawai‘i’s state and county Civil Defense offices. Hazard information is broadcast to the public through computerized warning services (e.g., radio, internet, reverse-911) and through an island-wide system of civil defense sirens.

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

heat wave • *a period of excessively hot weather that may also accompany high humidity.*

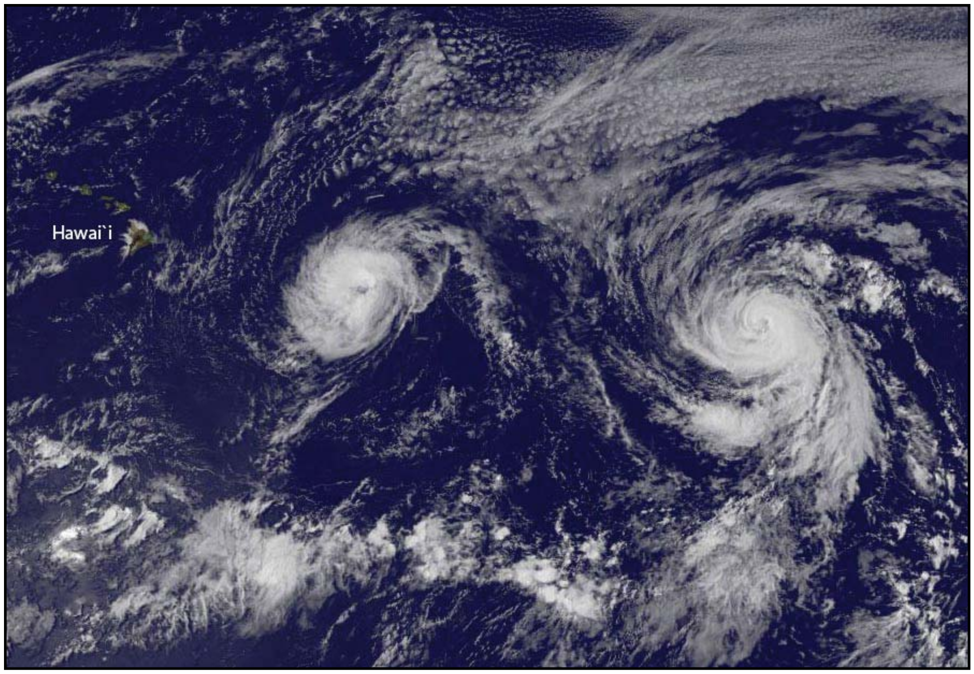

Figure 10.29: NASA MODIS image of hurricanes Iselle (left) and Julio (right) lining up on the Hawaiian Islands, August 6, 2014. Modern hazard forecasting and warning systems reduce the impact on humans.

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 West has been accompanied by more frequent **heat waves**, shorter winters, and an increased likelihood of drought and wildfires. The contiguous Western states are currently experiencing severe drought throughout, with the worst effects occurring in California and parts of Nevada (*Figure 10.30*). Increased dryness contributes to fire risk—in September 2014, the Eldorado National Forest near Sacramento, California experienced a massive wildfire that consumed more than 39,254 hectares (97,000 acres) of land and required the efforts of more than 8000 firefighters to combat the blaze.

See Chapter 9: Climate to learn more about how climate change will affect the West.

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

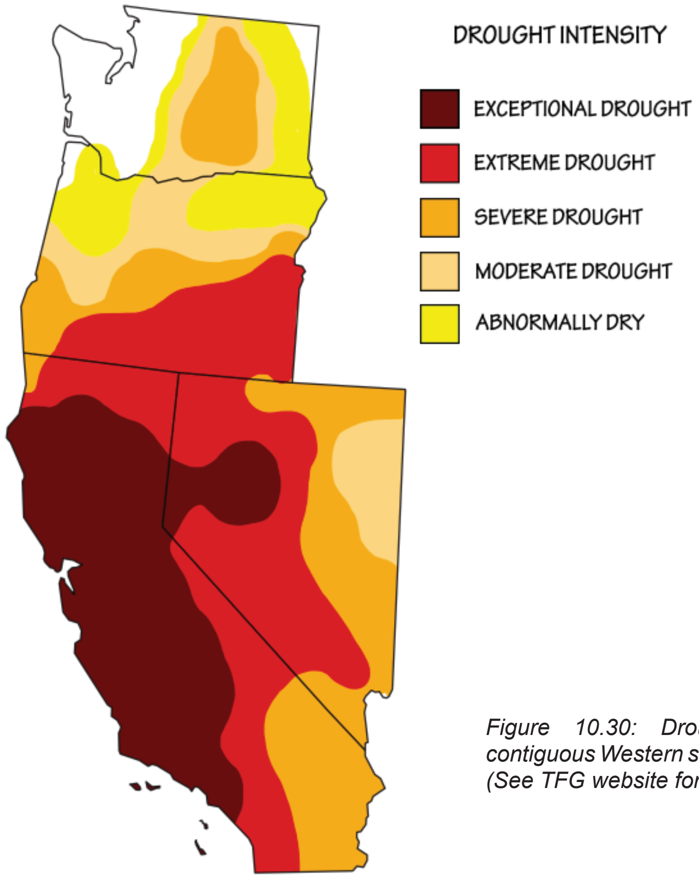

Figure 10.30: Drought severity in the contiguous Western states, as of August 2014. (See TFG website for full-color version.)

different impacts on rural and urban settings. In rural settings, agriculture and livestock can be greatly affected. Heat stress recommendations are issued to help farmers protect their animals, particularly pigs and poultry, which, unlike cattle, do not have sweat glands.

The impacts of heat waves on urban settings include a combination of the natural conditions of excessive heat and the social conditions of living in a densely populated space. Cities contain a considerable amount of pavement, which absorbs and gives off more heat than vegetation-covered land does. Air conditioning units that cool down the inside of buildings produce heat that is released outside. Pollution from cars and industrial manufacturing also elevates the outdoor temperature in cities. This phenomenon, in which cities experience higher temperatures than surrounding rural communities do, is known as the **heat island effect**. Other social conditions can cause an increase in the hazards associated with heat waves in urban areas. People who are in poor health, live in apartment buildings with no air conditioning, or are unable to leave their houses are at greatest risk of death during heat waves. In the summer of 2014, California broke a 120-year record for heat, with temperatures 2.5°C (4.6°F) hotter than average. Southern parts of the state also experienced severe heat waves in September and October of that year. The heat wave in September 2014 led to the cancellation of over 20 athletic events, as well as

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

tornado • *a vertical funnel-shaped storm with a visible horizontal rotation.*

over 100 schools shortening their school days. Los Angeles set a record for daily **energy** use, as people turned up their air conditioners in an effort to cool down. During the same month, Hawai'i's electric utilities struggled to generate enough electricity to power an associated spike in energy demand.

Water supply is also a critical issue for the Western states. Much of the West obtains its water from precipitation, snowmelt, and runoff, which will dramatically decrease in quantity as temperature and aridity rise. The Arctic is warming nearly twice as fast as the rest of the planet—summer sea ice around Alaska has decreased by about 12% every decade since the 1970s (*Figure 10.31*). With melting ice comes an increase in sea level, and all of the Western states except Nevada have a considerable amount of oceanic coastline which will be affected by sea level rise.

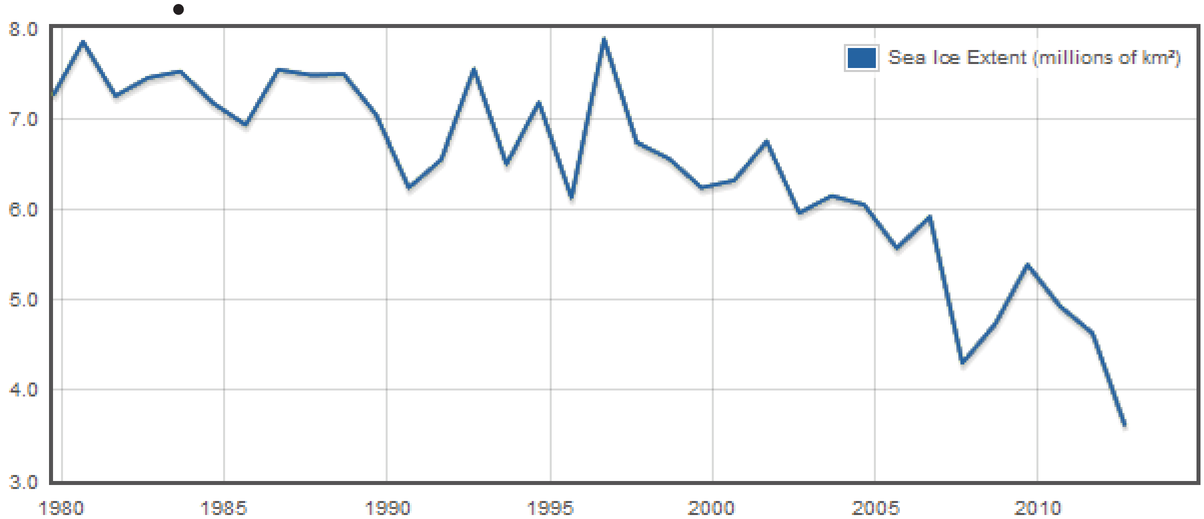

Figure 10.31: Extent of Arctic sea ice from 1979 to present. Measurements are made via satellite each September.

Increasing temperatures also allow for certain pests, such as ticks and mosquitoes, to live longer, thereby increasing the risk of contracting the diseases they carry. In addition, invasive insects that damage ecosystems, such as the spruce bark beetle in Alaska, will be better able to survive warmer winters, and will therefore increase and spread.

Another concern regarding hazards exacerbated by climate change in the West is whether or not there has been or will be an increase in the number or severity of storms, such as hurricanes and **tornadoes**. According to NASA, the present data is inconclusive in terms of whether hurricanes are already more severe, but there is a greater than 66% chance that global warming will cause more intense hurricanes in the 21st century. Since 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 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 10.32*).

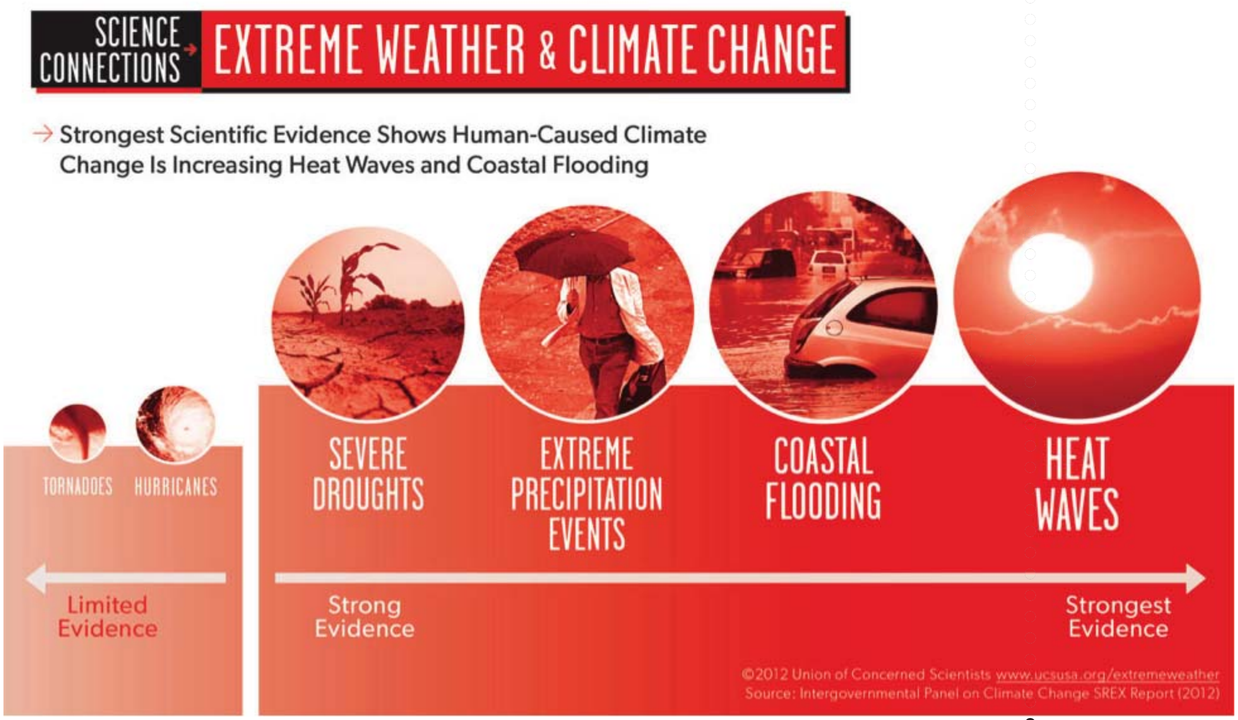

Figure 10.32: The strength of evidence supporting an increase in different types of extreme weather events caused by climate change. (See TFG website for full-color version.)

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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."*

Fieldwork 11

Safety

Safety and Logistics in the Field

At the Site

Considerations are different for an adult or a group of adults in the field than they are for taking students into the field, but certain measures related to safety are universal. At any field site, safety is the first priority. No photograph, measurement, or fossil is worth the risk of personal injury or death. To ensure safe and productive fieldwork, keep the following thoughts in mind:

- Always carry a small, standard first-aid kit.
- Wearing the proper clothing is very important. Long pants are recommended, as are sturdy boots, which will help prevent twisted ankles as you scurry over uneven or loose surfaces.
- While walking through a valley or next to any outcrop, always be on the lookout for rock falls. Remember, slopes with no vegetation tend to produce more falls.
- If more than one individual is climbing an outcrop, do not climb single file. Rocks dislodged from one climber can quickly tumble down the outcrop and hit the next climber.
- When using your rock hammer, protective eyewear should always be worn. If your hammer possesses a sharp pick opposite the flat surface, always use the flat surface when striking. And if you are working with others, notify all in the vicinity before striking any surface with your hammer.
- Never use one hammer to strike another. Metal chips can be broken off and thrown at high speeds.

Sunscreen, insect repellent, flashlights, food, and water should be considered in relation to environmental conditions and length of the field excursion. Please note that this chapter is written with shorter excursions in mind where substantial supplies will not generally be required. The next section offers more detail on the materials to take with you into the field.

Give appropriate consideration to group management. We suggest taking individual classes into the field for short trips before attempting either longer fieldwork excursions or trips with multiple classes. Managing larger groups or longer trips requires attention to logistics that will not be addressed in depth here. Whether the group is large or small, consider the benefits of a buddy system and measures to keep track of where everyone is—both children and adults. If groups are spread out on the trail, the lead group should stop at trail crossings to make sure everyone follows the intended trail. Younger students should not be left unsupervised for *any* length of time. Schedules and rendezvous points are important for longer trips and larger groups. All teachers and chaperones should have one another's cell phone numbers.

Things You Might Use in the Field

The Essentials and Near Essentials

As noted above, the essential materials for going in the field (besides yourselves) are clothing (especially footwear) that is suited to the weather and trail conditions and a first-aid kit appropriate to the situation. You will likely also want tools or devices to extend your senses, to preserve your observations, to collect materials (where safe and legal), to take photographs, and to store data, all of which will allow for continued observation and analysis after you return from the field. If your fieldwork is on the school grounds, or adjacent to it, you perhaps won't need anything different than what is needed on a typical class day, at least for the initial visit.

To extend your senses, start with simple things like magnifying loupes and rulers and potentially move on to include more sophisticated tools like probeware (to measure pH, temperature, and dissolved oxygen) or field microscopes. Since tools are used for both extending your senses and for capturing and preserving your observations, the most obvious tools for preserving one's observations are notebooks, pencils, cameras, GPS units, smartphones, and tablets.

As varied as field science is, a few items should be in every scientist's gear whether you are investigating rocks, observing streams, or documenting ecology. Even though processes and concepts are universal, each place is also unique, a product of its position on the Earth, its geological and ecological history, and the local human impacts. Making sense of why a place looks the way it does must take that context into account. Further, good science depends upon repeatability of observations: if another scientist (or your next class!) wants to analyze or build upon your observations, he or she must be able to know precisely where your study took place and how you made your observations. It is thus critical to locate the position of your studies on a map as precisely as possible. With modern GPS technology, it has never been easier to record a location to within a few meters, though you can certainly follow good science practices even if you don't have this capability. *Table 11.2* lists equipment and materials that are useful in the field.

Maps and Notebooks

Large-scale maps provide a way to see your field site in the context of other features in the area. At a closer scale they also provide a way to show the position of several sites relative to each other. At still higher resolution, maps provide the medium to store and display spatial information from one site. You will therefore probably want maps at all of these scales.

Large- and medium-scale maps for providing context can be found online. Google Maps and Google Earth are two of the best known interactive sources. If students need help understanding maps and scale, a helpful exercise is to create a "Powers of Ten" map of your schoolyard, starting with an overhead shot of the school yard that students recognize, then zooming out—making each of the new images increase in dimension by ten times—until one can see the site from the perspective of the whole Earth. A video tutorial, inspired

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	☐ **Ruler or scale card** ☐ Measuring tape or meter stick ☐ Magnifying loupe or hand lens (about 10× magnification) ☐ Water test kit ☐ Compass ☐ Clinometer ☐ Field microscope ☐ Field guides	☐ **Notebook** ☐ **Pencil** ☐ **Materials for collecting** o Baggies o Specimen labels o Sharpies ☐ Rock hammer ☐ Camera
Common sense *should be your guide when determining what is needed for a particular visit to the field. Trips that last a class period and are adjacent to the school may require nothing beyond materials for a typical class—a notebook and a pencil.*	**For Both Extending the Senses and Preserving Observations**	
	☐ **Maps** ☐ **Camera** (possibly with video) ☐ Probeware and interface (like the Vernier LabQuest) ☐ Digital field microscope ☐ GPS unit, smartphone, or tablet ☐ Apps used in the field might include: o GPS o Google Earth or other virtual globe o Skitch (or other image-annotating app) for adding notes to photos. Skitch also includes a map annotation function. o Photosynth or other panorama app o Video (the YouTube Capture app allows for basic video editing on your smartphone or tablet) o Other specialized photography apps o Audio recorder o Notes o Photo management software, such as Web Albums	

by the classic film, is available at http://www.virtualfieldwork.org. It is simple to add your field site to the same Google Earth file containing the Powers of Ten centered on your school. This can help students better understand the location of the field site in relation to the school.

Field scientists typically show information about their field site: the location of observations (such as photographs and specimen collection) and also the scientific data (such as rock type, position of faults, areas of bedrock exposure, water quality information, and much more). For these purposes you may want to have a paper copy of a map you can bring into the field upon which you can make notes. Commonly topographic maps are used as base maps, in part because the contours can help you locate yourself on the map (if it's not completely flat) and partly because the topography itself is often relevant to Earth and the environmental data being collected. If your field area is larger than about 100 meters (330 feet) on a side, you can create a topographic map tailored to your needs using online software (http://www.gpsvisualizer.com). USGS topographic maps of the entire US are available as free downloads at http://www.usgs.gov/pubprod/. You may wish to download the local map and take an excerpt of the area surrounding your site.

Needs

Positions of samples, photographs, and observations can be located using GPS. In this case, you can make notes about your GPS locations, and plot the locations on a computer later, or make use of an app like Skitch that allows you to annotate digital maps in the field. Photos taken with smartphones, tablets, and GPS-enabled cameras will include location data with pictures. Those familiar with Geographic Information Systems (GIS) can make elaborate maps using your own sets of coordinates and data. While GPS and GIS technology are now standard in most types of fieldwork, they are not essential for doing good fieldwork. Standard, intuitive tools for measuring are, however, quite helpful. A compass (either traditional or digital) can be helpful in orienting your field site in space, and a ruler and protractor can be helpful when drawing the field site in correct proportions (e.g., the position of samples along a transect or the angle of bedding or faults). Bring a clipboard so that you have a flat surface to write upon in the field—pencils and a good eraser are the best writing implements for drawing and annotating your map.

It is possible in principle to capture all your data electronically, but most field scientists still use a notebook even if they have access to the latest technology. Certain information can be captured very simply in the field with a pencil and paper while it may prove challenging with digital technology, such as when making annotated sketches of the field site and taking written notes. Normally pencil is used, in part because it doesn't smear if it gets wet, but also because it's erasable; while not essential, field scientists who know they may have to work in wet conditions will purchase notebooks with waterproof paper (Rite-in-the-Rain notebooks). An audio recorder (smartphone or standalone digital recorder) is handy when writing a lot of text is impractical, though it does create transcription work at the end of the day. Remember that it is considered a form of "best practice" to make sure that each entry includes the date, time, and locality.

Documentation and Specimen Collection

Photographs

Once at a field site it is easy to immediately begin taking photographs without recording notes to accompany them—a problem experienced by professional and amateur scientists alike. But the lack of proper documentation is perhaps the most common mistake made in the field, especially with digital photography, where it is easy to take tens or even hundreds of photographs at a single site. Also, before you begin photographing it is advisable to first explore the entire location and develop a plan for how you will communicate the site to your students back in the classroom. This plan will guide your photography, and the recorded notes will ensure that every image makes sense long after you've visited the site. Proper documentation includes the following steps:

- Note the location and orientation of the photographs you take. Recording this information on a map is very helpful.

- In each photograph, it is important to have a sense of scale. For smaller structures (like ripple marks or fossils) or close-ups of an outcrop or rock, it is important to show scale by using a common object, such as a penny, rock hammer, an unsharpened pencil, or (ideally) a clearly marked ruler. For larger structures, a really great scale is a person, so feel free to step into the picture! The importance of a scale cannot be overstated, as the proper identification of geologic features in photographs often depends on knowing the feature's size.

- In addition to showing scale within photographs, be sure to pay attention to different scales across the set of photographs you take. That is, include photographs across a wide range of scales, from the smallest fossil or mineral crystal to panoramic shots of the landscape. Maps and virtual globe software, such as Google Earth, can extend scales from the local landscape to a global perspective.

Drawings

Although photographs are key, simple sketches or drawings are also useful for documenting a field site. In fact, subtle changes in rock layers, for example, may not be visible in photographs, so to capture such features, drawing may be required. Drawing also forces you (or your students) to observe closely. It will be helpful to use either a Rite in the Rain notebook or a large, clear plastic bag to hold your notebook in case of rain. When drawing, keep in mind that you should document the same type of information that is documented in photographs (location, orientation, and scale). Drawing also requires close study in a way snapping a photograph does not. Louis Agassiz once said that "…a pencil is one of the best of eyes." While drawing, you have to think about the relationship of the elements you are representing, their scale, and their arrangement.

Annotating Photographs

The use of smartphones and tablets in the field allows for a hybrid of photographs and drawings. Many apps allow for captioning photos in the field, and some allow you to draw and write text on photos as you take them. Skitch is one such app, and it also allows for the taking of notes on the maps themselves. Photos taken on smartphones and tablets are also (typically) geo-referenced. This means that they can easily and quickly be included in a Google Earth or other GIS program in the precise location where the image was taken. If you are unable to annotate photographs in the field, or you wish to add more detail than is practical on your electronic device while you are at the field site, the "old fashioned" technique is to take a picture, then make a simple notebook sketch containing labels of key features. Later you can annotate a digital or printed version of the photograph using your field notes. If the conditions are poor for note taking either digitally or manually, it may be more practical to record audio notes that you can later match to your picture.

Using Field Guides

Select field guides appropriate to the focus of your work and consider whether or not you wish to bring others. The appropriate field guide might be something as simple as a single sheet with line drawings of the fossils common at your field site, a few pages containing a dichotomous key of common rock types, or a collection of field guides on fossils, birds, mammals, butterflies, rocks, flowering plants, and more. While scientists will come to know by sight the kinds of specimens commonly found at their site, they do not typically set out to memorize them, and uncommon things are sometimes found that send even experts back to their field guides.

Collecting Specimens

Rocks and fossils often provide significant clues for interpreting past environments. Layers of basalt indicate past volcanism, for example, whereas shales bearing trilobite and other fossils indicate deposition in a shallow sea. Collecting specimens from a site provides a wonderful opportunity to take a piece of the field into the classroom, allowing you to engage students in hands-on learning. Collecting specimens also permits further study away from a site where time and field conditions can impose certain limitations. You can and are encouraged to identify rocks, minerals, fossil types, and flora and fauna in the field. So, what do you need to know about collecting specimens?

- **You first need to confirm that collecting specimens at the site you are visiting is legal**. Typically, collecting is not allowed in parks, so be sure to check.

- Just as you made decisions about photography based on how you plan to communicate the site to students, collect specimens that will help tell the story of the site back in the classroom. If rock types change from area to area, either vertically or horizontally, then specimens of each type are ideal.

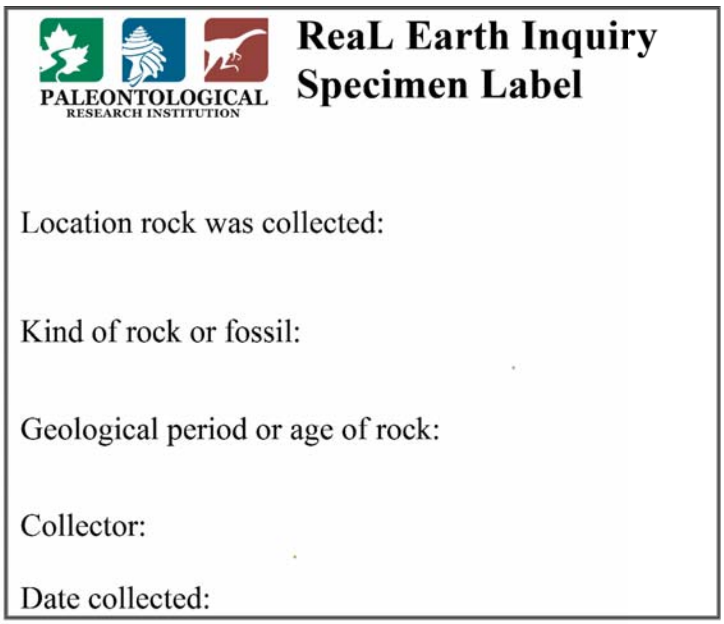
- Before collecting a specimen, take a photograph of it in situ, both close up as well as from a distance. Don’t forget to include an object for scale in the photograph!

- Document the location from which the specimen is collected, preferably on a map of the area. Labeling the specimen with a number that corresponds to a number on your map is an effective technique.

- Specimens should be broken directly from the outcrop so the exact source is known. Eroded rocks scattered about on the floor of the site may have originated from multiple locations.

- The weathered surface of rocks often carries a different appearance than a “fresh” break. Ideally, collected specimens possess one weathered surface but are otherwise not weathered. Rocks broken directly from outcrops will ensure fresh surfaces.

- As specimens are collected, place each in a separate resealable bag, noting on the bag with permanent marker each specimen's location as indicated on your map. Include a specimen label within the bag, including the information shown in *Figure 11.2*.


PALEONTOLOGICAL
RESEARCH INSTITUTION
ReaL Earth Inquiry
Specimen Label

Location rock was collected:

Kind of rock or fossil:

Geological period or age of rock:

Collector:

Date collected:

Figure 11.2: This specimen label, printed six to a page, is available for download at http://virtualfieldwork.org/Assessments_and_Student_Materials.html.

Back in the Classroom: Virtual Field Experiences (VFEs)

Following your trip to a field site, perhaps the most critical step after returning to your lab or classroom is to examine all of your photographs, illustrations, specimens, and notes associated with each. Sometimes even the most diligent geologist forgets to record notes that, in hindsight, are critical. It is therefore recommended that one makes sure that his or her notes are legible and complete. Recopy your notes. Such an activity will not only ensure legibility for the future, but it will help indicate any gaps in your note taking. If gaps exist, then it is easiest to fill them in when your memory of the site is fresh.

Once your materials from the site visit are in order, it is time to develop an activity that will allow your students to experience the site much like you did—but in the classroom. VFEs allow you to compile this information in a way that is easy to share with others who wish to learn about the site. Ideally, VFEs provide opportunities for open-ended exploration, just as actual fieldwork does. Scientists in the field are not limited to a single possible way to operate, nor do they have a guide explaining what they see at every turn. In the field, one might pick up a rock and take a closer look, or pull out a magnifying glass and look at a cliff face. Exploration drives inquiry in the field, and inquiry and exploration are key goals of VFEs.

The concept of VFEs can take on multiple forms. For example, kits containing maps, printed photographs, and specimens (with notes on the map indicating where the specimens were collected or where the photographs were taken) can be produced. Or, your digital photographs can be embedded within a PowerPoint or Prezi presentation, a website, or a Google Earth tour with placemarks containing photos, video, or other data in the exact locations where the specimens were collected. Maps can also be overlain. Historic maps can be included, and Google Earth has historical imagery included for much of the world. Many VFEs incorporate more than one technological platform.

Keep in mind that these electronic presentations may take on a very linear, directed feel. In that respect, be careful that your VFE does not turn into a Virtual Field Trip. Virtual Field Trips have become increasingly common at many levels of education, but these experiences are typically guided tours rather than opportunities for inquiry. An online search will yield many examples of these tours, as will a search of the Digital Library of Earth System Education (DLESE). Such resources clearly have value, but they are passive experiences for students. VFEs, in contrast, should stress the importance of inquiry; learning for understanding involves students figuring things out. The act of making new, or extending existing, VFEs may be the simplest way to bring inquiry to the use of VFEs.

In considering VFEs as a recurring practice, initial experiences are perhaps more guided than the later experiences; allow a gradual transfer of responsibility from teacher to student. But VFEs ideally offer the same opportunities for exploration as those provided at an actual field site, with occasional moments of discovery that lead to new questions about the site. By asking such questions and then seeking answers, students are doing science. And it is perfectly reasonable to virtually visit a site several times for further data collection, or even to study different concepts at the same site. Scientists, of course, do exactly the same thing.

Prezi and PowerPoint VFE Templates

This section discusses templates intended to simplify VFE production in addition to providing general information on VFE development and use. There are templates in both Prezi and PowerPoint formats, each with a version of the graphic organizer shown in *Figure 10.1* as its centerpiece. Questions in the graphic organizers and in the rest of the templates are written generically, so they may be applied to any site. The templates serve as starting tools that are useful for creating an “entry level” VFE. They are available at http://virtualfieldwork.org/Template.html. The template includes graphic organizers for both Earth and environmental science, with the environmental science organizer embedded within the geoscience organizer.

How are teachers using virtual fieldwork?

VFEs might be used as a single, in-class exercise, or they can be explored across an entire year. We hope that teachers who use and develop VFEs will eventually use them across the entire curriculum, but it makes sense to start smaller. There is no single correct approach to using VFEs in the classroom. Here are some examples of ways teachers are using virtual fieldwork:

- Students in a rural community are using Google Earth to create Powers of Ten tours centered on their homes (based on the Eames' classic film). This helps students to internalize the abstraction that is central to making maps and to build deeper understandings of scale.
- Students are making geologic maps of the local bedrock.
- Students are creating an interpretive guide for a county forest.
- Students are exploring lakes, dams, streams, outcrops, quarries, waterfalls, and more.

For more VFEs, see our growing database at http://virtualfieldwork.org/.

What do I need to consider as I begin to build my VFE?

Considerations fall into four categories:

- **Logistical:** What do I have the attitude, time, resources, and skills to do? (Attitude is listed first as it is the most important factor.)
- **Pedagogical:** How do I bring the scientific content together with technologies in a way that best builds enduring understandings of bigger ideas and overarching questions, as well as of the smaller scale ideas and questions I deem important?
- **Technological:** What hardware and software do I need to assemble the materials for the VFE and to make it accessible to my students? This may include traditional scientific tools, like a rock hammer or a compass, as well as the computer technologies discussed in this chapter and on our website.
- **Content:** What scientific knowledge, ideas, processes, and practices do I want my students to understand and be able to do at the end of the experience?

Of course, these categories overlap and interplay substantially—teachers of Earth science use Google Earth in different ways than other Google Earth users do.

11 Fieldwork

VFEs

Most of the remainder of this chapter is a set of checklists to help you address these different considerations when outlining your VFE design. Take it with you into the field as you collect pictures and other kinds of data for your VFE; use it to identify issues you think are most important for the development of your VFE. Most of the items in the checklists are there to start you thinking about how to address a particular issue. Content is listed last for the sake of readability, as the checklists for the content section are longer than they are for the other categories.

The framework for understanding how to effectively blend technology, pedagogy, and content knowledge is known by its acronym TPACK.

Table 11.3: A checklist of cross category issues. Many of the questions in the checklist relate to more than one of the categories identified above. Because of this overlap, only the cross-category issues and content sections are of significant length.

Have I considered this?	**Question:**	Logistical	Pedagogical	Technical	Content
	Do I have appropriate safety and first aid equipment and materials?	√		√	
	What content do I want to address?	√	√	√	√
	Do I have connections in mind to at least a couple of the bigger ideas and overarching questions? • The Earth is a system of systems. • The flow of energy drives the cycling of matter. • Life, including human life, influences and is influenced by the environment. • Physical and chemical principles are unchanging and drive both gradual and rapid changes in the Earth system. • To understand (deep) time and the scale of space, models and maps are necessary. • How do we know what we know? • How does what we know inform our decision-making?		√		√
	How much time do I realistically have to spend on VFE creation?	√			
	How much class time do I want to dedicate to VFEs?	√	√	√	√
	Am I okay with the trade-off between some expected frustration and the pedagogical payback?	√	√	√	√
	Can I productively engage students in VFE development? *Or is that something to aspire to for next year?*	√	√	√	√
	How does the technology I have serve the goals I wish to meet?	√		√	
	Do I have enough batteries for my powered equipment?	√		√	
	Is the site accessible to me? *This includes legal, safety and proximity considerations.*	√	√		
	Are my students familiar with the site? If not, is it accessible to *all* of my students? *If the answer to both questions is no, select another site.*	√	√		
	Are the required pedagogical, technological, and content skills and knowledge needed to create the VFE within my reach? *Ideally, select challenges that are just within (or just beyond) your reach so that you grow professionally.*	√	√	√	√
	Do I have the hardware (including field equipment) and software needed for VFE creation? *The bare essentials are an Internet-connected computer, a digital camera, and either PowerPoint or Google Earth.*	√	√	√	

Logistical

We hope that VFE development is used to expand teachers' skills and knowledge. Performing fieldwork for the first time can be overwhelming, but remember that science is a process, and not even professional scientists capture all that they need in one visit. With practice, and the proper attitude, you will become more and more comfortable when visiting the field.

Pedagogical

While most pedagogical questions also address other categories as noted above, there are issues that deserve explicit attention here.

- Does the data you are collecting go toward answering why this place looks the way it does? *Or is there a good reason to introduce distracting information?*

- If the site is especially striking or unusual, have you considered how to get yourself and your students beyond the “novelty space” of the location? Crudely summarized, novelty space is the idea that you can’t figure out what’s going on at a field site if you’re either awed by its beauty or freaked out by its perceived dangers. This is one of several reasons for choosing a site that is already familiar to the students.

Technological

Most technological issues are also logistical; these are addressed in the table above.

Content

Why does this place look the way it does? The driving question of our work can serve as an entry into any major topic in Earth or environmental science curricula. It also brings relevance to the science since we want to start with sites near the school that are already somewhat familiar to the students. We want students to look at the familiar with new eyes, and to become skilled at reading their local landscape. Ultimately, we want the skills built by reading the local landscape (being able to tell the story of why a place looks the way it does) to be transferable to *any* landscape.

What scientific content do you want your students to better understand through their work in the VFE? How does this fit into the larger goals of the course? Can you draw, and help your students to draw, connections to bigger ideas and overarching questions? What topics in Earth science can be addressed by doing fieldwork?

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.

VFEs

For the Geosciences:

For all of the following questions:

- How do you know? (What evidence is there?)
- What does it tell you about past environments?
- What does it imply about the future?

☐ **Describe the shape of the land.**

- Are there mountains, valleys, or hills?
- What are the valley shapes?
- What can cause valleys to form?
- What can cause mountains or hills to form?
- Are the mountains or hills young or old?
- What roles does tectonics play in shaping the site?

☐ **What effects has water had on the landscape?**

- Is water depositing material, eroding material, or both?
- Is the action of water primarily chemical, primarily physical, or both chemical and physical?

☐ **What effect has the climate had on the landscape?**

- Was the past climate different?
- What factors may have been affected or caused by climate?
- How has fire played a role in shaping the environment?

☐ **Describe the ecosystem.**

- See the ecosystem graphic organizer and checklist.

☐ **What does the arrangement of the rocks and soils indicate about past conditions?**

- Do the rocks seem to form a sequence?
- Where would you find the oldest rocks? The youngest rocks?
- Does the rock record include evidence of ancient disturbances? If yes, describe.
- Are there different kinds of rocks at different outcrops?

☐ **What types of rock and soils are there and what do they indicate about past conditions?**

Sediments and Sedimentary Rocks

- Is the sample clastic or organic /chemical?
- If clastic, what is the grain size?
- If organic, what minerals is it made out of?
- Are there fossils?

Metamorphic

- Is the rock foliated or non-foliated?
- What was the parent rock?

Igneous

- Did the rock form above or below ground?
- Is it felsic or mafic?

☐ **What effects has life, including human life, had on the landscape?**

- How have plants shaped the landscape?
- How have animals generally, and humans in particular, changed the landscape?
- On what scale?

For the Environmental Sciences:

For all of the following questions:

- How do you know? (What evidence is there?)
- What does it tell you about past environments?
- What does it imply about the future?

☐ **Describe how life shapes the land.**

- What are the pioneer plants?
- How do pioneer plants impact soil formation?
- How are animals shaping the land?
- Are there invasive species? If yes, what are they, and how are they changing the ecosystem?
- Have disturbances played a role in the introduction of invasives? If yes, describe.
- How are new invasives likely to change the ecosystem over the next century?

☐ **Describe the role of water in the ecosystem.**

- In what ways does water serve or disturb habitats?
- How does life move, use, and store water?

☐ **How has climate shaped the ecosystem?**

- How is the climate reflected by living things at the site?
- Describe any microclimates and how they affect life.
- Describe how sun and shadow affect life.
- What roles do fire, hurricanes, or other climate-related disturbances play in shaping this landscape?

☐ **Describe the role rocks and soil play in the ecosystem.**

- How does life change the rocks and soil at the site?
- How is life dependent upon the rocks and soil at the site?
- Does the rock record include evidence of ancient disturbances? If yes, describe.
- See also the geoscience questions.

☐ **Describe the types and arrangements of plants and animals and what they indicate about present and past environments.**

- Why do living things in the environment look the way they do?
- What life forms were the earliest to arrive?
- Describe how different life forms are distributed throughout the field site.
- What is the impact of invasive species and other disturbances?
- See also the **Describe how life shapes the land** section.

Plants

- How have plants shaped the landscape?
- How has the landscape affected the plants?

Animals

- How do animals contribute to plant distribution?
- How has the landscape affected the animals?

Other biota

☐ **What effects have humans had on the landscape?**

- What resources do humans use from here?
- How have humans changed the landscape?
- On what scale?

Closing 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.

Orion, N., & A. Hofstein, 1994, Factors that influence learning during a scientific field trip in a natural environment, *Journal of Research in Science Teaching,* 31: 1097–1119.

Russell, H. R., 1998, *Ten-Minute Field Trips: 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, & 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, & 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/.

Lambert, D., 2006, *The Field Guide to Geology, new edition,* Infobase Publishers, New York, 298 pp.

Lisle, R., P. Brabham, & J. Barnes, 2011, *Basic Geological Mapping,* John Wiley & Sons, Chichester, UK, 217 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 the *Big Ideas* chapter) and work across grade-levels to build understandings over time. This may mean, however, that your favorite topics are no longer explicitly listed in the learning goals.

Table A.1 contains abbreviated versions of the Concepts, Practices, and Ideas. You can find longer descriptions within the NGSS, and we'll look at one as an illustrative example. Consider the full description of Crosscutting Concept #3:

> *Scale, proportion, and quantity.* In considering phenomena, it is critical to recognize what is relevant at different measures of size, time, and energy and to recognize how changes in scale, proportion, or quantity affect a system's structure or performance.

It seems likely that most Americans do not have a good and durable understanding of this concept, yet it has relevance to many aspects of their daily lives. The same could be said of most, if not all, of the remaining concepts on the list.

The Crosscutting Concepts are described in some detail in Appendix G of NGSS, and the Scientific and Engineering Practices are described in Appendix F.

Such understandings are almost certainly more important than knowing particular facts about geologic history or the nature of disease (two topics not given deep attention in the NGSS). Indeed, it's only possible to understand geologic history or the nature of disease if you also understand these concepts!

While your favorite topics may not be explicitly mentioned in NGSS, that doesn't necessarily preclude them from being taught. There's a tremendous amount of content in these *Teacher-Friendly Guides*™ 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

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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.

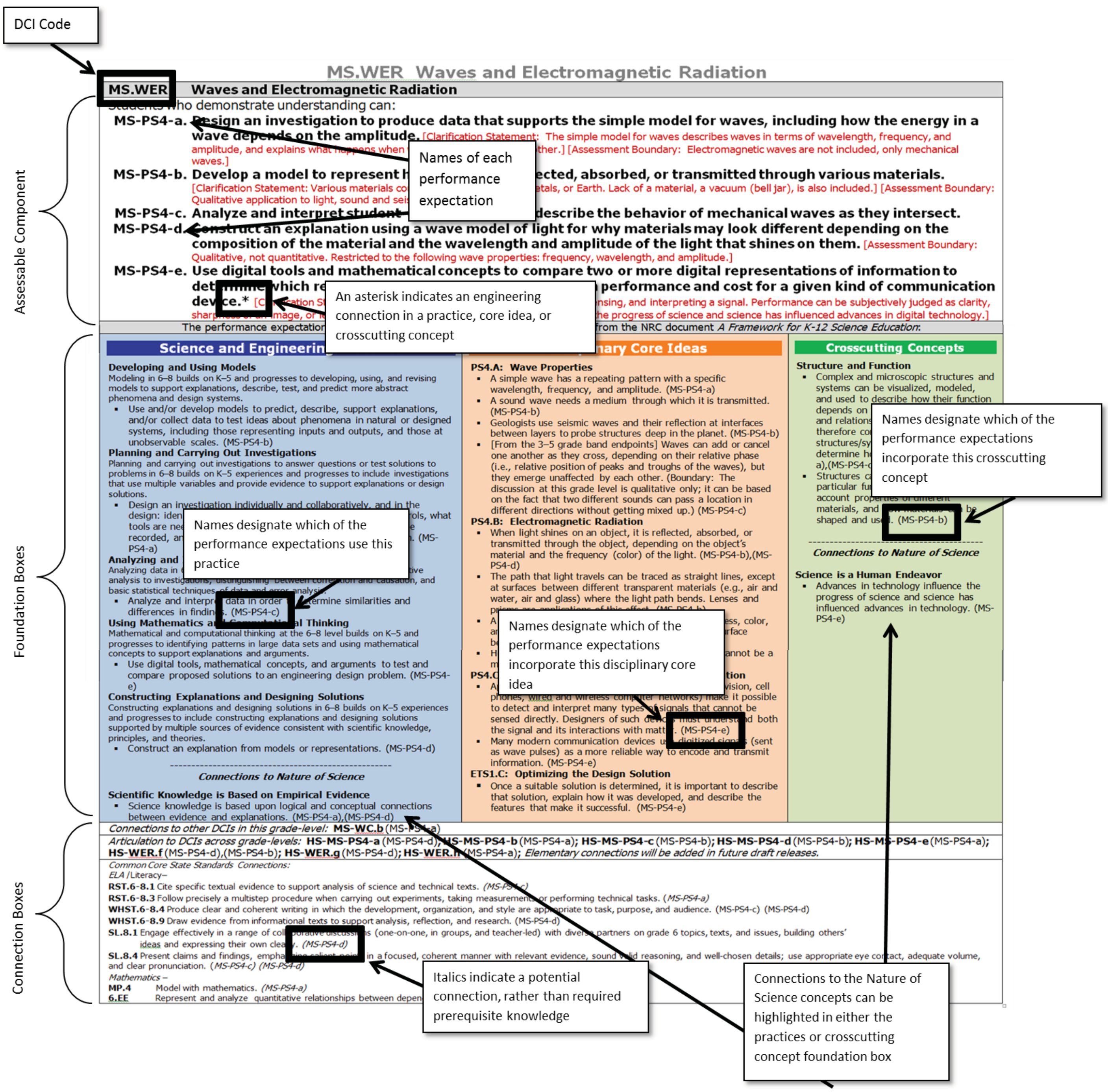

Figure A.1: The architecture of a standard. The NGSS is designed with the web in mind and features of its online architecture make it easier to understand than this diagram might indicate.

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* *__the cycling of__* 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 *__at varying time and spatial scales__*.

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.

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.

MS-ESS2-5. *Collect data to provide evidence for how* the motions and complex interactions of air masses *__results in changes__* in weather conditions.

MS-ESS2-6. *Develop and use a* *__model to describe how__* unequal heating and rotation of the Earth cause patterns of *__atmospheric and oceanic circulation that determine__* 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 (***__underlined italics__*** 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.

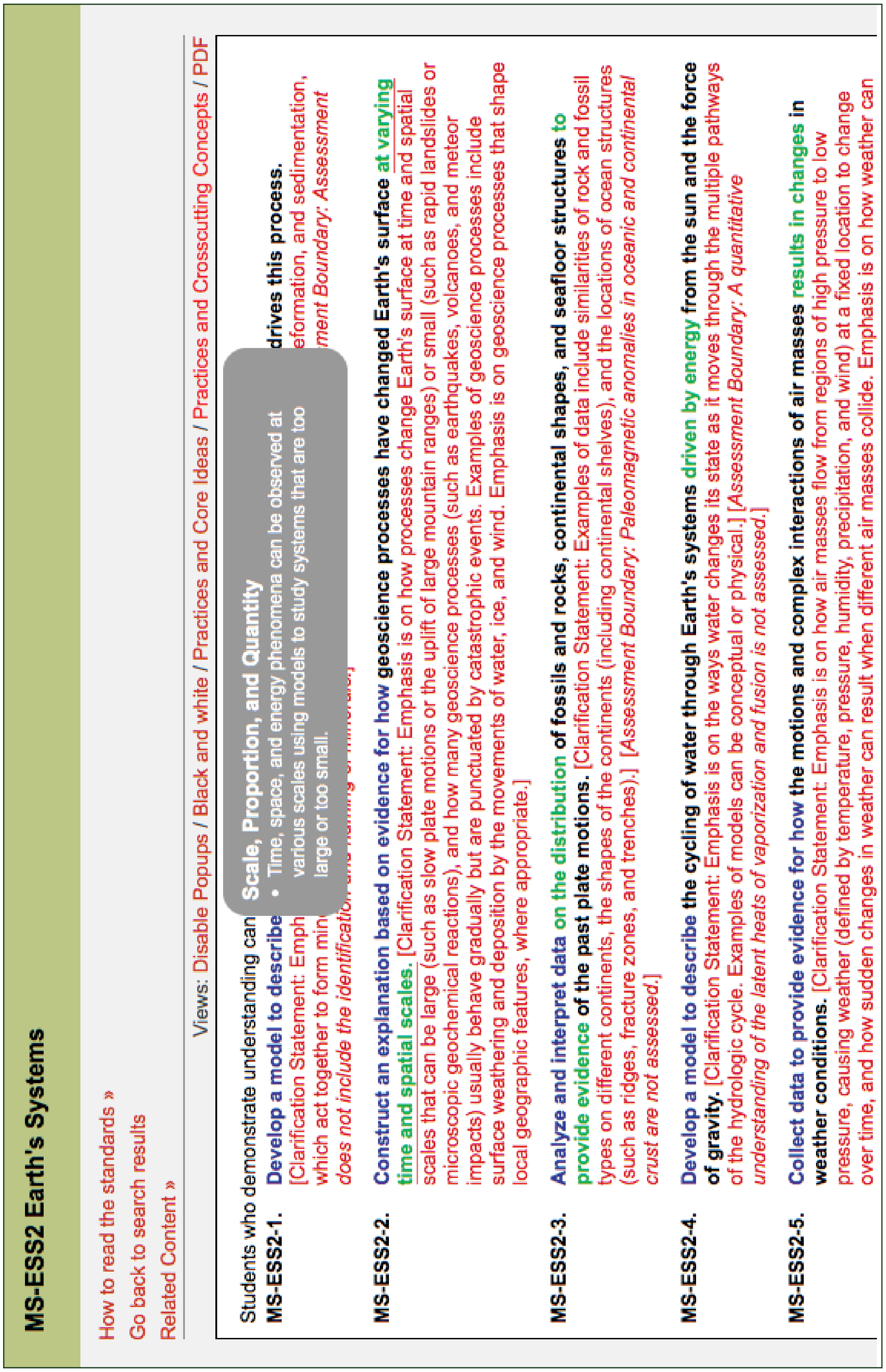

Figure A.2: A screen-grab of part of the middle school standard on Earth Systems: MS-ESS2. Shown here are the first three PEs, with the first partially obscured by a pop-up related to the CC in the second.

Appendix

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.

Appendix

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, & 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

'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. See also: lava
ablation zone	The front part of a glacier, where ice is lost due to melting and calving. See also: calving, glacier
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. See also: sedimentary rock, terrane
accretionary prism	a pile of sediments and ocean crust, scraped off a descending plate during subduction, and piled onto the overlying continental crust. See also: crust, plate, subduction
accumulation zone	the highly elevated part of a glacier, where annual snow accumulation outpaces snow loss. See also: glacier
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: convergent boundary, subduction, transform boundary
adaptive radiation	process in which many new species evolve, adapting to vacant ecological niches in a relatively short interval of geological time. Examples occur across a range of scales, from the diversification of numerous species from a single species (e.g., Galapagos finches) to the diversification of higher taxa into previously unoccupied environments or into niches vacated through mass extinction (e.g., mammals after the extinction of dinosaurs). See also: extinction
aeolian	pertaining to, caused by, or carried by the wind. Aeolian sediments are often polished, giving them a "frosty" appearance. The name comes from Aeolus, the Greek god of wind. See also: wind
aerosol	tiny solid or liquid particles in the air. Examples include dust, smoke, mist, and human-made substances such as particles emitted from factories and cars.
agate	a crystalline silicate rock with a colorful banded pattern. It is a variety of chalcedony. Agates usually occur as nodules in volcanic rock. See also: chalcedony, nodule, silica, volcanic

Glossary

aggregate	crushed stone or naturally occurring unlithified sand and gravel, used for construction, agriculture, and industry. Aggregate properties depends on the properties of the component rock. Rock quarried for chrushed stone includes, for example, granite and limestone. See also granite, limestone, lithification
Alfisols	a soil order; these are highly fertile and productive agricultural soils in which clays often accumulate below the surface. They are found in humid and subhumid climates. See also: climate, soil, soil orders
alkalic basalt	a fine-grained dark basaltic lava containing a high proportion of silicates, and relatively high in sodium and potassium. See also: basalt, lava, silica
alluvium, alluvial	a thick layer of river-deposited sediment.
amber	a yellow or yellowish-brown hard translucent fossil resin that sometimes preserves small soft-bodied organisms inside. See also: fossil
ammonoid, ammonite	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. See also: cephalopod, extinct
amphibole	a group of dark-colored silicate minerals, or either igneous or metamorphic origin. See also: igneous rock, mineral, metamorphism, silica
andesite	a fine-grained extrusive volcanic rock, with a silica content intermediate between that of basalt and dacite. See also: basalt, dacite, extrusive rock, silica, volcanic
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. See also: soil, soil order, volcanic
anthracite	a dense, shiny coal that has a high carbon content and little volatile matter. Anthracite is as much as 95% carbon. Found in deformed rocks, anthracite is the cleanest burning of the three types of coal, because it contains the highest amount of pure carbon. See also: coal

a Glossary

anthropogenic	caused or created by human activity.
archaeocyathid	a vase-shaped organism with a carbonate skeletons, 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. See also: Cambrian, extinction, reef
Archean	a geologic time period that extends from 4 billion to 2.5 billion years ago. It is part of the Precambrian. See also: geologic time scale, Precambrian
arête	a thin ridge of rock with an almost knife-like edge, formed when two glaciers erode parallel valleys. See also: erosion, glacier
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. See also: climate, salt, soil, soil order, weathering
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. See also: extinction, trilobite
asphalt	a black, sticky, semi-solid and viscous form of petroleum. See also: petroleum
asthenosphere	a thin semifluid layer of the Earth, below the outer rigid lithosphere, forming the upper part of the mantle. The heat and pressure created by the overlying lithosphere make the solid rock of the asthenosphere bend and move like metal when heated. The layer is thought to flow vertically and horizontally with circular convection currents, enabling sections of lithosphere to subside, rise, and undergo lateral movement. See also convection, lithosphere, mantle.
atmosphere	a layer of gases surrounding a planet. Earth's atmosphere protects living organisms from damage by solar ultraviolet radiation, and it is mostly composed of nitrogen. Oxygen is used by most organisms for respiration. Carbon dioxide is used by plants, algae and cyanobacteria for photosynthesis.

atoll	a circular or horseshoe-shaped coral reef, surrounded by deep water and enclosing a shallow lagoon. The rim of the coral often extends above the water, sometimes creating a small beach or sandbar. Atolls tend to form as reefs grow around the rim of extinct volcanoes. As the volcanic peak erodes and the volcano subsides beneath the water's surface, the reef grows upward and a lagoon is formed within the reef. Atolls range in diameter from 1 kilometer (0.6 miles) to more than 130 kilometers (81 miles). See also: caldera, erosion, reef, scleractinian coral
basalt	an extrusive igneous rock, and the most common rock type on the surface of the Earth. It forms the upper surface of all oceanic plates, and is the principal rock of ocean/seafloor ridges, oceanic islands, and high-volume continental eruptions. Basalt is fine-grained and mostly dark-colored, although it often weathers to reds and browns because of its high iron content. Basaltic magmas are produced by partial melting of the upper mantle. Materials melt when we increase their temperature, but a second way to melt a solid is to decrease the pressure. In the interior of the Earth this second mechanism—decompression—is far more important. When pressure on the mantle is released as it is forced up through the crust due to subduction, it becomes basaltic magma. See also: igneous, iron, magma, mantle, plate tectonics
basaltic andesite	a dark, fine-grained rock that is intermediate between basalt and andesite in silica content. Basaltic andesite is produced when the magmatic source of eruption is in transition between a deeper source, which tends to produce basalt, and a shallower source, which tends to produce andesite. See also: andesite, basalt, magma, silica
basement rocks	the foundation that underlies the surface geology of an area, generally composed of igneous or metamorphic crystalline rock. In certain areas, basement rock is exposed at the surface because of uplift or erosion. See also: erosion, igneous rock, metamorphic rock, uplift
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. See also: igneous rock, intrusion, pluton
bathymetry	the topography of an underwater landscape. See also: topography

b

Glossary

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. See also: metamorphism, sandstone, sedimentary rock, stromatolite
bentonite	a clay, formed from decomposed volcanic ash, with a high content of the mineral montmorillonite. See also clay, mineral.
biodiversity	the number of kinds of organisms at any given time and place. Global changes in biodiversity through geologic time tells paleontologists that something is happening to the rate of extinction or the rate of origin of new species. Regional changes are influenced by migration, or the number of species supported by available food and space resources. See also: extinction, geologic time scale
biofuel	carbon-based fuel produced from renewable sources of biomass like plants and garbage. Energy is obtained through combustion, so greenhouse gases are still produced. Because plants get their carbon from the air, burning them for energy and re-releasing it into the air has less effect on climate than fossil fuels, whose carbon is otherwise sequestered away from the atmosphere. See also: biomass, fuel
biomass	organic material from one or more organisms.
biota	the organisms living in a given region, including plants, animals, fungi, protists, and bacteria.
bitumen	any of various flammable mixtures of hydrocarbons and other substances, occurring naturally or obtained by distillation from coal or petroleum, that are a component of asphalt and tar and are used for surfacing roads and for waterproofing. See also: coal, petroleum
bituminous coal	a relatively soft coal containing a tarlike substance called bitumen, which is usually formed as a result of high pressure on lignite. See also bitumen, coal, lignite.

Glossary

bivalve	a marine or freshwater invertebrate animal belonging to the Class Bivalvia (or Pelecypoda) in the Phylum Mollusca. Bivalves are generally called “clams,” but they also include scallops, mussels, cockles, and oysters. Bivalves are characterized by right and left calcareous shells (valves) joined by a hinge. Most are filter feeders, collecting food particles from the water with their gills. During the Paleozoic, bivalves lived mostly on the surface of the ocean floor. In the Mesozoic, bivalves became extremely diverse and some evolved the ability to burrow into ocean floor sediments. See also: filter feeder, Mesozoic, Paleozoic
body fossils	fossils that consist of an actual part of an organism, such as a bone, shell, or leaf. See also: fossil
boreal	a cold temperate region relating to or characteristic of the sub-Arctic climatic zone, often dominated by conifers, birch, and poplar. See also: climate, conifer
boundary layer	the atmospheric layer closest to the surface of the Earth, which has a high relative humidity and is affected by the Earth's heat and moisture. See also: atmosphere
brachiopod	a marine invertebrate animal belonging to the Phylum Brachiopoda, and characterized by upper and lower calcareous shell valves joined by a hinge, and a crown of tentacles (lophophore) used for filter-feeding and respiration. Brachiopods are the most common fossil in Paleozoic sedimentary rocks. Brachiopods look somewhat similar to the clams that you find at the beach today. Brachiopods and bivalves both have a pair of hinged shells (valves) to protect themselves while feeding. However, the soft parts of modern brachiopods tell us that they are completely unrelated to bivalves. Brachiopods have a special structure formed by tissue with thousands of tiny hair-like tentacles stretched along a coiled piece of internal shell material. These tentacles catch and move small particles towards the mouth. This body plan is very different from that of bivalves, which have a larger fleshy body and collect particles with their gills. To tell the difference between a brachiopod and a bivalve, look for symmetry on the surface of the shell. Bivalve valves are of equal size and mirror image shapes. Brachiopods' bottom valves, however, are slightly bigger and often have a different shape. See also: filter feeder, bivalve, fossil, Paleozoic
breccia	a pyroclastic rock composed of volcanic fragments from an explosive eruption. See also: pyroclastic, volcanic
British Thermal Unit (BTU or Btu)	the most commonly used unit for heat energy. One Btu is approximately the amount of heat required to raise one pound of water by one degree Fahrenheit. A Btu is also about the amount of energy released by burning a single wooden match. See also: energy, heat

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bryozoan	a marine or freshwater, colonial invertebrate animal belonging to the Phylum Bryozoa, and characterized by an encrusting or branching calcareous skeleton from which multiple individuals (zooids) extend from small pores to filter-feed using crowns of tentacles (lophophores). Bryozoans have a long and exemplary fossil record. One of the more common Paleozoic varieties looks like fine mesh cloth with numerous tiny holes in which the individual animals in the colony lived. Although they function somewhat like coral, and are often found in similar environments, bryozoans are more closely related to brachiopods. See also brachiopod, fossil
calcite	a carbonate mineral, consisting of calcium carbonate ($CaCO_3$). Calcite is a common constituent of sedimentary rocks, particularly limestone. See also: carbonate rocks, calcium carbonate, limestone, mineral, sedimentary rock
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. See also: calcite
caldera	a collapsed, cauldron-like volcanic crater formed by the collapse of land following a volcanic eruption. See also: volcanism
calving	when ice breaks off from the end of a glacier (sometimes into a lake or ocean, sometimes over the edge of a cliff). See also: glacier
calyx	the head of a crinoid. See also: crinoid
Cambrian	a geologic time period lasting from 541 to 485 million years ago. During the Cambrian, multicellular marine organisms became increasingly diverse, as did their mineralized fossils. The Cambrian is part of the Paleozoic Era. See also: fossils, geologic time scale, Paleozoic
carbonate rocks	rocks formed by accumulation of calcium carbonate, often made of the skeletons of aquatic organisms such as corals, clams, snails, bryozoans, and brachiopods. These organisms thrive in warm, clear shallow waters common to tropical areas, therefore modern carbonate rocks are observed forming in places such as the Florida Keys and the Bahamas. They are also one of the dominant rock forms of the bottom of the ocean, where sediments form from the skeletons of planktonic organisms such as foraminifera. Carbonate rocks include limestone and dolostone. See also: brachiopod, bryozoan, dolostone, foraminifera, limestone

Carboniferous	a geologic time period that extends from 359 to 299 million years ago. It is divided into two subperiods, the Mississippian and the Pennsylvanian. By the Carboniferous, terrestrial life had become well established. The name Carboniferous means "coal-bearing," and it is during this time that many of today's coal beds were formed. The Carboniferous is part of the Paleozoic. See also: coal, geologic time scale, Mississippian, Pennsylvanian, Paleozoic
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. See also: mineral, 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. See also: geologic time scale, Mesozoic, Neogene, Paleogene, Quaternary
cephalopod	a marine invertebrate animal belonging to the Class Cephalopoda in the Phylum Mollusca, and characterized by a prominent head, arms and tentacles with suckers, and jet propulsion locomotion. Cephalopods are swimming predators with beak-shaped mouthparts. The shells of cephalopods range from long straight cones to spirals, but some have internal shells or no significant shell at all, like the octopus.The group includes belemnites, ammonoids, nautilus, squid, and octopuses. A mass extinction between the Cretaceous and Paleogene eliminated many varieties of cephalopods. See also: Cretaceous, mass extinction, Paleogene
chalcedony	a crystalline silicate mineral that occurs in a wide range of varieties. See also: mineral, silica
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. See also: copper, iron, mineral, pyrite
chalk	a soft, fine-grained, easily pulverized, white-to-grayish variety of limestone, composed of the shells of minute planktonic single-celled algae. See also: limestone

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chemical fossils	chemicals produced by an organism that leave behind an identifiable record in the geologic record. Chemical fossils provide some of the oldest evidence for life on Earth. See also: fossil
chemical reaction	a process that involves changes in the structure and energy content of atoms, molecules, or ions but not their nuclei. See also: energy
chert	a sedimentary rock composed of microcrystaline quartz. It is often found as nodules or concretions in limestone and other marine sedimentary rocks. As these rocks form, water moving through them transports small amounts of silicon dioxide that accumulate into clumps of microscopic crystals. The resulting rocks are extremely hard and have no planes of weakness. For thousands of years, humans exploited these qualities, breaking chert nodules into blades and other tools See also: concretion, nodule, sedimentary rock, silica, quartz
cinder	a type of pyroclastic particle in the form of gas-rich lava droplets that cool as they fall. See also: lava, pyroclastic
cirque	a large bowl-shaped depression carved by glacial erosion and located in mountainous regions. See also: erosion, glacier
clay	the common name for a number of very fine-grained, earthy materials that become plastic (flow or change shape) when wet. Chemically, clays are hydrous aluminum silicates. See also: silica
cleavage	a physical property of minerals. Cleavage occurs when a mineral breaks in a characteristic way along a specific plane of weakness. Mica and graphite have very strong cleavage, allowing them to easily break into thin sheets See also: graphite, mica, mineral
climate	a description of the average temperature, range of temperature, humidity, precipitation, and other atmospheric/hydrospheric conditions a region experiences over a period of many years (usually more than 30). These factors interact with and are influenced by other parts of the Earth system, including geology, geography, insolation, currents, and living things. The climate of a region represents the average weather over a long period of time. See also: weather
climate change	See global warming

coal	a combustible, compact black or dark-brown carbonaceous rock formed by the compaction of layers of partially decomposed vegetation. By far the greatest abundance of coal is located in strata of Carboniferous age. See also: Carboniferous
color (mineral)	a physical property of minerals. Color is determined by the presence and intensity of certain elements within the mineral. See also: mineral
color (soil)	a physical property of soils. Soil color is influenced by mineral content, the amount of organic material, and the amount of water it routinely holds. These colors are identified by a standard soil color chart called the Munsell chart. See also: soil
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. See also: basalt, intrusive, lava, tuff
commodity	a good for which there is demand, but which is treated as equivalent across all markets, no matter who produces it.
compression, compressional force	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. See also: mineral, sedimentary rock, soil
conglomerate	a sedimentary rock composed of multiple large and rounded fragments that have been cemented together in a fine-grained matrix. The fragments that make up a conglomeerate must be larger than grains of sand. See also: matrix, sand, sedimentary rock
conifer	a woody plant (tree) of the division Coniferophyta. Conifers bear cones that contain their seeds. See also: tree
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 microfossils, which have been widely used for biostratigraphy. Knowledge about their soft tissues still remains limited. See also: chordate, fossil

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Conservation of Energy	a principle stating that energy is neither created nor destroyed, but can be altered from one form to another. See also: energy
contact metamorphism	a metamorphic rock that has been altered by direct contact with magma. Changes that occur due to contact metamorphism are greatest at the point of contact. The further away the rock is from the point of contact, the less pronounced the change. See also: magma, metamorphism
convection	the rise of buoyant material and the sinking of denser material. In the mantle, variations in density are commonly caused by the melting of subducting materials. See also: mantle, subduction
convergent boundary	an active plate boundary where two tectonic plates are colliding with one another. Subduction occurs when an oceanic plate collides with a continental plate or another oceanic plate. If two continental plates collide, mountain building occurs. See also: active plate boundary, plate tectonics, subduction
copper	a ductile, malleable, reddish-brown metallic element (Cu). Copper is used extensively as wiring in the electrical industry as well as in alloys such as brass and bronze.
Cordilleran Ice Sheet	one of two continental glaciers that covered Canada and parts of the Western US during the last major Pleistocene ice age. See also: glacier, ice age, Pleistocene
craton	the old, underlying portion of a continent that is geologically stable relative to surrounding areas. The portion of a craton exposed at the surface is termed a shield, while that overlain by younger layers is often referred to as a platform. A craton can be thought of as the heart of a continent—it is typically the oldest, thickest, and most stable part of the bedrock. It is also usually far from the margins of tectonic plates, where new rock is formed and old destroyed. This rock has usually been metamorphosed at some point during its history, making it resistant to erosion. See also: metamorphism
creep	the tendency of a material to move slowly or deform 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. See also: chalk, geologic time scale, mass extinction, Mesozoic
crevasse	a deep crack in an ice sheet or glacier, which forms as a result of shear stress between different sections of the moving ice. See also: glacier, ice sheet
crinoid	a marine invertebrate animal belonging to the Class Crinoidea of the Phylum Echinodermata, and characterized by a head (calyx) with a mouth on the top surface surrounded by feeding arms. Several groups of stemmed echinoderms appeared in the early Paleozoic, including crinoids, blastoids, and cystoids. Crinoids have 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. See also: calyx, echinoderm
cross-bedding	layering within a bed in a series of rock strata that does not run parallel to the plane of stratification. Cross-beds form as flowing water or wind pushes sediment downcurrent, creating thin beds that slope gently in the direction of the flow as migrating ripples. The downstream slope of the ripple may be preserved as a thin layer dipping in the direction of the current, across the natural flat-lying repose of the beds. Another migrating ripple will form an additional layer on top of the previous one.
crust	the uppermost, rigid outer layer of the Earth, composed of tectonic plates. Two types of crust make up the lithosphere. Oceanic crust is denser but significantly thinner than continental crust, while continental crust is much thicker but less dense (and therefore buoyant). When continental crust collides with oceanic crust, the denser oceanic crust will be dragged (subducted) under the buoyant continental crust. Although mountains are created by these oceanic/continental crust collisions due to the compression of the two plates, much taller ranges are produced by continental/continental collisions. When two buoyant continental crusts collide, there is nowhere for the crust to go but up! The modern Himalayas, at the collision site of the Asian and Indian plates, are a good example of very tall mountains formed by a collision between two continental crusts. See also: active plate boundary, compression, lithosphere, subduction
Cryogenian	a geologic period lasting from 850 to 635 million years ago, during the Precambrian. During this period, the Earth was subject to a 200-million-year-long ice age. See also: ice age, Precambrian

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crystal form	a physical property of minerals, describing the shape of the mineral's crystal structure (not to be confused with cleavage). A mineral might be cubic, rhomboidal, hexagonal, or polyhedral. See also: cleavage, mineral
cyanobacteria	a group of bacteria, also called "blue-green algae," that obtain their energy through photosynthesis.
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. See also fossil, Mesozoic, tree
dacite	a fine-grained extrusive igneous rock, with a silica content intermediate between that of andesite and rhyolite. See also: andesite, extrusive, igneous rock, rhyolite, silica
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. See also: climate
degrade (energy)	the transformation of energy into a form in which it is less available for doing work, such as heat. See also: energy
density	a physical property of minerals, describing the mineral's mass per volume. See also: mineral
Devonian	a geologic time period spanning from 419 to 359 million years ago. The Devonian is also called the "age of fishes" due to the diversity of fish that radiated during this time. On land, seed-bearing plants appeared and terrestrial arthropods became established. The Devonian is part of the Paleozoic. See also: geologic time scale, Paleozoic
diamond	a mineral form of carbon, with the highest hardness of any material. Most natural diamonds are formed at high temperature and pressure deep in the Earth's mantle. See also: hardness, mantle, mineral
dike	a sheet of intrusive igneous or sedimentary rock that fills a crack in a pre-existing rock body. See also: intrusion, igneous rock, sedimentary rock

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. See also: Cretaceous, mass extinction
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. See also: active plate boundary, basalt, hydrothermal solution, lava, mantle, pillow basalt, plate, rift
dolomite	a carbonate mineral, consisting of calcium magnesium carbonate ($CaMg(CO_3)_2$). Dolomite is an important reservoir rock for petroleum, and also commonly hosts large ore deposits. See also: mineral, ore, petroleum
dolostone	a rock (also known as dolomitic limestone and once called magnesian limestone) primarily composed of dolomite, a carbonate mineral. It is normally formed when magnesium bonds with calcium carbonate in limestone, forming dolomite. See also: dolomite, limestone
double refraction	the result of light passing through a material that splits it into two polarized sets of rays, doubling images viewed through that material. For example, a single line on a sheet of paper will appear as two parallel lines when viewed through a clear calcite crystal. See also: calcite, mineral
drift	unconsolidated debris transported and deposited by a glacier. See also: 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. See also: glacier, till
dynamic metamorphism	See regional metamorphism
earthquake	a sudden release of energy in the Earth's crust that creates seismic waves. Earthquakes are common at active plate boundaries. See also: active plate boundary, seismic waves
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, See also: crinoid

Glossary

effervesce	to foam or fizz while releasing gas. Carbonate minerals will effervesce when exposed to hydrochloric acid. See also: carbonate rock, mineral
efficiency	the use of a relatively small amount of energy for a given task, purpose, or service; achieving a specific output with less energy input. See also: energy
endemic	native to a particular geographic area or range.
energy	the power derived from the use of physical or chemical resources. Everything we do depends upon energy—without it there would be no civilization, no sunlight, no food and no life. Energy moves people and goods, produces electricity, heats our homes and businesses, and is used in manufacturing and other industrial processes.
energy carrier	a source of energy, such as electricity, that has been subject to human-induced energy transfers or transformations. See also: energy
Entisols	a soil order; these are soils of relatively recent origin with little or no horizon development. They are commonly found in areas where erosion or deposition rates outstrip rates of soil development, such as floodplains, mountains, and badland areas. See also: erosion, horizon, soil, soil orders
Eocene	a geologic time period extending from 56 to 33 million years ago. The Eocene is an epoch of the Paleogene period. See also: Paleogene
erosion	the transport of weathered materials. Rocks are worn down and broken apart into finer grains by wind, rivers, wave action, freezing and thawing, and chemical breakdown. Over millions of years, weathering and erosion can reduce a mighty mountain range to low rolling hills. Some rocks wear down relatively quickly, while others can withstand the power of erosion for much longer. Softer, weaker rocks such as shale and poorly cemented sandstone and limestone are much more easily worn than hard, crystalline igneous and metamorphic rocks, or well-cemented sandstone and limestone. Harder rocks are often left standing as ridges because the surrounding softer, less resistant rocks were more quickly worn away. See also: igneous rock, metamorphic rock, sedimentary rock, weathering

erratic, glacial erratic	a piece of rock that differs from the type of rock native to the area in which it rests, carried there by glaciers often over long distances. Erratics are often distinctive because they are a different type of rock than the bedrock in the area to which they've been transported. For example, boulders and pebbles of igneous and metamorphic rocks are often found in areas where the bedrock is sedimentary; it is sometimes possible to locate the origin of an erratic if its composition and textures are highly distinctive. See also: glacier, igneous rock, metamorphic rock, sedimentary rock
esker	a sinuous, elongated ridge of sand and gravel. Most eskers formed within ice-walled tunnels carved by streams flowing beneath a glacier. After the ice melted away, the stream deposits remained as long winding ridges. Eskers are sometimes mined for their well-sorted sand and gravel. See also: glacier, gravel, sand
estuary	a place where freshwater and saltwater mix, created when sea level rises to flood a river valley.
evaporite	a sedimentary rock created by the precipitation of minerals directly from seawater, including gypsum, carbonate, and halite. See also: carbonate, gypsum, mineral, sedimentary rock
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. See also: joint, weathering
exhumation	the erosional uncovering or exposing of a geological feature that had been previously covered by deposited sediments. See also: erosion
exsolve	to come out of solution and, in the case of a gas, form bubbles.
extinction	the end of species or other taxonomic groups, marked by death of the last living individual. Paleontologists estimate that over 99% of all species that have ever existed are now extinct. The species of modern animals that we study in biology today represent less than 1% of what has lived throughout geologic time.
extrusion, extrusive rock	an igneous rock formed by the cooling of lava after magma escapes onto the surface of the Earth through volcanic craters and cracks in the Earth's crust. See also: crust, igneous rocks, magma
fault	a fracture in the Earth's crust in which the rock on one side of the fracture moves measurably in relation to the rock on the other side. See also: crust

Glossary

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 topgraphy. See also: fault, 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. See also: igneous rock, metamorphic rock, mineral, sedimentary rock
felsic	igneous rocks with high silica content and low iron and magnesium content. They are light in color and are typically found in continental crust. See also: crust, igneous rock, iron, silica
filter feeder	an animal that feeds by passing water through a filtering structure that traps food. The water may then be expelled and the food digested. This strategy is employed by a wide range of animals today, from clams and krill to flamingos and whales.
firn	compacted glacial ice, formed by the weight of snow on top. Individual flakes break down by melting, refreezing, and bonding to the snow around them, eventually forming compacted grains. See also: glacier
fjord	a deep, narrow, glacially scoured valley that is flooded by ocean water. See also: glacier
flank collapse	a dramatic mass wasting event that occurs when the flank of a shield volcano collapses under its own weight. Fractures formed by gravitational stress can slip rapidly, resulting in a massive collapse that shears off to create steep cliffs and huge debris fields. See also: fracture, mass wasting, shield volcano
flint	a hard, high-quality form of chert that occurs mainly as nodules and masses in sedimentary rock. Due to its hardness and the fact that it splits into thin, sharp flakes, flint was often used to make tools during the Stone Age. Flint will also create sparks when struck against steel, and has been used to ignite gunpowder in more modern times. See also: chert, sedimentary rock, nodule
floodplain	the land around a river that is prone to flooding. This area can be grassy, but the sediments under the surface are usually deposits from previous floods.

fluorite, fluorspar	the mineral form of calcium fluoride (CaF_2). Fluorite is used in a variety of commercial applications, including as lenses for microscopes, the production of some glass, and the chemical industry. Fluorite lent its name to the phenomenon of fluorescence, which occurs in some fluorites due to impurities in the crystal. See also: mineral
fluvial	See outwash plain
foliation	the arrangement of the constituents of a rock in leaflike layers, as in schists. During metamorphism, the weight of overlying rock can cause minerals to realign perpendicularly to the direction of pressure, layering them in a banded pattern. See also: metamorphism, schist
foraminifera	a class of aquatic protists that possess a calcareous or siliceous exoskeleton. Foraminifera have an extensive fossil record. See also: protist
fossil	preserved evidence of ancient life, including, for example, preserved skeletal or tissue material, molds or casts, and traces of behavior. Fossilization may alter biological material in a variety of ways, including permineralization, replacement, and compression. Remains are often classified as fossils when they are older than 10,000 years, the traditional start of the Holocene (Recent) epoch. However, this date is only a practical guideline—scientists studying successions of plant or animal remains would not recognize any sudden change in the material at 10,000 years, and would typically refer to all material buried in sediments as fossil material. The word fossil is derived from the Latin word fossilis, meaning “dug up.” See also: compression, Holocene, permineralization, replacement
fossil fuels	fuel for human use that is made from the remains of ancient biomass, referring to any hydrocarbon fuel source formed by natural processes from anaerobically decomposed organisms, primarily coal, petroleum, and natural gas (methane). Fossil fuels are non-renewable, meaning that because they take thousands to millions of years to form, the rate of use is far greater than the rate of formation, and eventually we will run out. See also: biomass, coal, fuel, natural gas, petroleum
fracture (mineral)	a physical property of minerals, formed when a mineral crystal breaks; also a crack in rocks, sometimes known as a joint. See also: mineral
frost wedging	weathering that occurs when water freezes and expands in cracks. See also: weathering

Glossary

fuel	a material substance that possesses internal energy that can be transferred to the surroundings for specific uses—included are petroleum, coal, and natural gas (the fossil fuels), and other materials, such as uranium, hydrogen, and biofuels. See also: biofuel, coal, energy, fossil fuel, natural gas, petroleum
gabbro	a usually coarse-grained, mafic and intrusive igneous rock. Most oceanic crust contains gabbro. See also: crust, igneous rock, intrusion, mafic
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. See also: soil, soil order, permafrost, weathering
gem, gemstone	a mineral that has been cut and polished for use as an ornament. See also: mineral
geode	a hollow, roughly spherical node of crystal that forms when minerals precipitate within hardened vesicles (gas bubbles) in volcanic rocks, or within dissolved nodules that leave openings within sedimentary rock. These geological structures occur in certain sedimentary and igneous rocks. See also: igneous rock, mineral, sedimentary rock, vesicular
geologic time scale	a standard timeline used to describe the age of rocks and fossils, and the events that formed them. It spans Earth's entire history, and is often subdivided into four major time periods: the Precambrian, Paleozoic, Mesozoic, and Cenozoic. See also: Cenozoic, Mesozoic, Paleozoic, Precambrian
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*. See also: tree

glacier	a body of dense ice on land that does not melt away annually and has sufficient mass to move under its own weight. Glaciers form when snow accumulates faster than it melts over many years. As long as melt does not exceed accumulation, the ice and snow pile up and become a self-sustaining system. As glaciers slowly flow, they abrade and erode the landscape around them to create crevasses, moraines, and other distinguishing features. Glaciers form only on land, and are much thicker than ice that forms on the surface of water. 99% of Earth's glacial ice exists as vast polar ice sheets, but glaciers are also found high in the mountains of every continent except Australia. See also: crevasse, erosion, ice sheet, moraine
glassy rock	a volcanic rock that cooled almost instantaneously, resulting in a rock with tiny crystals or no crystals at all. Obsidian, tuff, and scoria are examples of glassy rocks. See also: igneous rock, obsidian, scoria, tuff, volcanic
global warming	the current increase in the average temperature worldwide, caused by the buildup of greenhouse gases in the atmosphere. With the coming of the Industrial Age and exponential increases in human population, large amounts of gases have been released into the atmosphere (especially carbon dioxide) that give rise to global warming. The term "climate change" is preferred because warming contributes to other climatic changes such as precipitation and storm strength. See also: climate, greenhouse conditions, greenhouse gases
gneiss	a metamorphic rock that may form from granite or layered sedimentary rock such as sandstone or siltstone. Parallel bands of light and dark minerals give gneiss its striated texture. See also granite, metamorphic rock, mineral, sedimentary rock
gold	a soft, yellow, corrosion-resistant element (Au), which is the most malleable and ductile metal on Earth. Gold has an average abundance in the crust of only 0.004 parts per million. It can be profitably mined only where hydrothermal solutions have concentrated it. See also: crust, hydrothermal solution
granite	a common and widely occurring type of igneous rock. Granite usually has a medium- to coarse-grained texture, and is at least 20% quartz by volume. See also: igneous
granodiorite	a coarse-grained plutonic rock rich in the elements sodium and calcium, and in the minerals potassium, feldspar, and quartz. See also: feldspar, mineral, plutonic, quartz

Glossary

graphite	a mineral, and the most stable form of carbon. Graphite means "writing stone," a reference to its use as pencil lead. Graphite occurs in metamorphic rocks, igneous rocks, and meteorites. See also: igneous rock, metamorphic rock, mineral
graptolite	an extinct colonial invertebrate animal belonging to the Class Graptolithina of the Phylum Hemichordata, and characterized by individuals housed within a tubular or cup-like structure. The soft parts of a graptolite's body have never been clealry identified. See also: extinction
gravel	unconsolidated, semi-rounded rock fragments larger than 2 millimeters (0.08 inches) and smaller than 75 millimeters (3 inches).
greenhouse conditions	time periods when atmospheric greenhouse gas concnetrations are high and global temperatures are elevated. Sea levels are generally higher and glaciers diminish during these conditions. See also: glacier, global warming, greenhouse gases
greenhouse gas	a gas in the atmosphere that absorbs and emits heat. The primary greenhouse gases in the Earth's atmosphere are water vapor, carbon dioxide, methane, nitrous oxide, and ozone. See also: atmosphere, heat
greywacke	a variety of dark-colored sandstone that contains angular grains of quartz and feldspar embedded in clay. The presence of greywacke generally reflects an environment in which erosion and deposition occurred too quickly for chemical weathering to fully degrade the parent material. See also: erosion, feldspar, quartz, weathering
guyots	flat-topped underwater mountains, or seamounts, typically formed after a coral atoll is drowned, subsiding beneath the ocean surface faster than the fringing reef can grow upward, See also: atoll, erosion
gypsum	a soft sulfate mineral that is widely mined for its use as fertilizer and as a constituent of plaster. Alabaster, a fine-grained light colored variety of gypsum, has been used for sculpture making by many cultures since ancient times. See also: mineral, sulfur
Hadley cell	a tropical atmospheric circulation that features rising air near equator, poleward airflow 10–15 kilometers (6–9 miles) above the surface, descending air in the subtropics (near the latitudes of 30°N and 30°S), and surface flow toward the equator. Regions of rising air expand and cool; worldwide equatorial latitudes are therefore characterized by meteorological low pressures and high rainfall. The rising air cools, eventually becoming denser and sinking; this cool air has a low relative humidity, so subtropical regions have an arid climate. Surface airflow is deflected westward by the Earth's rotation, creating the trade winds. See also: atmosphere, climate, trade winds

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. See also: erosion, glacier
hardness	a physical property of minerals, specifying how hard the mineral is. Hardness helps us understand why some rocks are more or less resistant to weathering and erosion See also: erosion, mineral, Moh's Scale of Hardness, weathering
hardpan	a dense layer of soil, generally found below the topsoil layer, that is generally impervious to water. See also: soil
heat	the transfer of energy from one body to another as a result of a difference in temperature or a change in phase. Heat is transmitted through solids and fluids by conduction, through fluids by convection, and through empty space by radiation. See also: convection, energy
heat island effect	a phenomenon in which cities experience higher temperatures than 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. See also: weather
hectare	a metric unit of area defined as 10,000 square meters.
Histosols	a soil order; these are organic-rich soils found along lake coastal areas where poor drainage creates conditions of slow decomposition and peat (or muck) accumulates. See also: peat, soil, soil orders
Hoh rock assemblage	a mélange formed from a variety of chaotically jumbled sedimentary, metamorphic, and volcanic rocks that accreted to the Olympic Peninsula during the Eocene. See also: accretion, Eocene, mélange, metamorphic rock, sedimentary rock, volcanic

Glossary

Holocene	the most recent portion of the Quaternary, beginning about 11,700 years ago and continuing to the present. It is the most recent (and current) interglacial, an interval of glacial retreat. The Holocene also encompasses the global growth and impact of the human species. See also: interglacial, Quaternary
horizon (soil)	a layer in the soil, usually parallel to the surface, which has physical characteristcs (usually color and texture) that are different from the layers above and below it. Each type of soil usually contains three or four horizons. See also: soil
horn	a pointed rocky peak created by glacial erosion. See also: erosion, glacier
hornblende	a dark silicate mineral that can occur in a variety of forms. Hornblende is a common constituent of many igneous and metamorphic rocks. See also: igneous rock, metamorphic rock
hot spot	a volcanic region thought to be fed by underlying mantle that is anomalously hot compared with the mantle elsewhere. Hot spots form from plumes of magma rising off the mantle. Magma from the hot spot pushes its way up through the crust, creating an igneous intrusion and sometimes a volcano. Although the hot spot remains fixed, the plates of the lithosphere continue to move above it. As a plate continues to move over the hot spot, the original volcano shifts off of the hot spot and a new intrusion or volcano is formed. This gradually produces a chain of volcanic islands such as the Hawaiian Islands. Erosion of volcanoes may eventually wear down the crust to reveal the igneous intrusions that formed the volcano's magma chamber. See also: crust, erosion, igneous rocks, intrusion, lithosphere, magma, mantle, volcanic islands
humus	a soil horizon containing organic matter. See also: horizon, soil
Huronian glaciation	a glaciation beginning about 2.4 billion years ago, that covered the entire surface of the Earth in ice for as long as 300 million years. See also: glacier, ice age
hurricane	a rapidly rotating storm system with heavy winds, a low-pressure center, and a spiral arrangement of thunderstorms. These storms tend to form over large, warm bodies of water. Once winds have reached 119 kilometers per hour (74 miles per hour), such a storm is classified as a hurricane. Hurricanes usually develop an eye, which is visible as a small, round, cloud-free area at the center of the storm. The eye is an area of relative calm and low atmospheric pressure. The strongest thunderstorms and winds circulate just outside the eye, in the eyewall. See also: wind

hydrothermal solution	hot, salty water moving through rocks.These solutions are always enriched in salts (such as sodium chloride, potassium chloride, and calcium chloride) and thus are called “brines.” The brine is as salty or even saltier than seawater. Salty water can contain minute amounts of dissolved minerals such as gold, lead, copper, and zinc. The presence of salt in the water suppresses the precipitation of the metallic minerals from the brine because the chlorides in the salt preferentially bond with metals. Additionally, because the brine is hot, minerals are more easily dissolved, just as hot tea dissolves sugar more easily than cold tea. See also: copper, gold, lead, mineral, salt, zinc
ice age	a period of global cooling of the Earth's surface and atmosphere, resulting in the presence or expansion of ice sheets and glaciers. Throughout the Earth’s history, it has been periodically plunged into ice ages, dependent upon the climate and position of the continents. Over the past 2.6 million years, North America has experienced about 50 glacial advances and retreats. The most recent ice age ended about 12,000 years ago. See also: atmosphere, climate, ice sheet, glacier
ice cap	an ice field that lies over the tops of mountains. See also: ice field
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. See also: glacier, topography
ice lobe	a broad, rounded section of a continental glacier that flows out near the glacier's terminus, often through a broad trough. See also: glacier
ice sheet	a mass of glacial ice that covers part of a continent and has an area greater than 50,000 square kilometers (19,000 square miles). See also: glacier
iceberg	a large chunk of ice, generally ranging in height from 1 to 75 meters (3 to 246 feet) above sea level, that has broken off of an ice sheet or glacier and floats freely in open water. See also: glacier, ice sheet
ichthyosaur	an extinct Mesozoic marine reptile that was probably similar in size and habitat to the toothed whales, dolphins, and large sharks of today. See also: extinction, Mesozoic

Glossary

igneous rocks	rocks derived from the cooling of magma underground or molten lava on the Earth's surface. Igneous rocks differ not only in their cooling rates and subsequent crystal sizes, but also in their chemical compositions. Rocks found in continental crust, such as granite, have high silica content and low iron and magnesium content. They are light in color and are called felsic. Rocks found in oceanic crust, like basalt, are low in silica and high in iron and magnesium. They are dark in color and are called mafic. Although the composition of magma can be the same as lava, the texture of the rocks will be quite different due to different rates of cooling. It is because of this difference in genesis that geologists are able to make the distinction between extrusive and intrusive igneous rocks when encountered at an outcrop at the Earth's surface. See also: extrusion, felsic, intrusion, mafic, magma, lava
Inceptisols	a soil order; these are soils that exhibit only moderate weathering and development. They are often found on steep (relatively young) topography and overlying erosion-resistant bedrock. See also: soil, soil orders, topography, weathering
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. See also: igneous rock, intrusion
index fossil	a fossil used to determine the relative age of sedimentary deposits. An ideal index fossil lived during a short period of time, was geographically and environmentally widespread, and is easy to identify. Some of the most useful index fossils are hard-shelled organisms that were once part of the marine plankton. See also: fossil, sedimentary rock
inland sea	a shallow sea covering the central area of a continent during periods of high sea level. An inland sea is located on continental crust, while other seas are located on oceanic crust. An inland sea may or may not be connected to the ocean. For example, Hudson Bay is on the North American plate and connects to the Atlantic and Arctic Oceans, while the Caspian Sea is on the European plate but does not drain into any ocean at all. See also: crust
intensity (earthquake)	a subjective measurement that classifies the amount of shaking and damage done by an earthquake in a particular area. See also: earthquake, magnitude
interglacial	a period of geologic time between two successive glacial stages. See also: glacier
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. See also: crust, igneous, magma, pluton
iron	a metallic chemical element (Fe). Iron is most often found in combination with other elements, such as oxygen and sulfur, to form ores like hematite, magnetite, siderite, and pyrite. The ready availability of iron at Earth's surface made it one of the earliest mined mineral resources in the US. See also: hematite, magnetite, ore, pyrite, sulfur
isostasy	an equilibrium between the weight of the crust and the buoyancy of the mantle. See also: crust, mantle
jasper	a speckled or patterned silicate stone that appears in a wide range of colors. It is a variety of chalcedony. Jasper forms when silica precipitates in a fine particulate material such as soft sediment or volcanic ash. The particulates give the stone its color and patterns. See also: chalcedony, sedimentary rock, silica
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. See also: atmosphere
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. See also: energy
Jurassic	the geologic time period lasting from 201 to 145 million years ago. During the Jurassic, dinosaurs dominated the landscape and the first birds appeared. The Jurassic is the middle period of the Mesozoic. See also: geologic time scale, Mesozoic
kaolinite	a silicate clay mineral, also known as china clay. Kaolinite is the main ingredient in fine china dishes such as Wedgewood. See also: clay, mineral, silica

Glossary

karst topography	a kind of landscape defined by bedrock that has been weathered by dissolution in water, forming features like sinkholes, caves, and cliffs. Karst primarily forms in limestone bedrock. See also: limestone, topography, weathering
kettle	a lake formed where a large, isolated block of ice became separated from the retreating ice sheet. The weight of the ice leaves a shallow depression in the landscape that persists as a small lake. See also: ice sheet
kinetic energy	the energy of a body in motion (e.g., via friction). See also: energy
Köppen system	a commonly used system of climate categorization developed by Russian climatologist Wladimir Köppen. It is based on the kinds of vegetation that areas sustain, and defines 12 climate types: rain-forest, monsoon, tropical savanna, humid subtropical, humid continental, oceanic, Mediterranean, steppe, subarctic, tundra, polar ice cap, and desert. Updated by Rudolf Geiger, it has been refined to five groups each with two to four subgroups. See also: climate
Lagerstätte (pl. Lagerstätten)	fossil deposit containing animals or plants that are preserved unusually well, sometimes even including the soft organic tissues. Lagerstatten form in chemical environments that slow decay of organic tissues or enhance preservation through mineralization. Also, quick burial of the organism leaves no opportunity for disturbance of the fossils. Lagerstatten are important for the information they provide about soft-bodied organisms that we otherwise would know nothing about. See also: fossil
lahar	a pyroclastic debris flow or mudflow that typically flows down river valleys after a volcanic eruption. Lahars can be very destructive, as they can reach thicknesses of over 140 meters (460 feet) and travel at tens of meters (yards) per second. See also: debris flow, pyroclastic, volcanism
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: debris flow, 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: Cretaceous, orogeny

last glacial maximum	the most recent time the ice sheets reached their largest size and extended farthest towards the equator, about 26,000 to 19,000 years ago. Ice sheets over North America melted back until about 10,000 years ago—they have been relatively stable since that time. See also: ice sheet
lava	molten rock located on the Earth's surface. When magma rises to the surface, typically through a volcano or rift, it becomes lava. Lava cools much more quickly than magma because it is at the surface, exposed to the atmosphere or ocean water where temperatures are much cooler. Such rocks, with little time to crystallize, have small or no crystals. See also: magma, rift, volcanism
lava tube	a natural tube formed by lava flowing beneath the hardened surface of a lava flow. See also: lava
Law of Superposition	the geological principle that states that unless rock layers have been overturned or intruded, older rocks are found at the bottom and younger rocks are found at the top of a sedimentary sequence. See also: intrusion, stratigraphy
lead	a metallic chemical element (Pb). Lead was one of the first metals mined in North America, where it was sought after especially for making shot. It is used in batteries, communication systems, and building construction.
leeward	downwind; facing away from the wind (not subject to orographic precipitation, and thus dryer). See also: orographic precipitation, wind
lignite	a soft, brownish-black coal in which the alteration of plant matter has proceeded farther than in peat but not as far as in bituminous coal. See also: bituminous coal, coal, peat
limestone	a sedimentary rock composed of calcium carbonate ($CaCO_3$). Most limestones are formed by the deposition and consolidation of the skeletons of marine invertebrates; a few originate in chemical precipitation from solution. Limestone is ordinarily white but can be colored by impurities such as iron oxide (making it brown, yellow, or red), or organic carbon (making it blue, black, or gray). The rock's texture varies from coarse to fine. See also: iron, sedimentary rock
lithification	the process of creating sedimentary rock through the compaction or sementation of soft sediment. The word comes from the Greek *lithos*, meaning “rock.” See also: sedimentary rock

Glossary

lithosphere	the outermost layer of the Earth, comprising a rigid crust and upper mantle broken up into many plates. The plates of the lithosphere move with the underlying asthenosphere, on average about 5 centimeters (2 inches) per year and as much as 18 centimeters (7 inches) per year. See also: asthenosphere, crust, mantle
littoral cone	a volcanic ash or tuff cone formed when a lava flow runs into a body of water; "littoral" refers to nearshore. See also: lava, tuff, volcanic ash, volcanism
loam	a soil containing equal amounts of clay, silt, and sand. See also: clay, soil, sand, silt
lode	an ore deposit that fills a fissure or crack in a rock formation; alternately, an ore vein that is embedded between layers of rock. See also: ore
loess	very fine grained, wind-blown sediment, usually rock flour left behind by the grinding action of flowing glaciers. See also: rock flour
luminescence	to give off light.
luster	a physical property of minerals, describing the appearance of the mineral's surface in reflected light, and how brilliant or dull it is. Luster can range from metallic and reflective to opaque, vitreous like glass, translucent, or dull and earthy. See also: mineral
mafic	igneous rocks that contain a group of dark-colored minerals, with relatively high concentrations of magnesium and iron compared to felsic igneous rocks. See also: felsic, igneous rock
magma	molten rock located below the surface of the Earth. Magma can cool beneath the surface to form intrusive igneous rocks. However, if magma rises to the surface without cooling enough to crystallize, it might break through the crust at the surface to form lava. See also: crust, igneous, intrusive rock, lava
magnetic	affected by or capable of producing a magnetic field.

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. See also: earthquake, intensity, seismic waves
mammoth	an extinct terrestrial vertebrate animal belonging to the Order Proboscidea of the Class Mammalia. Mammoths are from the same line of proboscideans that gave rise to African and Asian elephants. They had tall bodies with a rather high "domed" skull, and teeth with numerous parallel rows of ridges. Mammoths are among the most common Pleistocene vertebrate fossils in North America, Europe, and Asia. See also: extinction, fossil, Pleistocene
mantle	the layer of the Earth between the crust and core. It consists of solid silicate rocks that, over long intervals of time, flow like a highly viscous liquid. Convection currents within the mantle drive the motion of plate tectonics. See also: convection, magma, plate tectonics, silica
marble	a metamorphic rock composed of recrystallized carbonate minerals, most commonly calcite or dolomite. Not everything commercially called a marble is "true marble," which lacks fossils and is recrystallized from limestone. See also: calcite, dolomite, limestone, metamorphic, mineral
mass extinction	the extinction of a large percentage of the Earth's species over a relatively short span of geologic time. Unfortunately, this is not just a phenomenon of the past: it is estimated that the extinction rate on Earth right now may be as much as 1000 times higher than normal, and that we are currently experiencing a mass extinction event. See also: geologic time scale, extinction
mass wasting	a process in which soil and rock move down a slope in a large mass. This can occur both on land (such as a landslide) or underwater (such as a turbidity current). See also: turbidity current
mastodon	an extinct terrestrial vertebrate animal belonging to the Order Proboscidea of the Class Mammalia, and characterized by an elephant-like shape and size, and massive molar teeth with conical projections. Mastodons are among the most common Pleistocene vertebrate fossils in North America. See also: extinction, fossil, Pleistocene
matrix	a fine-grained mass of material around and embedding larger grains or crystals. The term matrix can also describe sediment or rock in which a fossil is embedded. See also: fossil

Glossary

megathrust	powerful earthquakes occurring at subduction zones, where one plate is forced beneath another. Since 1990, all earthquakes of magnitude 9.0 or greater have been megathrust earthquakes. See also: earthquake, subduction
mélange	a mixture of fragmented rocks produced in a subduction zone. See also: subduction
Mesozoic	a geologic time period that spans from 252 to 66 million years ago. This period is also called the "age of reptiles" since dinosaurs and other reptiles dominated both marine and terrestrial ecosystems. During this time, the last of the Earth's major supercontinents, Pangaea, formed and later broke up, producing the Earth's current geography. The Mesozoic contains the Triassic, Jurassic, and Cretaceous periods. See also: Cretaceous, geologic time scale, Jurassic, Pangaea, Triassic
metamorphism, metamorphic rocks	rocks formed by the recrystallization and realignment of minerals in pre-existing sedimentary, igneous, and metamorphic rocks when exposed to high enough temperature and/or pressure. This can be a result of plate movements, very deep burial, or contact with molten rock or superheated water. This process destroys many features in the rock that would have revealed its previous history, transforming it into an entirely new form. Tectonic forces can cause minerals to realign perpendicularly to the direction of pressure, layering them in a pattern called foliation, as exemplified in gneiss and schist. Recrystallization, as seen in marble and quartzite, results as rock is heated to high temperatures, and individual grains reform as interlocking crystals, making the resulting metamorphic rock harder than its parent rock. See also: gneiss, igneous rock, marble, quartzite, schist, sedimentary rock
mica	a large group of sheetlike silicate minerals. See also: mineral
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. See also: crust, terrane
Milankovitch Cycles	cyclical changes in the amount of heat received from the sun, associated with how the Earth's orbit, tilt, and wobble alter its position with respect to the sun. These changes affect the global climate, most notably alterations of glacial and interglacial intervals. See also: climate

mineral	a naturally occurring solid with a specific chemical composition and crystalline structure. Minerals are identified based on their physical properties, including hardness, luster, color, crystal form, cleavage, density, and streak. There are over 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. See also: amphibole, color (mineral), cleavage, crystal form, density, feldspar, igneous rock, luster, metamorphic rock, mica, mineralogy, pyroxene, quartz, sedimentary rock, streak
mineralogy	the branch of geology that studies the chemical and physical properties and formation of minerals. See also: mineral
Miocene	a geological 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. See also: ice age, Neogene
Mississippian	a subperiod of the Carboniferous, spanning from 359 to 323 million years ago. See also: Carboniferous
Mohs Scale of Hardness	the scale of relative hardness of minerals, developed by the Austrian mineralogist, Frederich Mohs, in 1824. The scale is very useful as a means for identifying minerals or quickly determining hardness. A piece of glass has a hardness of approximately 5 on the scale; our fingernails are just over 2; a knife blade is just over 5. Diamond ranks at 10 as the hardest mineral. See also: hardness, mineral
Mollisols	a soil order; these are agricultural soils made highly productive due to a very fertile, organic-rich surface layer. See also: soil, soil orders
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.
Monterey Formation	a distinctive light-colored sedimentary rock unit that formed in the Miocene seas. Its buff color comes from its high silica content, derived from microfossils such as diatoms. Outcrops from the Monterey Formation are visible along California's coast and peninsula, and on some of the offshore islands. It is composed primarily of shale, and it is the source rock for most of California's oil. See also: Miocene, oil, sedimentary rock, shale, silica

Glossary

moraine	an accumulation of unconsolidated glacial debris (soil and rock) that can occur in currently glaciated and formerly glaciated regions, such as those areas acted upon by a past ice age. The debris is scraped from the ground and pushed forward by the glacier, to be left behind when the ice melts. Thus, many moraines mark the terminus or edge of a glacier. Lateral moraines can also occur in between and at the sides of glaciers or ice lobes. See also: glacier, ice age, soil
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. See also: Cretaceous, extinction
natural gas	a hydrocarbon gas mixture composed primarily of methane (CH_4), but also small quantites of hydrocarbons such as ethane and propane. See also: fossil fuel
natural hazard	events that result from natural processes and that have significant impacts on human beings.
Neogene	the geologic time period extending from 23 to 2.6 million years ago. During the Neogene, global climate cooled, the continents moved close to their current positions, mammals and birds continued to evolve, and the first hominins appeared. The Neogene is a portion of the Cenozoic. See also: Cenozoic
nodule	a small, irregular or rounded mineral deposit that has a different composition from the sedimentary rock that encloses it. Nodules typically form when minerals precipitate from a supersaturated solution within or around features such as biotic remains. See also: mineral, sedimentary rock
nuclear	a reaction, as in fission, fusion, or radioactive decay, that alters the energy, composition, or structure of an atomic nucleus. See also: radioactive
obsidian	a glassy volcanic rock, formed when felsic lava cools rapidly. Although obsidian is dark in color, it is composed mainly of silicon dioxide (SiO_2), and its dark color is a result of the rapid cooling process. Obsidian is extremely brittle and breaks with very sharp edges. It was valuable to Stone Age cultures for its use as cutting implements or arrowheads. See also: felsic, glassy, lava, volcanic
oil	See petroleum

Oligocene	a geologic time interval spanning from about 34 to 23 million years ago. It is an epoch of the Paleogene. See also: geologic time scale, Paleogene
olivine	an iron-magnesium silicate mineral ($(Mg,Fe)_2SiO_4$) that is a common constituent of magnesium-rich, silica-poor igneous rocks. See also: igneous rocks, iron, silica, mineral, talc
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. See also: gem, mineral, silica
ophiolite	a section of the Earth's oceanic crust and the underlying upper mantle that has been uplifted and exposed above sea level and often thrust onto continental crustal rocks. Ophiolites are often formed during subduction - as oceanic crust is subducted, some of the deep-sea sediments overlying the crust, the oceanic crust itself, and sometimes rock from the upper mantle, can be scraped off the descending plate and accreted to the continental crust. See also: crust, mantle, subduction, uplift
Ordovician	a geologic time period spanning from 485 to 443 million years ago. During the Ordovician, invertebrates dominated the oceans and fish began to diversify. The Ordovician is part of the Paleozoic. See also: geologic time scale, Paleozoic
ore	a type of rock that contains minerals with valuable elements, including metals, that are economically viable to extract. See also: mineral
oreodont	an extinct ungulate (hoofed animal) related to modern camels. Oreodonts lived in woodlands and grasslands throughout North America during the Oligocene and Miocene. See also: Miocene, Oligocene
orogeny	a mountain-building event generally caused by colliding plates and compression of the edge of the continents. Orogeny is derived from the Greek word *oro*, meaning mountain. See also: compression, plate tectonics
orographic precipitation	rainfall caused when wind pushes a mass of humid air up the side of an elevated land formation like a mountain. As the air rises, it cools, and the moisture precipitates out. See also: wind

Glossary

outwash plain	large sandy flats created by sediment-laden water deposited when a glacier melts. Outwash sediments are also called fluvial material. See also: glacier, sand
oxidation	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. See also: chemical reaction
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. See also: aluminum, iron, soil, soil order, weathering
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. See also: basalt, glassy, lava
paleobiogeography	the study of the geographic distribution of fossil organisms in the geologic past. See also: fossil
paleoecology	the study of the relationships of fossil organisms to one another and their environment. See also: fossil
Paleogene	the geologic time period extending from 66 to 23 million years ago. During the Paleogene, mammals and birds diversified into many of the niches that had previously been held by dinosaurs. The Paleogene is the first part of the Cenozoic. See also: Cenozoic, dinosaur, geologic time scale
paleogeographic maps	maps that portray the estimated ancient geography of the Earth. They often appear in sequences designed to show the geologic development of a region. Because an enormous amount of data is required to construct even a small paleogeographic map, reconstructions often show only general details and are frequently subject to considerable uncertainty.
Paleozoic	a geologic time period that extends from 541 to 252 million years ago. Fossil evidence shows that during this time period, life evolved in the oceans and gradually colonized the land. The Paleozoic includes the Cambrian, Ordovician, Silurian, Devonian, Carboniferous, and Permian periods. See also: Cambrian, Carboniferous, Devonian, geologic time scale, Ordovician, Permian, Silurian

Pangaea	supercontinent, meaning "all Earth," which formed over 250 million years ago and lasted for almost 100 million years. All of the Earth's continents were joined in a giant supercontinent. Pangaea eventually rifted apart and separated into the continents in their current configuration.
parent material	the original geologic material from which soil formed. This can be bedrock, preexisting soils, or other materials such as till or loess. See also: loess, soil, till
passive margin	a tectonically quiet continental edge, such as the eastern margin of North America, where crustal collision or rifting is not occurring. See also: crust, plates, rift
patterned ground	patterns and sorting in the soil caused by repeated freezing and thawing, which causes repeated heaving upwards and settling of the rocks and pebbles in the soil. See also: soil
peat	an accumulation of partially decayed plant matter. Under proper heat and pressure, it will turn into lignite coal over geologic periods of time. As much as 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. See also: anthracite, coal, lignite
peds	clumps of soil, identified by their shape, which may take the form of balls, blocks, columns, and plates. These structures are easiest to see in recently plowed fields, where the soil is often granular and loose or lumpy. See also: soil
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. See also feldspar, igneous rocks, magma, metamorphism, mica, mineral, quartz, silica
Pennsylvanian	a subperiod of the Carboniferous, spanning from 323 to 299 million years ago. See also: Carboniferous
perennial	continuous; year-round or occurring on a yearly basis.
peridotite	a coarse-grained plutonic rock containing minerals, such as olivine, which make up the Earth's mantle. See also: mantle, mineral, pluton

Glossary

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. See also: soil
permeable, permeability	a capacity for fluids and gas (such as water, oil and natural gas) to move through fractures within a rock, or the spaces between its grains. Sandstone, limestone, and fractured rocks of any kind generally are permeable. Shale, on the other hand, is usually impermeable because the small, flat clay particles that make up the rock are tightly packed into a dense rock with very little space between particles. Poorly sorted sedimentary rocks can also be impermeable because smaller grains fill in the spaces between the bigger grains, restricting the movement of fluids. See also: clay, limestone, petroleum, sandstone, sedimentary rocks, shale
Permian	the geologic time period lasting from 299 to 252 million years ago. During the Permian, the world's landmass was combined into the supercontinent Pangaea. The Permian is the last period of the Paleozoic. It ended with the largest mass extinction in Earth's history, which wiped out 70% of terrestrialanimal species and 90% of all marine animal species. See also: geologic time scale, mass extinction, Paleozoic, Pangaea
permineralization	a fossilization method where empty spaces (such as in a bone or shell) are filled by minerals. See also: fossil
petroleum	a naturally occurring, flammable liquid found in geologic formations beneath the Earth's surface and consisting primarily of hydrocarbons. Petroleum, also called oil, is a fossil fuel, formed when large masses of dead organisms (usually algae or plankton) are buried underneath sediments and subjected to intense heat and pressure. Today, petroleum is used to manufacture a wide variety of materials, and it is commonly refined into various types of fuels. It is estimated that 90 million barrels are consumed globally every day. See also: fossil fuel
Phanerozoic	a generalized term used to describe the entirety of geological history after the Precambrian, from 541 million years ago to the present. See also: geologic time scale
phenocryst	a large and generally conspicuous crystal which has been enclosed in a much finer-grained igneous rock. Phenocrysts may occur in all types of igneous rock, but are most common in felsic rocks. See also: felsic, igneous rock
phyllite	a metamorphic rock that is intermediate in grade between slate and schist. See also: metamorphic rock, schist, slate

pillow basalt	basaltic lava that forms in a characteristic "pillow" shape due to its extrusion underwater. See also: basalt, extrusion, lava
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. See also: gold, mineral
plate tectonics	the way by which the plates of the Earth's crust move and interact with one another at their boundaries. The Earth is dynamic, consisting of constantly moving plates that are made of rigid continental and oceanic lithosphere overlying a churning, plastically flowing asthenosphere. These plates are slowly pulling apart, colliding, or sliding past one another with great force, creating strings of volcanic islands, new ocean floor, earthquakes, and mountains. See also: asthenosphere, crust, earthquake, lithosphere, volcanic islands
plates	large, rigid pieces of the Earth's crust and upper mantle, which move and interact with one another at their boundaries. See also: crust, mantle, plate tectonics
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. See also: calcite, gypsum, halite, 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. See also: ice age, ice sheet, Quaternary
plesiosaur	a member of a group of extinct long-necked Mesozoic marine reptiles. See also: extinction, Mesozoic
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 prceding the onset of Pleistocene glaciations. See also: geologic time scale, glacier, Neogene
plucking	process in which a glacier "plucks" sediments and larger chunks of rock from the bedrock. The flowing ice cracks and breaks rock as it passes over, pieces of which become incorporated into the sheet or bulldozed forward, in front of the glacier’s margin. See also: glacier

Glossary

pluton, plutonic rock	a large body of intrusive igneous rock that formed under the Earth's surface through the slow crystallization of magma. The term comes from the name of Pluto, Roman god of the underworld. See also: igneous rock, intrusion, magma
pluvial lake	a landlocked basin that fills with rainwater or meltwater during times of glaciation. See also: glacier
porosity	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. See also: joint
power (energy)	the rate at which energy is transferred, usually measured in watts or, less frequently, horsepower. See also: energy, watt
Precambrian	a geologic time period that spans from the formation of Earth (4.6 billion years ago) to the beginning of the Cambrian (541 million years ago). Relatively little is known about this time period since very few fossils or unaltered rocks have survived. What few clues exist indicate that life first appeared on the planet as long as 3.9 billion years ago in the form of single-celled organisms. The Precambrian contains the Hadean, Archean and Proterozoic eons. See also: Archean, geologic time scale, Proterozoic
primary energy source	a source of energy found in nature, that has not been subject to any human-induced energy transfers or transformations (like conversion to electricity). Examples include fossil fuels, solar, wind, and hydropower. See also: energy, fossil fuel
Proterozoic	a geologic time interval that extends from 2.5 billion to 541 million years ago. It is part of the Precambrian. During this eon, the Earth transitioned to an oxygenated atmosphere and eukaryotic cells, including fungi, plants, and animals, originated. See also: geologic time scale, Precambrian
protists	a diverse group of single-celled eukaryotes. See also: eukaryote
protolith	the original parent rock from which a metamorphosed rock is formed. See also: metamorphism

Glossary

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. See also: magma, pyroclastic
pyroclastic	rocks that form during explosive volcanic eruptions, and are composed from a variety of different volcanic ejecta. The term comes from Greek, and means "broken fire." Pyroclastic debris of all types is known as tephra. See also: volcanism
pyroxene	dark-colored rock-forming silicate minerals containing iron and magnesium, found in many igneous and metamorphic rocks. They are often present in volcanic rocks. See also: igneous rock, iron, metamorphic rock, silica, volcanic
quartz	the second most abundant mineral in the Earth's continental crust (after feldspar), made up of silicon and oxygen (SiO_2). It makes up more than 10% of the crust by mass. There are a wide variety of types of quartz: onyx, agate, and petrified wood are fibrous, microcrystalline varieties collectively known as chalcedony. Although agate is naturally banded with layers of different colors and porosity, commercial varieties of agate are often artificially colored. Flint, chert and jasper are granular microcrystalline varieties of quartz, with the bright red color of jasper due to the inclusion of small amounts of iron within the mineral structure. The most common, coarsely crystalline varieties include massive quartz veins, the distinct, well formed crystals of "rock crystal", and an array of colored quartz, including amethyst (purple), rose quartz (pink), smoky quartz (gray), citrine (orange), and milky quartz (white). See also: chalcedony, chert, crust, flint, iron, jasper, mineral
quartzite	a hard metamorphic rock that was originally sandstone. Quartzite usually forms from sandstone that was metamorphosed through tectonic compression within orogenic belts. Quartzite is quarried for use as a building and decorative stone. See also: compression, metamorphism, orogeny, sandstone
Quaternary	a geologic time period that extends from 2.6 million years ago to the present. This period is largely defined by the periodic advance and retreat of continental glaciers. The Quaternary is part of the Cenozoic. See also: Cenozoic, geologic time scale, glacier
radioactive	when an unstable atom loses energy by emitting radiation.
radiocarbon dating	a method of determining the age of a biological object by measuring the ratio of carbon isotopes ^{14}C and ^{12}C. Because the decay rate of ^{14}C is 5000 years, it is useful for numerical dating as far back as 50,000 years. Beyond this point, nearly all of the ^{14}C has decayed.

Glossary

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. See also: luster, ore
recrystallization	the change in structure of mineral crystals that make up rocks, or the formation of new mineral crystals within the rock. Recrystallization commonly occurs during metamorphism. When rocks are metamorphosed, individual grains that make up the original rock are melted slightly and recrystallize. The pressure allows crystals to grow into a tighter, interlocking arrangement than in an unmetamorphosed rock. See also: metamorphism, mineral
reef	a feature lying beneath the surface of the water, which is a buildup of sediment or other material built by organisms, and which has positive relief from the sea floor. While some reefs result from abiotic processes such as deposition or wave action, the best-known reefs are built by corals and other marine organisms.
regional metamorphism	a metamorphic rock that has been altered due to deep burial and great pressure. This type of metamorphic rock tends to occur in long belts at the center of mountain ranges. Different types of metamorphic rock are created depending on the gradients of heat and pressure applied. See also: metamorphism
regression	a drop in sea level.
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. See also: energy
replacement	a fossilization method by which the original material is chemically replaced by a more stable mineral. See also: fossil
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. See also: erode, mineral, weathering
rhyolite, rhyolitic	a felsic volcanic rock high in abundance of quartz and feldspar. See also: feldspar, felsic, quartz, volcanic

rift	a break or crack in the crust that can be caused by tensional stress as a landmass breaks apart into separate plates. See also: crust, plate tectonics
rip-rap	rock and rubble used to fortify shorelines, streambeds, pilings, and other structures against erosion. See also: erosion
ripple marks	surface features created when sediment deposits are agitated, typically by water currents or wind. The crests and troughs formed by this agitation are occasionally preserved, providing information about the flow of water or wind in the paleoenvironment. See also: lithification, sedimentary rock
rock flour	very fine sediments and clay resulting from the grinding action of glaciers. See also clay, glacier.
Rodinia	a supercontinent that contained most or all of Earth's landmass, between 1.1 billion and 750 million years ago, during the Precambrian. Geologists are not sure of the exact size and shape of Rodinia. It was analagous to but not the same supercontinent as Pangaea, which formed was assembled several hundred million years later during the Permian. See also: Pangaea, Permian, Precambrian
roof pendant	a downward projection of metamorphosed basement rock that hangs exposed above an uplifted igneous intrusion. See also: basement rock, igneous rock, intrusive, metamorphic rock
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. See also: bivlave, Cretaceous, extinction, Jurassic, reef
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." See also: extinction, Ordovician, Permian
salt	a mineral composed primarily of sodium chloride (NaCl). In its natural form, it is called rock salt or halite. Salt is essential for animal life, and is a necessary part of the diet. In addition, salt is used for de-icing roads in winter and is also an important part of the chemical industry. See also: mineral

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 0.05–2 millimeters in diameter. See also: weathering
sandstone	sedimentary rock formed by cementing together grains of sand. See also: sand, sedimentary rocks
scheelite	a yellow-brown mineral that is often found in association with quartz, and is an important ore of tungsten. See also: mineral, ore, quartz
schist	a medium grade metamorphic rock with sheet-like crystals flattened in one plane. The flattened crystals are often muscovite or biotite mica, but they can also be talc, graphite, or hornblende. See also: graphite, hornblende, metamorphism, mica, talc
scleractinian coral	a modern "stony" coral; a colonial or solitary marine invertebrate animal belonging to the Order Scleractinia in the Class Anthozoa of the Phylum Cnidaria, and characterized by an encrusting calcareous skeleton from which multiple individuals (polyps) extend from small pores to capture prey with small tentacles equipped with stinging cells (nematocysts). Although scleractinians look somewhat similar to extinct rugose and tabulate corals, each group possesses distinctive features in the shape of the skeletal cup holding the individual polyps. Modern scleractinians host commensal algae (zooxanthellae) whose photosynthetic activities supply the coral with energy.
scoria	a highly vesicular form of basalt. It tends to form as cinders in the early stages of a volcanic eruption, when gas bubbles are still caught up in the frothy erupting magma. Once the gas has escaped, the remaining magma can flow out, creating basalt lava flows that spread out over the landscape. See also: basalt, magma, vesicular, volcanic
scour, scouring	erosion resulting from glacial abrasion on the landscape. See also: erosion, glacier
sedimentary rocks	rocks formed through the accumulation and consolidation of grains of broken rock, crystals, skeletal fragments, and organic matter. Sediment that forms from weathering is transported by wind or water to a depositional environment such as a lakebed or ocean floor; here they build up, burying and compacting lower layers. As water permeates the sediment, dissolved minerals may precipitate out, filling the spaces between particles and cementing them together. Sedimentary rocks may also accrete from fragments of the shells or skeletal material of marine organisms like clams and coral. Sedimentary rocks are classified by their sediment size or their mineral content. Each one reveals the story of the depositional environment where its sediments accumulated and the history of its lithification. See also: erosion, lithification, mineral, weathering

seismic waves	the shock waves or vibrations radiating in all directions from the center of an earthquake or other tectonic event. See also: earthquake
seismometer	an instrument that measures seismic waves (movements) within the ground. These measurements help us map the interior of the Earth, as well as locate the areas where earthquakes and other seismic events begin. See also: seismic waves
serpentinite	a metamorphic rock formed when peridotite from a subducting plate reacts with water, producing a light, slippery, green rock. See also: metamorphic rock, subduction
shale	a dark, fine-grained, laminated sedimentary rock formed by the compression of successive layers of silt- and clay-rich sediment. Shale is weak and often breaks along thin layers. Shale that is especially rich in unoxidized carbon is dark grey or black. These organic-rich black shales are often source rocks for petroleum and natural gas. See also: clay, compression, natural gas, petroleum, sedimentary rock, silt
shield volcano	a volcano with a low profile and gradual slope, so named for its likeness to the profile of an ancient warrior's shield. Shield volcanoes erupt low-viscosity magma that is more fluid than the "sticky" silica-rich lavas that build up stratovolcanoes. Repeated eruptions of fluid lava build large, gently sloping mountains with an expansive size. See also: lava, magma, silica, stratovolcano, volcanism
silica	a chemical compound also known as silicon dioxide (SiO_2). Silica is most commonly found as quartz, and is also secreted as skeletal material in various organisms. It is one of the most abundant materials in the crust. See also: quartz
silt	granular sediment most commonly composed of quartz and feldspar crystals. Particles of silt have diameters of less than 0.074 millimeters. See also: feldspar, quartz
Silurian	a geologic time period spanning from 443 to 419 million years ago. During the Silurian, jawed and bony fish diversified, and life first began to appear on land. The Silurian is part of the Paleozoic. See also: geologic time scale, Paleozoic
silver	a metallic chemical element (Ag). Silver is used in photographic film emulsions, utensils and other tableware, and electronic equipment.

Glossary

slate	a fine-grained, foliated metamorphic rock derived from a shale composed of volcanic ash or clay. See also: clay, foliation, metamorphic rock, shale, volcanic ash
snail	See gastropod
soil	the collection of natural materials that collect on Earth's surface, above the bedrock. Soil consists of layers (horizons) of two key ingredients: plant litter, such as dead grasses, leaves, and fallen debris, and sediment derived from the weathering of rock. Both of these components can influence the texture and consistency of the soil, as well as the minerals available for consumption by plants. The word is derived from the Latin "*solum*," which means "floor" or "ground." See also: horizon (soil), mineral, weathering
soil orders	the twelve major units of soil taxonomy, which are defined by diagnostic horizons, composition, soil structures, and other characteristics. Soil orders depend mainly on climate and the organisms within the soil. These orders are further broken down into 64 suborders based on properties that influence soil development and plant growth, with the most important property being how wet the soil is throughout the year. See also soil, soil taxonomy
soil taxonomy	The system used to classify soils based on their properties. See also: soil
solifluction	a type of mass wasting where waterlogged sediment moves slowly downslope, over impermeable material. Solifluction is similar to a landslide or mudslide. See also: mass wasting
spheroidal weathering	a type of chemical weathering in which the rough edges of a rock wear away evenly, gradually revealing a smooth, rounded surface. This type of weathering often occurs at lower elevations where freezing is infrequent, and is similar to exfoliation (which is a form of mechanical weathering). See also: exfoliation, weathering
Spodosols	a soil order; these are acidic soils in which aluminum and iron oxides accumulate below the surface. They typically form under pine vegetation and sandy parent material. See also: iron, sand, soil, soil orders
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, Cambrian, sedimentary rock

stratigraphy, stratigraphic	the branch of geology specifically concerned with the arrangement and age of rock units. See also: Law of Superposition
stratovolcano	a conical volcano made up of many lava flows as well as layers of ash and breccia from explosive eruptions. Stratovolcanoes are often characterized by their periodic violent eruptions, which occur due to their presence at subduction zones. While young stratovolcanoes tend to have steep cone shapes, the symmetrical conical shape is readily disfigured by massive eruptions. Many older stratovolcanoes contain collapsed craters called calderas. See also: breccia, caldera, lava, subduction, volcanic ash
streak	a physical property of minerals, obtained by dragging the mineral across a porcelain plate and effectively powdering it. During identification, the color of the powder eliminates the conflating variables of external weathering, crystal form, or impurities. See also: crystal form, mineral, weathering
stromatolite	regularly banded accumulations of sediment created by the trapping and cementation of sediment grains in bacterial mats (especially photosynthetic cyanobacteria). Cyanobacteria emit a sticky substance that binds settling clay grains and creates a chemical environment leading to the precipitation of calcium carbonate. The calcium carbonate then hardens the underlying layers of bacterial mats, while the living bacteria move upward so that they are not buried. Over time, this cycle of growth combined with sediment capture creates a rounded structure filled with banded layers. Stromatolites peaked in abundance around 1.25 billion years ago, and likely declined due to the evolution of grazing organisms. Today, stromatolites exist in only a few locations worldwide, such as Shark Bay, Australia. Modern stromatolites form thick layers only in stressful environments, such as very salty water, that exclude animal grazers. Even though there are still modern stromatolites, the term is often used to refer specifically to fossils. See also: fossil
subduction	the process by which one plate moves under another, sinking into the mantle. This usually occurs at convergent plate boundaries. Denser plates are more likely to subduct under more buoyant plates, as when oceanic crust sinks beneath continental crust. See also: active plate boundary, convergent boundary, crust, mantle
sulfur	a bright yellow chemical element (S) that is essential to life. It acts as an oxidizing or reducing agent, and occurs commonly in raw form as well as in minerals. See also: mineral
sustainable	able to be maintained at a steady level without exhausting natural resources or causing severe ecological damage, as in a behavior or practice.
suture	the area where two continental plates have joined together through continental collision. See also: convergent boundary, plate tectonics

Glossary

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.
tabulate coral	an extinct form of colonial coral that often formed honeycomb-shaped colonies of hexagonal cells. See also: extinction
talc	hydrated magnesium silicate, formed during hydrothermal alteration accompanying metamorphism. Talc can be formed from calcite, dolomite, silica, and some ultramafic rocks. See also: calcite, dolomite, mafic, metamorphism, silica
tephra	fragmented material produced by a volcanic eruption. Airborne tephra fragments are called pyroclastic. See also: pyroclastic, volcanic
terrace	a flat or gently sloped embankment or ridge occurring on a hillside, and often along the margin of (or slightly above) a body of water, representing a previous water level.
terrane	a piece of crustal material that has broken off from its parent continent and become attached to another plate. Due to their disparate origins, terranes have distinctly different geologic characteristics than the surrounding rocks. Florida is a good example of an exotic terrane, originating as part of the supercontinent Gondwana. Parts of the western coast of North America (including Alaska and the Northeastern US) are also terranes that have been sutured onto the coast. See also: crust, plate tectonics, suture
Tertiary	an unoffical but still commonly used term for the time period spanning from 66 million to 2.5 million years ago, incluidng the Paleogene, Neogene, and part of the Pleistocene. Although the Tertiary period was officially phased out in 2008 by the International Commission on Stratigraphy, it can still be found in scientific literature. (In contrast, the Carboniferous and Pennsylvanian & Mississippian periods all enjoy official status, with the latter pair being more commonly used in the US.) See also: Carboniferous, Mississippian, Neogene, Paleogene, Pennsylvanian, Pleistocene, stratigraphy
tholeiitic basalt	a highly fluid basaltic lava that is high in silicates, magnesium, and iron. See also: basalt, iron, lava, silica
till	unconsolidated sediment that is eroded from the bedrock, then carried and eventually depositied by glaciers as they recede. Till may include a mixture of clay, sand, gravel, and even boulders. The term originated with farmers living in glaciated areas who were constantly removing rocks from their fields while breaking the soil for planting, a process known as tilling. See also: clay, erosion, glacier, sand
titanium	a metallic chemical element (Ti). Titanium is important because it is lightweight nature, strength and resistance to corrosion.

Glossary

topography	the landscape of an area, including the presence or absence of hills and the slopes between high and low areas. These changes in elevation over a particular area are generally the result of a combination of deposition, erosion, uplift and subsidence. These processes that can happen over an enormous range of timescales. See also: bathymetry, erosion, uplift
topsoil	the surface or upper layer of soil, as distinct from the subsoil, and usually containing organic matter. See also: soil
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. See also: fossil
trachyte	a fine-grained extrusive igneous rock, with a composition high in alkali feldspar. See also: extrusion, feldspar, igneous rock
trade wind inversion	a reversal of the typical atmospheric situation directly above the Earth's surface, where air temperature decreases with altitude. The inversion occurs when the sinking air that forms the trade winds is pushed downward by a high pressure system in the subtropics, and warms as it descends. This creates a layer in which warm air lies above cold air, or an inversion. This layer prevents warm, moist air from rising and limits the formation of tall clouds. See also: atmosphere, trade winds, wind
trade winds	a major tropical wind system, involving the flow of high-pressure subtropical air to the low-pressure equatorial zone. These winds blow westward, due to Earth's rotation; the name "trade winds" comes from their use by sailing captains to establish trade routes from Europe to the Americas. The trade winds are responsible for steering equatorial storms and transporting African dust across the Atlantic Ocean. See also: wind
transform boundary	an active plate boundary in which the crustal plates move sideways past one another. See also: active plate boundary
tree	any woody perennial plant with a central trunk. Not all trees are closely related; different kinds of plants have evolved the tree form through geological time. The trees of the Paleozoic were more closely related to club mosses or ferns than they were to today's trees. See also: Paleozoic, perennial

Glossary

Triassic	a geologic time period that spans from 252 to 201 million years ago. During this period, dinosaurs, pterosaurs, and the first mammals appear and begin to diversify. The Triassic begins directly after the Permian-Triassic mass extinction event, and is the first period of the Mesozoic. See also: geologic time scale, mass extinction, Mesozoic
trilobite	an extinct marine invertebrate animal belonging to the Class Trilobita of the Phylum Arthropoda, and characterized by a three-part body and a chitinous exoskeleton divided longitudinally into three lobes. Trilobites have been extinct since the end of the Paleozoic. Trilobites were primitive arthropods distantly related to horseshoe crabs. As bottom dwellers, they were present in a variety of environments. Like crabs and lobsters, trilobites molted their exoskeletons when they grew. Most fossils of trilobites are actually molts, broken as they were shed off the trilobite. Thus, it is common to find only parts of trilobites, such as the head, mid-section, or tail. See also: extinction, Paleozoic
tropical depression	an organized, rotating system of clouds and thunderstorms. A tropical storm has wind speeds of less than 63 kilometers per hour (39 miles per hour). It has no eye, and lacks the shape and organization of a more powerful hurricane. See also: hurricane
tsunami	a series of ocean waves that are generated by sudden displacement of water, usually caused by an earthquake, landslide, or volcanic explosions (but also from other sources such as meteor impacts, nuclear explosions, and glacier calving). Unlike a wind-generated sea wave, a tsunami wave has an extremely long wavelength. A very large wind wave could have a wavelength of 200 meters (650 feet), while a typical tsunami has a wavelength of 200 kilometers (120 miles). Tsunamis can travel at 800 kilometers per hour (500 miles per hour) in the open ocean. While at sea, a tsunami has a long wavelength, but a small wave height—ships in the open ocean may never notice the passing of a tsunami wave. As the wave approaches shore, however, the wavelength decreases and the wave height (amplitude) increases. See also: calving, glacier, earthquake, volcanic
tufa	a carbonate sedimentary rock, formed by evaporation of water around the mouth of a hot spring or other seep, causing calcium carbonate to precipitate out of solution. Tufa often forms as a thick, bulbous deposit. See also: calcium carbonate, carbonate rocks, sedimentary rock
tuff	a pyroclastic rock made of consolidated volcanic ash. Tuff is the result of pyroclastic flows, in which the violent expansion of hot gas shreds the erupting magma into tiny particles that cool in the air to form dense clouds of volcanic ash. The tremendous explosions that are necessary to create ash-flow tuffs are caused by rhyolitic magma, which is felsic. High silica content makes the magma quite viscous, preventing gas bubbles from easily escaping, thus leading to pressure build-ups that are released by explosive eruptions. The ash flows from these violent explosions tend to hug the ground, eventually solidifying into tuffs. Tuffs and other pyroclastic materials are vesicular (porous) due to gases expanding within the material as it cools. See also: felsic, magma, pyroclastic, rhyolitic, silica, vesicular

turbidite	a thick sediment deposit formed during the flow of a turbidity current. Turbidite sediments are deposited in a graded pattern from the edge of the continental shelf down the continental slope, with the largest particles at the bottom (as they are the heaviest, and settle from the flow more quickly), and smaller particles on top. Turbidites commonly form in a shape called an abyssal fan, which spreads out in a wide teardrop shape from the source onto the abyssal plain of the deep sea. See also: turbidity current
turbidity current	a submarine sediment avalanche. These fast-moving currents of sediment are often caused by earthquakes or other geological disturbances that loosen sediment on a continental shelf. These massive sediment flows have extreme erosive potential, and often carve out underwater canyons. Turbidity currents deposit huge amounts of sediment during flow; such deposits are called turbidites. Because of the rate at which turbidity currents deposit dense sediments, they are often responsible for the effective preservation of many fossil organisms, which are swept up from shallow marine environments and buried in the deep sea. See also: fossil
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. See also: climate, clay, iron, soil, soil order
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. See also igneous rocks, iron, mafic, mineral.
uplift	upward movement of the crust due to compression, subduction, or mountain building. Uplift can also occur as a rebounding effect after the removal of an ice sheet reduces the amount of weight pressing on the crust. See also: compression, crust, ice sheet, subduction
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. See also: clay, soil, soil order
vesicular	porous or pitted with vesicles (cavities). Some extrusive igneous rocks have a vesicular texture. See also: extrusive, igneous rock
volcanic ash	fine, unconsolidated pyroclastic grains under 2 millimeters (0.08 inches) in diameter. Consolidated ash becomes tuff. See also: pyroclastic, tuff

Glossary

volcanic islands	a string of islands created when molten rock rises upwards through oceanic crust. Volcanic islands are common in several contexts, including at subduction zones between colliding oceanic plates, above oceanic hot spots, and along mid-ocean ridges. At subduction zones, the friction between the plates generates enough heat and pressure to melt some of the crust. In the case of hot spots, islands form as magma from the mantle breaks through the sea floor. See also: crust, hot spot, magma, mantle, plate tectonics, subduction, volcanism
volcanic, volcanism	the eruption of molten rock onto the surface of the crust. Most volcanic eruptions occur along tectonic plate boundaries, but may also occur at hot spots. Rocks that form from molten rock on the surface are also called volcanic. Prior to eruption, magma ascends from the mantle to a relatively shallow (1–10 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. See also: hot spot, magma, mantle, plate tectonics
water table	the upper surface of groundwater, that is, the underground level at which groundwater is accessible.
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. See also: energy, joule, power
weather	the measure of short-term conditions of the atmosphere such as temperature, wind speed, and humidity. These conditions vary with the time of day, the season, and yearly or multi-year cycles.
weathering	the breakdown of rocks by physical or chemical means. Rocks are constantly being worn down and broken apart into finer and finer grains by wind, rivers, wave action, freezing and thawing, and chemical breakdown. Over millions of years, weathering and erosion can reduce a mighty mountain range to low rolling hills. Some rocks wear down relatively quickly, while others can withstand the power of erosion for much longer. Softer, weaker rocks such as shale and poorly cemented sandstone and limestone are much more easily worn away than hard, crystalline igneous and metamorphic rocks, or well-cemented sandstone and limestone. Harder rocks are often left standing alone as ridges because surrounding softer, less resistant rocks were more quickly worn away. See also: erosion, igneous rock, metamorphic rock, sedimentary rock
wind	the movement of air from areas of high pressure to areas of low pressure. The greater the temperature difference, the greater the air pressure difference and, consequently, the greater the speed at which the air will move.

windward	upwind; facing into the prevailing winds, and thus subject to orographic precipitation. See also: orographic precipitation, wind
zinc	a metallic chemical element (Zn, atomic number 30). Zinc is typically used in metal alloys and galvanized steel.

General Resources

On the Earth System Science of North America

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Resources for Earth Science and Geography Instruction, by Mike Francek, Central Michigan University, http://webs.cmich.edu/resgi/.
Science in Your Backyard, US Geological Survey, http://www.usgs.gov/state/. (State-by-state compilation of Earth science-related data, most of which will need to be adapted for education uses.)
SERC (The Science Education Resource Center) K-12 resources, http://serc.carleton.edu/k12/index.html. (Hundreds of classroom activities organized by grade level and topic as well as guidance on effective teaching.)
SERC Earth Exploration Toolbook, http://serc.carleton.edu/eet/index.html. (Collection of online Earth system science activities introducing scientific data sets and analysis tools.)
Windows to the Universe, from the National Earth Science Teachers Association, http://www.windows2universe.org/.

Science education organizations

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Acknowledgments

We are grateful to the following reviewers, each of whom edited one or more chapters of the *The Teacher-Friendly Guide™ to the Earth Science of the Western US*: Warren D. Allmon, Scott Babcock, Robert De Groot, Don Duggan-Haas, Bryan Isacks, Robert Kay, Judith T. Parrish, and Harold Wershow.

Richard Kissel managed early development of *The Teacher-Friendly Guide™* series. The glossary was developed by Paula Mikkelsen and Andrielle Swaby.

Funding for this Guide came from National Science Foundation DR K-12 grant DRL-0733303 to the Paleontological Research Institution. Funding to start *The Teacher-Friendly Guide™* series was provided by the Arthur Vining Davis Foundations. Jane (Ansley) Picconi did page layout for the first Guide in the series, *The Teacher-Friendly Guide™ to the Geology of the Northeastern US* (Paleontological Research Institution special publication 24, 2000), many features of which have been adopted for this Guide.

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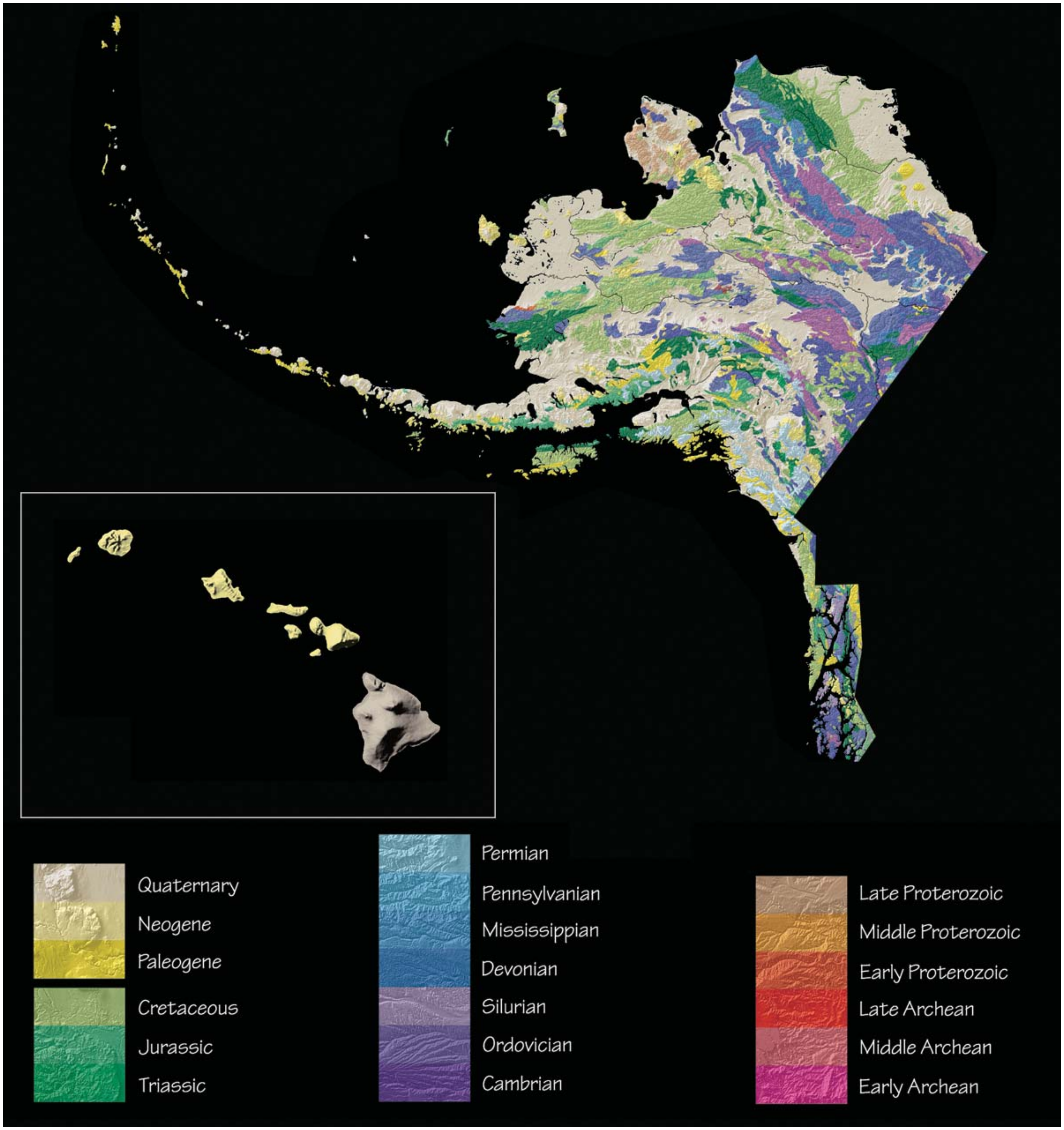
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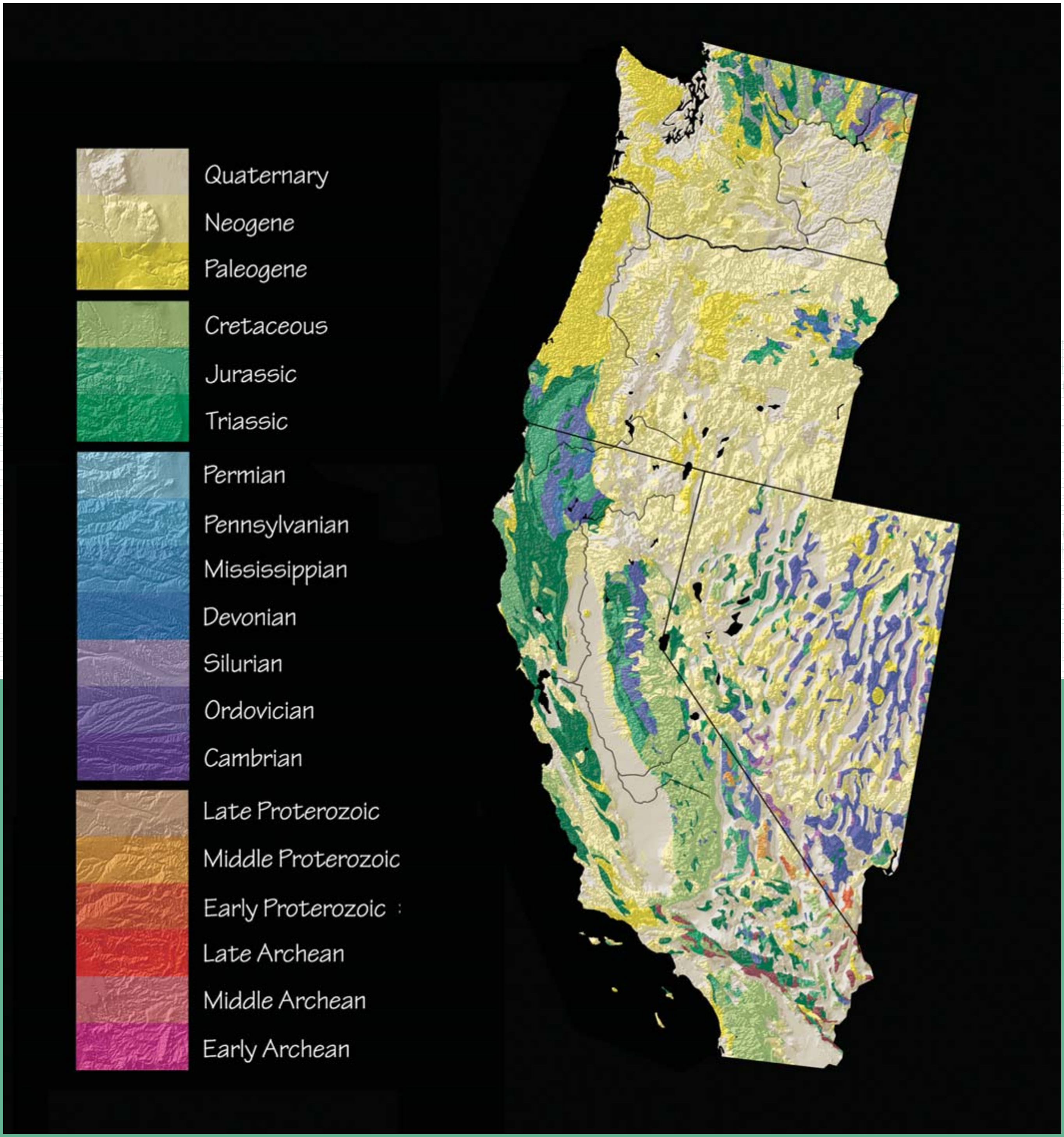

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