

INSTRUCTOR'S MANUAL

ESSENTIALS OF GEOLOGY

FIFTH EDITION

Stephen Marshak

Instructor's Manual by

John Werner

SEMINOLE STATE COLLEGE OF FLORIDA

W • W • NORTON & COMPANY • NEW YORK • LONDON

W. W. Norton & Company has been independent since its founding in 1923, when William Warder Norton and Mary D. Herter Norton first published lectures delivered at the People's Institute, the adult education division of New York City's Cooper Union. The Nortons soon expanded their program beyond the Institute, publishing books by celebrated academics from America and abroad. By mid-century, the two major pillars of Norton's publishing program—trade books and college texts—were firmly established. In the 1950s, the Norton family transferred control of the company to its employees, and today—with a staff of four hundred and a comparable number of trade, college, and professional titles published each year—W. W. Norton & Company stands as the largest and oldest publishing house owned wholly by its employees.

Copyright © 2016, 2013, 2009, 2007, 2004 by W. W. Norton & Company, Inc.

All rights reserved.

Printed in the United States of America

Associate Editor: Cailin Barrett-Bressack

Production Manager: Ben Reynolds

W. W. Norton & Company, Inc., 500 Fifth Avenue, New York, NY 10110

wwnorton.com

W. W. Norton & Company, Ltd., Castle House, 75/76 Wells Street, London W1T 3QT

1 2 3 4 5 6 7 8 9 0

SmartWork5 Online Homework

The new Smartwork5 online assessment available for use with *Essentials of Geology*, Fifth Edition features visual assignments developed with the eye of the author, with focused feedback. Because students learn best when they can interact with art as well as with text, Smartwork5 includes drag-and-drop figure-based questions, animation- and video-based questions, and What a Geologist Sees photo interpretations. Smartwork5 also provides questions based on real field examples, via the Geotours Workbook, and helps students check their knowledge as they go by working with reading-based questions and pre-made and easy-to-assign reading quizzes.

Designed to be intuitive and easy to use for both students and instructors, Smartwork5 makes it a snap to assign, assess, and report on student performance, and to keep the class on track. Smartwork5 now works with tablet and mobile environments, and also has single sign-on capability with your institution's learning management system.

Smartwork5 is available for free with most newly purchased print or electronic versions of the text. Immediate online access can also be purchased at digital.wwnorton.com/essgeo5. Smartwork5 is easy to implement, and your local Norton representative will be happy to help you get started.

Norton Coursepacks for Campus Learning Management Systems

Available at no cost to professors or students, Norton Coursepacks bring high-quality Norton digital media into your campus Learning Management System. For *Essentials of Geology*, Norton Coursepack content includes: access to the test bank, with new essay questions for every chapter courtesy of Heather Lehto of Angelo State University, completely revised quiz questions by Cynthia Liutkus-Pierce of Appalachian State University, new visual questions for each chapter by Brian Zimmer of Appalachian State University, flashcards, animations, streaming video, and links to the e-book.

To download the Norton Coursepack for your campus LMS, go to wwnorton.com/instructors.

INSTRUCTOR'S MANUAL CONTENTS

CHAPTER 1	7
The Earth in Context	
CHAPTER 2	18
The Way the Earth Works: Plate Tectonics	
CHAPTER 3	28
Patterns in Nature: Minerals	
INTERLUDE A	34
Rock Groups	
CHAPTER 4	38
Up from the Inferno: Magma and Igneous Rocks	
CHAPTER 5	46
The Wrath of Vulcan: Volcanic Eruptions	
INTERLUDE B	53
A Surface Veneer: Sediments and Soils	
CHAPTER 6	56
Pages of Earth's Past: Sedimentary Rocks	
CHAPTER 7	64
Metamorphism: A Process of Change	
INTERLUDE C	71
The Rock Cycle	
CHAPTER 8	74
A Violent Pulse: Earthquakes	
INTERLUDE D	84
The Earth's Interior Revisited: Insights from Geophysics	
CHAPTER 9	88
Crags, Cracks, and Crumples: Crustal Deformation and Mountain Building	
INTERLUDE E	96
Memories of Past Life: Fossils and Evolution	
CHAPTER 10	101
Deep Time: How Old Is Old?	
CHAPTER 11	111
A Biography of Earth	
Chapter 12	118
Riches in Rock: Energy and Mineral Resources	
INTERLUDE F	130
An Introduction to Landscapes and the Hydrologic Cycle	
CHAPTER 13	133
Unsafe Ground: Landslides and Other Mass Movements	

CHAPTER 14	139
Streams and Running Water	
CHAPTER 15	147
Restless Realm: Oceans and Coasts	
CHAPTER 16	155
A Hidden Reserve: Groundwater	
CHAPTER 17	163
Dry Regions: The Geology of Deserts	
CHAPTER 18	171
Amazing Ice: Glaciers and Ice Ages	
CHAPTER 19	180
Global Change in the Earth System	

CHAPTER 1

The Earth in Context

Learning Objectives

1. Students should be aware of the Big Bang theory. Distant galaxies are all moving away from us. The farthest galaxies are receding from us the fastest. All matter in the Universe was contained in a single point, approximately 13.8 billion years ago. At that time, the Universe explosively came into existence.
2. Stars, including our Sun, are nuclear-fusion reactors. For most of their life histories (on the order of billions of years), hydrogen atoms are fused together to form helium. Later stages in stellar evolution include fusion of helium atoms and other, heavier elements; ultimately, iron is the heaviest element that can be produced through fusion reactions within stars.
3. After their cycles of fusion are complete, large stars violently explode (forming supernovas), producing elements heavier than iron and leaving behind a residue of diffuse nebulae, which may be recycled to form a new star at some future point.
4. Our Solar System is approximately 4.57 Ga (billion years old). All eight planets revolve around the Sun in coplanar, elliptical orbits. All planets orbit in the same direction (counterclockwise, as viewed from above Earth's North Pole). These facts imply simultaneous planetary formation from a swirling nebula surrounding the Sun (the similarities in orbits would then be a natural result of conservation of angular momentum). The planets accreted from this nebula through gravitational attraction and haphazard collisions. Pluto, long considered the "ninth planet," has seen its status demoted; astronomers now recognize eight major planets.
5. The terrestrial planets (Mercury, Venus, Earth, and Mars) are relatively small, dense, and rocky worlds. The giant planets are predominantly composed of the light gases hydrogen and helium (Jupiter and Saturn) or ices (Uranus and Neptune); they are

much larger and much less dense than the terrestrial planets.

6. Our Moon is thought to have originated from debris accumulated when a protoplanet collided with Earth approximately 4.53 Ga.
7. The Earth System is subdivided into the atmosphere (gases and aerosols that envelop the planet), hydrosphere (Earth's water), geosphere (solid Earth), and biosphere (living things).
8. Earth is chemically divided into a thin, rocky crust dominated by silicate minerals, a thick mantle composed mostly of iron- and magnesium-rich silicates (subject locally to partial melting), and a thick, metallic core made primarily of iron (the outer portion of which is liquid). Students should know how seismic waves tell us that the outer core must be liquid.
9. Physically, the uppermost layers of Earth are the rigid lithosphere (crust and uppermost mantle) and the asthenosphere, which is weaker and flows plastically. The "plates" of plate tectonics theory are discrete slabs of lithosphere, which move with respect to one another atop the asthenosphere.

Summary from the Text

The geocentric model placed Earth at the center of the Universe. The heliocentric model placed the Sun at the center.

The Earth is one of eight planets orbiting the Sun. The Solar System lies on the outer edge of the Milky Way galaxy. The Universe contains hundreds of billions of galaxies.

Most astronomers agree that this expansion began after the Big Bang, a cataclysmic explosion that occurred about 13.7 billion years ago.

The first atoms (hydrogen and helium) of the Universe developed within minutes of the Big Bang. These atoms formed vast gas clouds, called nebulae.

Only very small atoms formed during Big Bang nucleosynthesis. The Earth, and the life forms on it, contain elements that could have been produced only during the life cycle

of stars—intermediate-sized atoms formed by fusion during supernovae explosions. Thus, we are all made of stardust.

Gravity caused clumps of gas in the nebulae to coalesce into flattened disks with bulbous centers. As the central ball of this accretionary disk collapsed inward, it became a warm protostar. Eventually, the ball became so hot and dense that fusion reactions began, and it became a true star.

Planets developed from nebulae, the rings of gas and dust surrounding newborn stars. Matter in these nebulae condensed into planetesimals, which then clumped together to form protoplanets, and finally, true planets. Inner rings became the terrestrial planets; outer rings grew into giant planets, which consist mostly of gas and/or ice.

The Moon formed from debris ejected when a protoplanet collided with Earth in the young Solar System.

When a protoplanet grows large enough, it eventually becomes warm enough inside to differentiate into a core and mantle, and then to assume a near-spherical shape when it becomes so soft that gravity can smooth out irregularities.

The Earth has a magnetic field that shields it from solar wind and cosmic rays.

A layer of gas surrounds the Earth. This atmosphere, which consists of 78% N₂, 21% O₂, and 1% other gases, can be subdivided into layers. Air pressure decreases with increasing elevation.

The surface of Earth can be divided into land (30%) and ocean (70%). Most of the land surface lies within 1 km of sea level. Earth's land surface has a great variety of landscapes due to variations in elevation and climate.

Earth materials include organic chemicals, minerals, glasses, rocks, melts, and volatiles. Most rocks on Earth contain silica (SiO₂). We distinguish among various basic rock types based on the proportion of silica.

The Earth's interior can be divided into three distinct layers: the very thin crust, the rocky mantle, and the metallic core.

Pressure and temperature both increase with depth in the Earth. The rate at which temperature increases as depth increases is the geothermal gradient.

The crust is a thin skin that varies in thickness from 7–10 km (beneath oceans) to 25–70 km (beneath the continents). Oceanic crust is mafic in composition, whereas

average upper-continental crust is felsic to intermediate. The mantle is composed of ultramafic rock. The core is made of iron alloy.

Studies of seismic waves reveal that the mantle can be subdivided into an upper mantle and a lower mantle. The core can be subdivided into the liquid outer core and a solid inner core. Circulation of the outer core produces the Earth's magnetic field.

The crust plus the upper part of the mantle constitute the lithosphere, a rigid shell. The lithosphere lies over the asthenosphere, mantle that can flow.

Video and Animation Files

FORMATION OF THE SOLAR SYSTEM

Number: 1.1

Length: 3 minutes, 17 seconds

Summary: This video provides an overview of the Nebular Theory of Solar System origins. Emphasis is on the action of gravity condensing diffuse material and solar wind ejecting volatiles to leave refractory materials enriched in inner protoplanetary rings.

Classroom Use: This video could be shown on the first day of class to put the Earth in context within the Universe and to explain our understanding of Solar System formation.

Review and Discussion Questions:

1. What is the difference between volatile and refractory materials?
2. Why would we find more of the latter in planets such as Earth that formed near the Sun?

FORMATION OF THE EARTH

Number: 1.2

Length: 2 minutes, 29 seconds

Summary: This video examines the accretionary process that transformed Earth from planetesimal to protoplanet to full planet. It emphasizes the formation of the Earth's metallic core and Moon.

Classroom Use: This video makes a natural follow-up to 1.1, further illustrating how our planet came about.

Review and Discussion Questions:

1. Why is so much of the Earth's iron found in the core?
2. For a short time after the formation of the Moon, the Earth is thought to have had a volcanically dominated atmosphere. Which two gases would have been most abundant in the atmosphere at that time, and what became of them?

Answers to Review Questions

1. Contrast the geocentric and heliocentric Universe concepts.

ANS: The geocentric concept placed Earth at the center of the Universe, with the Sun and the other planets revolving around it. The heliocentric concept placed the Sun at the center, with Earth and the other planets revolving around it.

2. What is the ecliptic, and why are the orbits of planets within the plane of the ecliptic? Why is Pluto no longer considered to be a planet?

ANS: The ecliptic is the plane defined by the orbits of the major planets of our Solar System. The planets reside together in this plane because they formed from matter within the rotating protoplanetary disk surrounding the early Sun. Pluto is no longer considered a planet because it has not swept its orbit clear of other objects.

3. Explain the expanding Universe theory.

ANS: When we look at distant galaxies, we find that they are all moving away from our own, with the farthest galaxies moving away the fastest. This movement suggests that the entire observable Universe is expanding outward.

4. What is the Big Bang, and when did it occur?

ANS: The Big Bang is an explosive phase of expansion of matter and space that occurred at the beginning of our Universe, 13.8 billion years ago.

5. Describe the steps in the formation of our Solar System according to the nebular theory.

ANS: The mass in our Sun and the surrounding Solar System condensed from a swirling nebula (cloud of gas and dust). At the center of the nebula, most of the mass condensed to form the Sun, which graduated from protostar status when it became sufficiently massive—and thus hot enough—to fuse hydrogen. Within a flat protoplanetary disk surrounding the Sun, planets arose from gravity-driven accretion and the collisions of

smaller bodies termed *planetesimals* and *protoplanets*. Light gases and other volatiles were ejected from the inner portion of the disk as the Sun's heat intensified, so the terrestrial planets ended up as smaller spheres of relatively high-density refractory substances (rock and metal). Farther out, the gas-giant planets incorporated abundant volatiles such as hydrogen and helium to become much more massive but less dense.

6. Why isn't the Earth homogenous?

ANS: Early in Earth history, all of its matter was molten. Gravity caused the heavier metals (primarily iron) to sink toward the center of the planet, forming a core distinct from the rocky mantle of the Earth.

7. Describe how the Moon was formed.

ANS: The Moon formed when a protoplanet approximately the size of Mars collided with Earth early in the history of the Solar System. The force of the impact ejected material similar in composition to Earth's mantle. This mantle-like mass cooled and solidified, resulting in our Moon.

8. Why is Earth round?

ANS: Gravity forces objects the size of Earth to be nearly spherical (the most compact shape, minimizing the distance of points from the center).

9. What is Earth's magnetic field? Draw a representation of the field on a piece of paper. What causes aurorae?

ANS: The magnetic field of Earth is a region of space affected by the magnetic force of Earth (see Fig. 1.12c for a sketch). Aurorae are caused by high-energy charged particles traveling along Earth's magnetic field lines and interacting with the gases in the atmosphere.

10. What is Earth's atmosphere composed of? Why would you die of suffocation if you were to eject from a fighter plane at an elevation of 12 km without an oxygen tank?

ANS: Earth's atmosphere is mostly nitrogen and oxygen, with minor amounts of argon, carbon dioxide, and other gases. The atmosphere becomes less and less dense with altitude; at 12 km, oxygen molecules are too sparse to support human life.

11. What is the proportion of land area to sea area on Earth?

ANS: Earth consists of 30% land area as opposed to 70% sea area.

12. Describe the major categories of materials constituting the Earth. Does the crust have the same composition as the whole Earth? On what basis do geologists distinguish among different kinds of silicate rock?

ANS: Categories of materials include **organic chemicals**, which make up the majority of living matter. These carbon- and hydrogen-based compounds (including oil and natural gas) can be quite complex, sometimes incorporating oxygen (as in sugars, starches, and fats), sometimes nitrogen (as in proteins), and, occasionally, some phosphorus and sulfur.

Minerals are solid, inorganic materials in which there is a fixed arrangement of atoms (often termed a *crystalline lattice*). Quartz and calcite are important, familiar examples. Mineral crystals are commonly weathered to produce fragments with rough or rounded surfaces, which are termed *grains*. **Glasses** are physically solid structures in which the atoms are internally disordered (as in liquids, but without the tendency to rapidly flow). Commercial glass is produced when quartz is melted and then cooled rapidly (quenched in cool water), so that atoms cannot align themselves into the quartz crystalline arrangement before the rigidity of cooling sets in. **Grains** are individual mineral crystals within rock or loose fragments of minerals or rocks. **Rocks** are cohesive aggregates of crystals or grains or solid masses of natural glass. Igneous rocks crystallize from molten (liquid) rock. Sedimentary rocks arise from the cementation of loose grains (sand, mud, pebbles, etc.) and through chemical precipitation (from the ocean or continental bodies of water). Metamorphic rocks arise from heat- and pressure-induced alteration of pre-existent rock (without melting). Grains are crystals within rock or loose fragments of crystals. **Sediments** are loose accumulations of mineral grains. **Metals** are solids made up of metallic elements only (to a strong approximation), such as gold, iron, and copper. (Naturally occurring metals are a subset of minerals.) **Melts** are hot liquids that crystallize at surface temperatures to form igneous rocks. Melts within Earth are termed *magma*; melts extruded on the surface are termed *lava*. **Volatiles** are substances that are stable in a gaseous state at the relatively low temperatures of Earth's surface. Geologists distinguish silicate rocks on the basis of silica content and grain size.

13. What are the principal layers of Earth? What happens to earthquake waves when they reach the boundary between layers?

ANS: Major layers of Earth are the very thin crust, the rocky mantle, and metallic core. Earthquake waves reaching boundary layers between these layers may be reflected or refracted (bent).

14. How do temperature and pressure change with increasing depth in the Earth?

ANS: Both temperature and pressure steadily increase with increasing depth.

15. What are meteorites, and how does the study of them provide insight into the character of the Earth's interior?

ANS: Meteorites are objects that have fallen from space and impacted the Earth. Meteorites may be rocky or metallic or a combination of the two. Most meteorites are thought to represent early pieces of our Solar System, and thus, they can be used as a model for the Earth's interior.

16. What is the Moho? Describe the difference between continental crust and oceanic crust.

ANS: The Moho is the crust-mantle boundary, recognized by an abrupt change in seismic-wave velocities. Continental crust is thicker, more silicic, and more variable in chemistry than oceanic crust.

17. What is the mantle composed of? Is there any melt in it?

ANS: The mantle is mostly made of an ultramafic silicate rock termed *peridotite*. There is a small amount of melt in the upper mantle.

18. What is the core composed of? How do the inner and outer cores differ? Which one produces the magnetic field?

ANS: The core is mostly iron; the inner part is solid, whereas the outer part is liquid. Circulation of iron atoms in the liquid outer core generates Earth's magnetic field.

19. What is the difference between the lithosphere and the asthenosphere? At what depth does the lithosphere-asthenosphere boundary occur? Is this above or below the Moho? Is the asthenosphere entirely liquid?

ANS: The lithosphere is relatively cool and rigid compared to the hot, soft asthenosphere, which flows more readily. The lithosphere consists of the crust (oceanic basalt and gabbro, or continental granite), plus the uppermost mantle (peridotite) down to a depth of about 100 to 150 km. This boundary lies below the Moho. The asthenosphere is primarily solid rock, but is molten in places.

On Further Thought

20. Are all stars that we see today considered to be first-generation stars? What is the evidence for your answer?

ANS: No. Many observed stars are too enriched in heavier elements to be first-generation stars.

21. Why are the giant planets, which contain abundant gas and ice, farther from the Sun?

ANS: Close to the Sun, solar wind was great enough to drive off the great volumes of light gases and volatiles that are necessary for giant planets to form.

22. Recent observations suggest that the Moon has a very small, solid core that is less than 3% of its mass. In comparison, Earth's core is about 33% of its mass. Explain why this difference might exist.

ANS: This observation is well explained by the impact theory of Moon formation. Under this scenario, a small protoplanet collided with Earth early in its history. The core of the impactor sank into the Earth, contributing to Earth's large core, and the Moon formed from ejected material that was mostly mantle-like in composition. As the Moon cooled, only a small amount of iron was available to sink and form a lunar core.

23. The Moon has virtually no magnetosphere. Why?

ANS: Unlike the Earth, the Moon has no liquid metallic layer inside.

24. Popular media sometimes imply that the crust floats on a “sea of magma.” Is this a correct image of the mantle just below the Moho? Explain your answer.

ANS: No; the mantle just beneath the crust is not only solid but rigid, and along with the crust, it forms the lithosphere. Even the asthenosphere is mostly solid, though weak and ductile.

CHAPTER 2

The Way the Earth Works: Plate Tectonics

Learning Objectives

1. The plates of plate tectonics are discrete slabs of lithosphere (crust and rigid portion of the mantle) that move with respect to each other. They glide over a weak layer of the mantle termed the asthenosphere. Boundaries between plates are convergent (where plates move toward each other, with material from one of the plates subducted into the mantle), divergent (where plates are pushed apart at a mid-ocean ridge), or transform (where plates slide past each other). Relative plate motions are about a few centimeters a year (a common analogy is that these rates approximate the rate of human fingernail growth).
2. Plate motion at all three boundary types triggers earthquakes. Plate boundaries are delineated by belts of high historical earthquake frequency.
3. Volcanism is associated with both convergent (volcanic arcs) and divergent (mid-ocean ridges) boundaries but not transform boundaries.
4. Only oceanic lithosphere is dense enough to be subducted at convergent boundaries. When continental lithosphere converges on another continent, a mountainous collision zone is formed, and the two plates involved become sutured together. Conversely, a single large plate can become rifted apart when its lithosphere is stretched, thinned, and broken apart by a developing ridge.
5. Students should be aware of Wegener's amassed evidence for continental drift. The fit of coastal outlines and the distribution of rocks, fossils, and ancient climatic belts all strongly suggest that the continents were once aligned to form a supercontinent named Pangaea. Wegener's ideas had few supporters during his lifetime because he could not provide a workable mechanism through which continents could move with

respect to one another.

6. During the 20th century, paleomagnetic data showed that continents must have drifted, because the rocks of isolated continents produce unequal apparent polar-wander paths for the north magnetic pole. Additionally, within the rocks of a single continent, magnetic inclination angles may change over time; this theory is only readily explained through continental drift in a northward or southward direction.
7. Seafloor spreading was proven in the late 1960s by examination of marine magnetic anomalies, which are symmetric about the mid-ocean ridges. Combined with radiometric dates, these patterns clearly show that oceanic crust is created at the ridges and spreads outward, with crustal age increasing away from the ridge axis in either direction. Areas of positive anomaly (including the ridges themselves) arise from rocks that crystallized and cooled during times when Earth's magnetic polarity was normal (the same as it is today); rocks producing negative anomalies cooled during times of reversed polarity.
8. Together, the evidence for seafloor spreading and continental drift have been combined with geophysical observations to form the basis of our modern understanding of plate tectonics—the unifying theory of geology that explains the distribution of earthquakes, volcanism, and mountain building, and the links among these phenomena.

Summary from the Text

Alfred Wegener proposed that continents had once been joined together to form a single huge supercontinent (Pangaea) and had subsequently drifted apart. This idea is the continental-drift hypothesis.

Wegener drew from several different sources of data to support his hypothesis: (1) the matching of the coastlines, (2) the distribution of late Paleozoic glaciers, (3) the distribution of late Paleozoic equatorial climatic belts. (4) the distribution of fossil

species, and (5) correlation of distinctive rock assemblages that are now on opposite sides of the ocean.

Rocks retain a record of the Earth's magnetic field that existed at the time the rocks formed. This record is called paleomagnetism. By measuring paleomagnetism in successively older rocks, geologists discovered apparent polar-wander paths.

The contrasts among apparent polar-wander paths for different continents serve as proof of continental drift.

Around 1960, Harry Hess proposed the hypothesis of seafloor spreading. According to this hypothesis, new seafloor forms at mid-ocean ridges, and then it spreads symmetrically away from the ridge axis. Eventually, the ocean floor sinks back into the mantle at deep-ocean trenches.

Geologists documented that Earth's magnetic field reverses polarity every now and then. Magnetic reversals explain the existence of stripe-like marine magnetic anomalies.

A proof of seafloor spreading came from the interpretation of marine magnetic anomalies and from drilling studies which proved that seafloor gets progressively older away from a mid-ocean ridge.

The lithosphere is broken into discrete plates that move relative to one another. Continental drift and seafloor spreading are manifestations of plate movement.

Most earthquakes and volcanoes occur along plate boundaries; the interiors of plates remain relatively rigid and intact.

There are three types of plate boundaries—divergent, convergent, and transform—distinguished from one another by the movement the plate on one side of the boundary makes relative to the plate on the other side.

Divergent boundaries are marked by mid-ocean ridges. At divergent boundaries, seafloor spreading produces new oceanic lithosphere.

Convergent boundaries are marked by deep-ocean trenches and volcanic arcs. At convergent boundaries, oceanic lithosphere subducts beneath an overriding plate.

Transform boundaries are marked by large faults at which one plate slides sideways past another.

Triple junctions are points where three plate boundaries intersect.

Hot spots are places where volcanism occurs at an isolated volcano. As a plate

moves over the hot spot, the volcano moves off and dies, and a new volcano forms over the hot spot; the chain of volcanoes defines a hot-spot track. Hot spots may be caused by mantle plumes.

During rifting, continental lithosphere stretches and thins. If it finally breaks apart, a new mid-ocean ridge forms, and seafloor spreading begins.

Convergent-plate boundaries cease to exist when a buoyant piece of crust (a continent or an island arc) moves into a subduction zone. When that happens, collision occurs. Collision can thicken crust and build large mountain belts.

Ridge-push force and slab-pull force contribute to driving plate motions. Plates move at rates of about 1 to 15 cm per year. GPS satellite measurements can detect these motions.

Video and Animation Files

BREAKUP OF PANGAEA

Number: Video 2.1

Length: 3 minutes, 44 seconds

Summary: This video uses paleogeographic maps to show how Pangaea formed and broke apart to produce the world we are familiar with today. Details include the rate of seafloor spreading and its variability along the mid-Atlantic ridge. The video also shows satellite imagery of folded rock in the Appalachian region that formed with the collisions that built Pangaea.

Classroom Use: This video would help the student visualize that changes that the distribution of continents has seen over time. It also gives the student an appreciation of the geological complexity of the Central American and Caribbean region.

Review and Discussion Questions:

1. Is Pangaea the only known supercontinent in Earth history?
2. Dinosaur fossils have been found on all major continents. Given that nearly all

dinosaur species do not appear to be strong swimmers, how is this fact explained?

PLATE BOUNDARIES

Number: Animation 2.1

Length: 11 min.

Summary: Relative plate motion for all major subcategories of divergent, convergent, and transform-plate boundaries are animated, and the major geologic features of each boundary are described and have their origins explained.

Classroom Use: This animation would be very helpful to students as they try to understand plate tectonics as a dynamic system.

Review and Discussion Questions:

1. Where in the ocean basins would you find the oceanic lithosphere to be thinnest?
2. What are the major differences between transform faults and fracture zones?

Answers to Review Questions

1. What was Wegener's continental-drift hypothesis? What was his evidence? Why didn't other geologists accept Wegener's proposal of continental drift, at first?

ANS: Wegener stated that the continents had once been contiguous, forming a supercontinent (which he termed *Pangaea*), and that they later moved apart to form their present configuration.

Evidence Wegener used to support his hypothesis was taken from four lines of observation. (1) In many places, the coastal outlines of the continents seem to fit together like the pieces of a jigsaw puzzle, suggesting that at one time, the two continents were linked. (2) The fossil record of plant and animal life at the time of *Pangaea*'s proposed existence show that species of plants, freshwater animals, and bulky terrestrial animals were found in lands separated by vast and deep ocean basins, if the distribution of continents was the same as that seen today. It was hard to imagine how these species

could have distributed themselves so widely across the globe without continental drift.

(3) Rock units match up between continents across the Atlantic Ocean basin (such as Africa and South America). (4) Ancient climatic belts (including an ancient glaciation) make sense if the continents were aligned to form Pangaea at the time, but they are inconsistent with modern geography.

Wegener's ideas were initially rejected by most geologists because they could not conceive of forces great enough to move continents. Wegener himself could not provide a sufficient mechanism.

2. How do apparent polar-wander paths show that the continents have moved?

ANS: The apparent polar-wander paths for two different continents do not agree concerning the position of the ancient magnetic north pole. Although it is possible for the magnetic pole to wander, it is impossible for it to be in two places at the same time. Therefore, the discrepancy must be explained as a consequence of drifting continents.

3. Describe the hypothesis of seafloor spreading.

ANS: Seafloor spreading is the idea that new oceanic basalt is produced at mid-ocean ridges and spreads laterally to either side. It is the push of oceanic basalts that causes the continents to drift over Earth's surface.

4. Describe the pattern of marine magnetic anomalies across a mid-ocean ridge. How is this pattern explained?

ANS: Over the ridge crest, Earth's magnetic field is anomalously strong (a positive anomaly). This elongate belt of positive anomaly is flanked on either side by belts of anomalously weak magnetic field strength (negative anomaly). The alternating sequence of positive and negative anomalies continues in either direction outward from the ridge, forming a pattern that possesses mirror-image symmetry about the ridge axis. The explanation for the pattern is that magnetic fields of crystals formed in the most recent past have remnant magnetism in concert with today's global magnetic field (and are said to have normal polarity). Extra field strength derives from the alignment of all these mini-magnets reinforcing the modern dipole. The same is true for all positive anomalies, representing crystallization and cooling that took place during times when Earth's

magnetic polarity was the same as it is today. Negative anomalies are derived from bodies of rock that crystallized and cooled during times when Earth's magnetic field had a polarity opposite to that of today. The magnetic fields of these rocks destructively interfere with the modern dipole, weakening the observed magnetic strength. Thus, the marine magnetic anomalies are produced by the combination of seafloor spreading through time with magnetic polarity reversals through time.

5. How did drilling into the seafloor contribute further proof of seafloor spreading? How did the seafloor-spreading hypothesis explain variations in ocean floor heat flow?

ANS: Sediments atop oceanic basalts become thicker away from mid-ocean ridges, and the lowermost (oldest) layers become progressively older with increasing distance from the ridge. Heat flow is greatest at mid-ocean ridges, which is consistent with the seafloor-spreading model in which new seafloor is produced as igneous rock solidifying from rising hot magma at these spreading centers.

6. What are the characteristics of a lithosphere plate? Can a single plate include both continental and oceanic lithosphere?

ANS: The lithosphere is the rocky portion of Earth, relatively cool and rigid as compared to underlying mantle material (the hotter, weaker asthenosphere). The lithosphere is composed of the crust and the uppermost portion of the mantle. A single plate may consist of both continental and oceanic lithosphere in different regions.

7. How does oceanic lithosphere differ from continental lithosphere in thickness, composition, and density?

ANS: Oceanic lithosphere is thinner, more mafic in its crustal component (largely basalt, whereas continental crust is granitic), and denser.

8. How do we identify a plate boundary?

ANS: Plate boundaries are marked by linear or arc-like segments of relatively high earthquake frequency (earthquake belts).

9. Describe the three types of plate boundaries.

ANS: Divergent-plate boundaries exist where lithosphere on either side moves away from the boundary. At convergent-plate boundaries, lithosphere on either side comes together, bringing either subduction (if oceanic lithosphere is involved) or collision (of two continental plates). At transform-plate boundaries, plates slide past each other.

10. How does crust form along a mid-ocean ridge?

ANS: The high-heat flux at the ridge melts mantle material to form magma, which is relatively light and rises to the surface. Some of the magma crystallizes beneath the surface (as gabbro or in thin basaltic dikes), and some erupts to form volcanic lava, which flows and ultimately solidifies to form pillow basalt.

11. Why is the oldest oceanic lithosphere less than 200 Ma?

ANS: All oceanic lithosphere produced prior to 200 Ma has been subducted down trenches.

12. What are the major geologic features of a convergent boundary?

ANS: If the convergent boundary is a subduction zone, it is marked by a deep trench where the subducting oceanic plate bends downward in opposition to the horizontal overriding plate. Sediments scrape off the subducting plate to form an accretionary prism at the edge of the overriding plate. Behind the prism, melting associated with the subducting plate produces either a volcanic continental arc or a volcanic island arc. If a collisional boundary is present instead of a subduction zone, then a broad, thick, nonvolcanic mountain range will be present.

13. Why are transform-plate boundaries required on an Earth with spreading and subducting plate boundaries?

ANS: Transform-plate boundaries are necessary to connect either a pair of ridge segments producing seafloor spreading in opposite directions, or a pair of trenches with opposite directions of subduction, or a ridge to a trench.

14. What is a triple junction?

ANS: A triple junction is a point at which three plate boundaries meet.

15. How is a hot-spot track produced, and how can hot-spot tracks be used to track the past motions of a plate?

ANS: A large volume of very hot rock from within the mantle rises at the hot spot and produces abundant magma, yielding copious volcanism to form the hot spot. Hot spots are relatively stable points, whereas the plates that overlie them, and that bear the associated volcanoes, are moving. Over periods of millions of years, as a plate slides over the hot spot, extinct volcanoes are ferried in the direction of plate motion, while new volcanoes are formed at the hot spot.

16. Describe the characteristics of a continental rift, and give examples of where this process is occurring today.

ANS: Continental rifts appear as elongate valleys bounded on either side by faults. Volcanism occurs along the rift as asthenosphere rises to accommodate the thinning lithosphere and melts. Rifts can be found in East Africa and in the Great Basin of the western United States.

17. Describe the process of continental collision, and give examples of where this process has occurred.

ANS: Continental rock is not dense enough to subduct beneath an overriding, opposed continental plate and will thus collide with it, suturing itself with the adjacent plate, folding the rocks in the zone of collision, and thickening the crust locally to form a nonvolcanic mountain range. The Appalachians and Himalayas are examples of mountain ranges that formed from this process of collision.

18. Discuss the major forces that move lithosphere plates.

ANS: Ridge push is a driving force that arises because elevated lithosphere at a ridge pushes downward on less-elevated lithosphere to either side. Slab pull is a driving force that arises at subduction zones due to old, cold, dense oceanic lithosphere sinking into the less dense asthenosphere.

19. Explain the difference between relative-plate velocity and absolute-plate velocity.

ANS: Relative-plate velocity describes rates of motion calculated for the movement of

material on one plate with respect to material from an adjacent plate (or with respect to a plate boundary). Absolute-plate velocity is calculated using age and distance data from the material on a plate, with the distance calculated from a hot spot or other fixed point of reference on Earth's surface.

On Further Thought

20. Why are the marine magnetic anomalies bordering the East Pacific Rise in the Pacific Ocean wider than those bordering the Mid-Atlantic Ridge?

ANS: The East Pacific Rise is spreading faster, so it produces a greater width of basalt in the time intervals between polarity reversals.

21. The North Atlantic Ocean is 3,600 km wide. Seafloor spreading along the Mid-Atlantic Ridge occurs at 2 cm per year. When did rifting start to open the Atlantic?

ANS: Assuming a constant rate of seafloor spreading during the interval, the Atlantic started to open up approximately 180 million years ago.

CHAPTER 3

Patterns in Nature: Minerals

Learning Objectives

1. Students should be aware of all aspects (natural occurrence, formation through geologic processes, solid form, fixed crystalline structure, definable chemical composition) of the definition of a mineral, so that they can easily distinguish minerals from nonmineral matter.
2. Minerals are identified using physical properties; students should know all of the most commonly used properties (streak, color, hardness, luster, specific gravity, crystal habit, and cleavage) and how these properties are assessed. The distinctive attributes of halite (salty taste), magnetite (magnetism), and calcite (reaction to weak hydrochloric acid) should be known as well.
3. Minerals making up rock are formed in five ways: solidification from a melt, solid-state diffusion through a pre-existing crystal, precipitation from a water solution, precipitation from a gas, and biomineralization (activities of organisms).
4. The vast majority of Earth's minerals are silicates; students should know the arrangement and composition of silicon-oxygen tetrahedra that form the basis of these minerals.
5. Variation in the degree of oxygen sharing among tetrahedra allows for the great diversity of crystalline form found in silicates; tetrahedra may be spatially isolated or linked to form chains, sheets, or three-dimensional frameworks.
6. Some minerals are prized as gemstones. Many other minerals have commercial uses.

Summary from the Text

Minerals are naturally occurring solids, formed by geologic processes, with a definable chemical composition and an internal structure characterized by an orderly arrangement of atoms, ions, or molecules in a crystalline lattice. Most minerals are inorganic.

Biogenic minerals, such as those in clam shells, are produced by organisms through a process called biomineralization.

In the crystalline lattice of minerals, atoms occur in a specific pattern—one of nature's finest examples of ordering.

Minerals can form by solidification of a melt, precipitation from a water solution, diffusion through a solid, metabolism of organisms, and precipitation from a gas.

Mineralogists have identified about 4,000 different types of minerals. Each has a name and distinctive physical properties (such as color, streak, luster, hardness, specific gravity, crystal habit, cleavage, magnetism, reactivity to acids).

The unique physical properties of a mineral reflect its chemical composition and crystal structure. By observing these physical properties, you can identify minerals.

The most convenient way to classify minerals is to group them according to their chemical composition. Mineral classes include silicates, oxides, sulfides, sulfates, halides, carbonates, and native metals.

Silicate minerals are the most common minerals on Earth. The silicon-oxygen tetrahedron, a silicon atom surrounded by four oxygen atoms, serves as the fundamental building block of silicate minerals.

Groups of silicate minerals are distinguished from one another by the ways in which the silicon-oxygen tetrahedra that constitute them are linked.

Gemstones are minerals known for their beauty and rarity. The facets on cut gems used in jewelry are made by grinding and polishing the stones with a faceting machine.

Answers to Review Questions

1. What is a mineral, as geologists understand the term? How is this definition different from the everyday usage of the word?

ANS: A mineral is a naturally occurring solid, formed by geologic processes, that has a crystalline structure and a definable chemical composition. In everyday speech, the term mineral is used to refer to one of the chemical elements that is necessary for nutrition.

2. Why is glass not a mineral?

ANS: Glass is atomically disordered, having no fixed crystalline arrangement. Because there is no fixed spatial arrangement for the atoms within glass, glass fails the “crystalline structure” requirement in the definition of a mineral.

3. Salt is a mineral, but the plastic making up an inexpensive pen is not. Why not?

ANS: The plastic is not a mineral because it lacks crystal structure and does not occur naturally.

4. Describe the several ways in which mineral crystals can form.

ANS: Crystals can solidify from a melt, freezing from hot liquid rock in the formation of igneous rock. Crystals can also form through solid-state diffusion, in which new crystals are formed from the atoms that were present in a pre-existing mineral. Movement of atoms or ions to form the new structure can be driven by heat and pressure; thus, solid-state diffusion is associated with metamorphic rock formation. Mineral crystals can form through precipitation from water or from gas. Precipitation of crystals might be due to inorganic physical processes, but it might also result from the metabolic activities of organisms.

5. Why do some minerals occur as euhedral crystals, whereas others occur as anhedral grains?

ANS: Euhedral crystals (those with clearly defined faces and edges) develop when crystal growth occurs in unoccupied space; crystal geometry is determined by the internal lattice structure of the elements making up the mineral. More commonly in igneous

rocks, numerous crystals form more or less simultaneously in a tightly packed space. In this case, the competing crystals intertwine as they crystallize, forming irregular boundaries. Such crystals lack the clearly defined faces of exemplary euhedral crystals and are termed *anhedral grains* (their irregular shapes are reminiscent of those of weathered grains of sediment).

6. List and define the principal physical properties used to identify a mineral. Which minerals react with acid to produce CO₂?

ANS: Hardness (resistance to scratching), cleavage (tendency of crystals to break along planes of weakness), color (self-explanatory), luster (qualitative assessment of the way in which the mineral reflects light), crystal form or habit (the shape of visible crystals or crystal aggregates), streak (the color of the mineral in powdered form), and specific gravity (mass per unit volume of the mineral). Carbonate minerals (such as calcite) react with acids to release CO₂.

7. How can you determine the hardness of a mineral? What is the Mohs hardness scale?

ANS: Mineral hardness is determined through scratch tests. A relatively hard mineral can scratch a softer mineral, but the converse statement is not true. The Mohs hardness scale is an ordinal scale of scratch resistance, with rankings from 1 (talc) at the soft end of the scale to 10 (diamond) at the hard end.

8. How do you distinguish cleavage surfaces from crystal faces on a mineral? How does each type of surface form?

ANS: Cleavage planes occur in parallel sets; crystal faces are solitary, occurring only at the surface of the crystal. Cleavage surfaces arise due to planes of weak bonding within the crystal and can be seen because of crystal breakage (or near breakage). Crystal faces are formed by the growth of the crystal.

9. What is the prime characteristic that geologists use to separate minerals into classes?

ANS: Minerals are divided on the basis of chemical composition (more precisely, the anion[s] present in the mineral).

10. What is a silicon-oxygen tetrahedron? What is the anionic group that occurs in

carbonate minerals?

ANS: A silicon-oxygen tetrahedron is a pyramid-shaped structure consisting of a silicon atom surrounded by four oxygen atoms; it is an anionic group with a 4- charge. The anionic group in carbonate minerals is CO_3^{2-} .

11. On what basis do mineralogists organize silicate minerals into distinct groups?

ANS: Silicates are subdivided into distinct groups on the basis of the amount of oxygen-sharing between neighboring silicon-oxygen tetrahedra.

12. What is the relationship between the way in which silicon-oxygen tetrahedra bond in micas and the characteristic cleavage of micas?

ANS: In micas, each silicon-oxygen tetrahedron shares three oxygen atoms with adjacent, coplanar tetrahedra. The shared silicon-oxygen bonds within these planes are very strong, but bonds perpendicular to sheets are much weaker. Cleavage in micas thus occurs along planes with a single orientation, parallel to the sheets.

13. Why are some minerals considered gemstones? How do you make the facets on a gem?

ANS: Gemstones are minerals that are valued for their aesthetic beauty. Facets on gems are cut by a faceting machine and do not usually represent original crystal faces or cleavage planes.

On Further Thought

14. Compare the chemical formula of magnetite with that of biotite. Considering that iron is a relatively heavy element, which mineral has the greater specific gravity?

ANS: Both contain iron and oxygen, but biotite also contains a variety of other, lighter elements, including silicon, magnesium, and hydrogen. Iron is a far more abundant component of magnetite than it is of biotite. Thus, magnetite has a greater specific gravity

than biotite.

15. Imagine that you are given two milky white crystals, each about 2 cm across. You are told that one of the crystals is composed of plagioclase and the other of quartz. How can you determine which is which?

ANS: The quickest and easiest way (at least for introductory students who often have difficulty assessing cleavage) is a hardness test; quartz will scratch plagioclase, but the converse is not true. Quartz also lacks cleavage, whereas feldspars, like plagioclase, possess two cleavage directions. Plagioclase typically exhibits striations that can be seen when the specimen is rotated in light.

16. Could you use crushed calcite to grind and form facets on a diamond? Why or why not?

ANS: You could not; diamond is much harder than calcite, and the result of such efforts would be to powder the calcite.

INTERLUDE A

Rock Groups

Learning Objectives

1. Students should understand the geological definition of rock.
2. Students should know the basis that geologists use to assign rocks into one of three classes.
3. Students should be familiar with the tools that can be used to study rocks.

Summary of the Text

Rock is a coherent, naturally occurring solid, consisting of an aggregate of minerals or a mass of glass. Nonglassy rocks can be classified as crystalline or clastic.

Bedrock consists of in-place rock that is still connected to the underlying crust.

Outcrops, exposures of bedrock at the Earth's surface, can be natural or manmade.

Geologists classify a rock as igneous, sedimentary, or metamorphic based on how the rock formed.

A variety of characteristics prove helpful in describing rocks. Examples include grain size, shape, composition, texture, and the nature of layering.

Hand lenses, microscopes (after making thin sections), and sophisticated electronic equipment help geologists interpret the origin of rocks.

Video and Animation Files

ROCK GROUPS

Number: A.1

Summary: This animation defines rocks as coherent, brittle solids composed of crystals of one or more minerals or shards of volcanic glass. It makes clear the distinctions between igneous, sedimentary, and metamorphic rocks, and emphasizes the difference between the interlocking texture of crystalline rocks and the cemented texture of clastic rocks. The animation also explores the techniques geologists use to study rocks at outcrop and in the laboratory in thin-section.

Classroom Use: This animation could be used as a supplement to a reading assignment or as a pre-lab demonstration of the difference between interlocking and cemented textures in rock samples.

Review and Discussion Questions:

1. Is a jigsaw puzzle a good analogy for rocks with cemented texture, or interlocking texture? How about a Rice Krispies™ treat?
2. A geologist examines a rock carefully under a microscope and notices that it consists of sand-sized grains of quartz held together by smaller, interlocking crystals. Is this an igneous, sedimentary, or metamorphic rock?

Answers to Review Questions

1. What is the geologist's definition of the term *rock*? Can a brick be considered to be a rock? Explain your answer.

ANS: A rock is a coherent, naturally occurring solid that consists of an aggregate of minerals or a body of glass. Bricks are not rocks under this definition because they do not occur naturally.

2. Explain the difference between a clastic and crystalline rock.

ANS: A clastic rock is composed of grains held together by cement; crystalline rocks hold together due to mineral crystals mutually interlocking.

3. Give examples of different kinds of rock outcrops. Can you find outcrops everywhere?

Explain your answer.

ANS: An outcrop might occur as rock extending upward in the middle of a field, a ledge against the side of a cliff, a stream cut, or a roadcut or other human-made excavation. Outcrops are not found everywhere; in many places, rock is covered by sediment, soil, water, or urban development.

4. What is the principal basis that geologists use to classify rocks into three classes? What are these classes?

ANS: Geologists divide rocks into three classes on the basis of the way in which the rock forms. The three classes of rock are igneous, metamorphic, and sedimentary.

5. Explain the difference between an equant and an inequant grain.

ANS: An equant grain is approximately the same linear size in all three spatial dimensions. An inequant grain has a least one dimension that is of unequal length to another.

6. What are two examples of layering that occur in rock?

ANS: Layering includes sedimentary bedding and metamorphic foliation.

7. What are thin sections, how are they examined, and what do they allow you to see?

ANS: Thin sections are slices of rock that are 0.03 mm thick. They are examined with a petrographic microscope, and they allow you to see minute details of texture and mineral composition of the rock.

8. What kinds of high-tech equipment can be used to study rocks?

ANS: Rocks are often studied with such high-tech electronic equipment as scanning

electron microscopes, electron microprobes, mass spectrometers, and X-ray diffractometers.

CHAPTER 4

Up from the Inferno: Magma and Igneous Rocks

Learning Objectives

1. Students should know that igneous rocks make up a majority of the crust and mantle of Earth.
2. Igneous rocks solidify (freeze) from melt (either extrusively from lava or intrusively from magma); melts are derived from pressure release, the addition of volatiles, or heat transfer from rising magma.
3. Igneous rocks are classified based on, which may be crystalline, fragmental, or glassy, and also based on mineral composition (felsic, intermediate, mafic, or ultramafic). Crystalline textures include coarse-grained (visible, phaneritic) and fine-grained (invisible, aphanitic) examples. Coarse-grained rocks cooled more slowly than fine-grained rocks. Grain size and composition should be known for six standard igneous rocks: granite, diorite, gabbro, rhyolite, andesite, and basalt.
4. Students should know the basic information summed by Bowen's reaction series, such as the high crystallization temperatures of olivine and calcium-plagioclase as compared to quartz and K-feldspar and that ultramafic and mafic rocks solidify at greater temperatures than do intermediate and felsic rocks.
5. Students should be familiar with the distinctions among the three types of intrusions: dikes, sills, and plutons.
6. Students should be familiar with the major geologic settings for volcanism: mid-ocean ridges, island and continental volcanic arcs, hot spots, and continental rifts.

Summary from the Text

Magma is liquid rock (melt) under Earth's surface. Lava is melt that has erupted from a volcano at Earth's surface.

Magma forms when hot rock in the Earth melts. Melting occurs only under certain circumstances: when the pressure decreases, when volatiles are added to hot rock, and when magma rising from the mantle transfers heat into the crust.

Magma occurs in a range of compositions: felsic (silicic), intermediate, mafic, and ultramafic. The composition of magma reflects the original composition of the rock from which the magma formed and the way the magma evolves.

Magma rises from the depth because of its buoyancy and because of pressure caused by the weight of overlying rock.

Melt viscosity depends on its composition. Felsic melt is more viscous than mafic melt.

Extrusive igneous rocks solidify from lava that erupts out of a volcano. Intrusive igneous rocks develop from magma that freezes inside the Earth.

Lava may solidify to form flows, or it may explode into the air to form pyroclastic debris, including ash.

Intrusive igneous rocks form when magma intrudes into pre-existing rock below Earth's surface. Tabular intrusions that cut across layering are dikes, and those that form parallel to layering are sills. Blob-shaped intrusions are called plutons. Huge intrusions, made up of many plutons, are known as batholiths.

The rate at which intrusive magma cools depends on the depth at which it intrudes, the size and shape of the magma body, and whether circulating groundwater is present. The cooling time influences the texture of an igneous rock.

Igneous rocks are classified according to texture and composition.

Plate tectonics theory can explain why igneous rocks form where they do. Magma forms at continental or island volcanic arcs along convergent margins mostly because of the addition of volatiles to the asthenosphere above the subducting slab causes flux

melting. Igneous rocks form at hot spots due to decompression melting of a rising mantle plume. Igneous rocks form at rifts as a result of decompression melting of the asthenosphere below the thinning lithosphere or heat transfer from mantle melts into crustal rocks. Igneous rocks form along mid-ocean ridges because of decompression melting of the rising asthenosphere.

Video and Animation Files

PARTIAL MELTING

Number: Video 4.1

Length: 2 minutes, 46 seconds

Summary: This video shows that rock within the Earth does not melt entirely and shows how this affects the chemistry of magmas, making them more felsic than parent rocks from which they arise.

Classroom Use: This video might be assigned as part of homework on igneous rocks, or shown in class to get students to think about igneous rock origins and the contrast between mantle and crustal rock chemistry.

Review and Discussion Questions:

1. How is the melting of rock similar to the melting of water ice, and how is it different?
2. Partial melting of ultramafic mantle rock yields magma with which type of chemistry?

LAVA COMPOSITION

Number: Animation 4.1

Length: 4 minutes, 35 seconds

Summary: This partly interactive animation depicts the processes that allow magma chemistry to vary within the Earth: partial melting, fractional crystallization,

assimilation of surrounding rock, and magma mixing.

Classroom Use: This animation might be assigned formally as homework or recommended more informally as a study aid.

Review and Discussion Questions:

1. Do the first crystals forming within a magma chamber tend to be relatively silica-rich or iron- and magnesium-rich?
2. How does the fractional crystallization process affect the chemistry of the magma left behind in a liquid state?

Answers to Review Questions

1. How is the process of freezing magma similar to that of freezing water? How is it different?

ANS: Crystallization from magma is similar to freezing water in that crystals form from the liquid state upon passage of the liquid through a critical temperature (or range of temperatures). The most striking difference is in the temperature of crystallization. Additionally, multiple minerals crystallize from magma; more mafic minerals crystallize first, and more silicic minerals crystallize later at cooler temperatures.

2. What is the source of heat in the Earth?

ANS: Earth has derived heat from collisions, gravitational compression, decay of radioactive isotopes, meteoric bombardment, and differentiation.

3. Describe the three processes that are responsible for the formation of magmas.

ANS: (1) Decreasing pressure may cause the liquid state of a mineral assemblage to be thermodynamically favored over solid crystals. (2) The addition of volatiles (such as water and carbon dioxide) to a system of crystals (rock) may cause the liquid state to be thermodynamically favored. (3) If a system of crystals obtains heat from a nearby source—such as a neighboring body of magma—it may melt.

4. Why are there so many different compositions of magmas? Does partial melting

produce magma with the same composition as the parent rock from which it was derived?

ANS: Numerous processes can alter magmatic. Changes in chemistry can occur through fractional crystallization of melt, partial melting of rock, and contamination through the melting and assimilation of surrounding host rock. In addition to these processes that produce a chemical change, original (melted) source rocks vary. Melts also vary with respect to volatile content.

Partial melting produces melts that are more felsic than the parent rocks that melted to form them. This result arises from the fact that minerals with high temperatures of crystallization (which characterize more mafic rocks) will be preferentially left behind as solid rock during the partial melting process.

5. Why do magmas rise from depth to the surface of Earth?

ANS: Magmas rise because they are less dense than the rocks that surround them, and at depth, there is great pressure that squeezes magma upward, where the pressure is less.

6. Explain the process of fractional crystallization.

ANS: Magmas cool gradually within the Earth, and a small portion of the magma will start to solidify, forming crystals. The first crystals to form will be minerals that have a high temperature of crystallization. These tend to be iron- and magnesium-rich minerals that characterize relatively mafic rocks. These relatively dense solid crystals will sink within the magma body, and the magma left behind is now both more felsic in chemistry and also less dense than it was prior to fractional crystallization. It may rise within farther toward the surface, leaving these crystals behind. The fractional crystallization process drives the chemistry of magmas to become consistently more felsic, and is important in the explanation of why continental rocks are so much more felsic than oceanic rocks or mantle rocks.

7. What factors control the viscosity of a melt?

ANS: Felsic (silicic) melts are more viscous than mafic melts because silica tetrahedra mutually link to form complex structures that cannot move as rapidly as the simple structures found in more mafic melts. High volatile content, including water content, lessens viscosity. Cooler magmas are more viscous than hotter magmas of the same

composition.

8. What factors control the cooling time of a magma within the crust?

ANS: Magmas that cool deep within Earth cool more slowly than those that cool near the surface. Large, globular bodies of magma cool more slowly than those that are smaller and sheet-like. Cool groundwater can absorb heat from magma and transport the heat away from the source, greatly increasing the cooling rate. Hot, circulating groundwater can have the opposite effect.

9. What is the difference between a sill and a dike, and how do both differ from a pluton?

ANS: Dikes are intrusions that cut across layered rocks; sills are intrusions that form parallel to them. Both dikes and sills are tabular in shape; plutons are blob-shaped.

10. How does grain size reflect the cooling time of a magma?

ANS: Large, thermodynamically stable crystals form when a melt cools and crystallizes gradually. Rapidly cooling and crystallizing melts do not leave sufficient time for large crystals to become organized.

11. What does the mixture of grain sizes in a porphyritic igneous rock indicate about its cooling history?

ANS: Porphyritic igneous rocks occur when an initial phase of gradual cooling within the Earth gives way to much more rapid cooling subsequent to eruption.

12. Describe the way magmas are produced in subduction zones.

ANS: Below 150 km, heat causes volatiles within the subducting oceanic, lithospheric slab to be released into the ultramafic asthenosphere of the overriding plate. Partial melting of the asthenosphere produces basaltic magma, which migrates upward through the lithosphere of the overriding plate to erupt at the surface. Depending on the amount of fractional crystallization that occurs during transit, the originally basaltic (mafic) magma may extrude as an intermediate or a rhyolitic (silicic) melt.

13. What process in the mantle may be responsible for causing hot-spot volcanoes to form?

ANS: These volcanoes may form when an isolated, cylindrical plume of hot material from the lower mantle rises upward. When it reaches the lithosphere, pressure is low enough to initiate partial melting, forming basaltic (mafic) melt from the ultramafic rock. The melt rises farther to reside in a magma chamber in the crust until it erupts, forming a volcano.

14. Describe how magmas are produced at continental rifts. Why can you find both basalt and rhyolite in such settings?

ANS: Rifting force thins out the lithosphere locally, decreasing the pressure on the underlying asthenosphere. This pressure release triggers partial melting to yield basaltic magma, which may extrude to the surface rapidly to produce basalt or melt the surrounding crust to produce a more silica-rich melt that produces rhyolite.

15. Why does melting take place beneath the axis of a mid-ocean ridge?

ANS: Hot asthenosphere rises to take the place of material that has spread to either side of the axis. Closer to the surface, pressure is less than at the depth from which the asthenospheric material rose, so the asthenosphere partially melts.

16. What is a large igneous province (LIP)?

ANS: A large igneous province (LIP) is a region in the crust that contains an unusually large volume of igneous rock.

On Further Thought

17. If you look at the Moon, even without a telescope, you see broad areas where its surface appears relatively darker and smoother. These areas are individually called *mare* (plural: *maria*), from the Latin word for sea. The term is misleading because they are not bodies of water but rather plains of igneous rock formed after huge meteors struck the Moon and formed very deep craters. These impacts occurred early in the history of the

Moon, when its interior was warmer. With this background information in mind, propose a cause for the igneous activity, and suggest the type of igneous rock that fills the mare. (Hint: Think about how the presence of a deep crater affects pressure in the region below the crater, and consider the viscosity of a magma that could spread over such a broad area.)

ANS: Although thoroughly solid today, the Moon once had enough internal heat (from initial formation through impact, continued bombardment early in its history, and radioactive isotopes) to form melts. These melts erupted at the surface in places and cooled quickly, producing fine-grained extrusive rock. The broad area encompassed by each mare suggests that they formed from lava with low viscosity and are thus basalts (confirmed by looking at lunar rock samples).

18. Would you expect felsic pyroclastic flows to erupt from a mid-ocean ridge? Explain the reasoning that led you to your answer.

ANS: No. At the mid-ocean ridges, basaltic melts emerge quite rapidly from depth. They do not have sufficient time to undergo substantial chemical change through fractional crystallization, and there are no felsic rocks nearby that might be melted and added to the magma bodies.

CHAPTER 5

The Wrath of Vulcan: Volcanic Eruptions

Learning Objectives

1. Students should know that volcanic eruptions are a significant geologic hazard to human life, but that they also have benefitted society by fertilizing soils.
2. Students should be familiar with the three primary volcanic products: lava, gas, and pyroclastic debris. They should know why some eruptions are dominated by lava flow and others by pyroclastic debris, and that each type of eruption can occur within a single volcano at different times.
3. Students should be familiar with three types of volcanoes—cinder cones, shield volcanoes, and stratovolcanoes—and how each is produced.
4. Students should be familiar with the mineralogically based classification of lavas (similar to igneous rock classification), and they should know how water content, temperature, and chemistry affect lava viscosity. Similarly, they should know that basaltic lavas erupt at higher temperatures than rhyolitic lavas and are not associated with large-scale explosive eruptions as rhyolitic and intermediate melts are.
5. Students should know the variety of volcanoclastic debris products (ash, lapilli, blocks, bombs, tephra, tuff, and ignimbrite) and the variety of dangers (ash fall, pyroclastic flow, lahars) associated with volcanic eruptions.
6. Volcanoes are common at convergent and divergent plate boundaries and generally absent at transform boundaries, but they may arise in plate interiors in association with hot spots.
7. Earth is not unique in possessing volcanoes. The largest known is an extinct shield volcano, Olympus Mons, found on Mars. Io, a moon of Jupiter is volcanically active.

Summary from the Text

Volcanoes are vents at which molten rock (lava), pyroclastic debris, gas, and aerosols erupt at Earth's surface.

The characteristics of a lava flow depend on its viscosity, which in turn depends on its temperature and composition.

Basaltic lava can flow great distances. Pahoehoe flows have smooth, ropy surfaces, whereas a'a flows have rough, rubbly surfaces. Andesitic and rhyolitic lava flows tend to pile into mounds at a volcano's vent.

Pyroclastic debris includes powder-sized ash, marble-sized lapilli, and apple- to refrigerator-sized blocks and bombs. Some debris falls from the air, and some settles from pyroclastic flows.

The summit of an erupting volcano usually includes a crater. Collapse of a volcano, when a large magma chamber drains, can yield a much larger bowl-shaped depression called a caldera.

A volcano's shape depends on the type of eruption. Shield volcanoes are broad, gentle domes, and cinder cones are steep-sided, symmetrical hills. Stratovolcanoes (composite volcanoes) can become quite large and consist of alternating layers of pyroclastic debris and lava.

The type of eruption depends on the lava's viscosity and gas content. Effusive eruptions produce flows, and explosive eruptions produce pyroclastic debris. Typically, the former are basaltic and the latter are andesitic or rhyolitic.

Different kinds of volcanoes form in different geologic settings, as explained by plate tectonics theory.

Volcanic eruptions pose many hazards: lava flows overrun roads and towns, ash falls blanket the landscape, pyroclastic flows incinerate towns and fields, landslides and lahars bury the land surface, earthquakes topple structures and rupture dams, tsunamis wash away coastal towns, and invisible gases suffocate people and animals.

Eruptions can be predicted by earthquake activity, changes in heat flow, changes in shape of the volcano, and changes in the volume of gas and steam.

We can minimize the consequences of an eruption by avoiding construction in danger zones.

Immense flood basalts cover portions of the Moon. The largest known volcano, Olympus Mons, towers over the surface of Mars. Satellites have documented evidence for eruptions on moons of Jupiter and Saturn.

Video and Animation Files

HOT SPOT FORMATION

Number: Animation 5.1

Length: 4 minutes, 33 seconds

Summary: This animation demonstrates how a hot spot produces a chain of volcanic features on the seafloor and how plate motion affects the geometry of the chain. A second module gives specific information about the Hawaiian hot spot.

Classroom Use: This animation might be used to show how plate motion and changes in plate motion could affect the geometry of a hot spot volcanic chain.

Review and Discussion Questions:

1. Why do hot spots form chains of volcanoes rather than one very large volcano?
2. How old are the oldest volcanic features produced by the Hawaiian hot spot? Why do we think the hot spot itself might be older than this date?

VOLCANOES AND TYPES OF LAVA FLOW

Number: Animation 5.2

Summary: This animation looks at the different eruptive styles displayed by volcanoes, and how eruptive style and magmatic composition influence the size and shape of a volcano. It depicts and describes cinder cones, shield volcanoes,

stratovolcanoes, and lava domes.

Classroom Use: This would be a useful visual in class to show students how eruptions shape volcanoes.

Review and Discussion Questions:

1. How is a Hawaiian style eruption different from the eruptions that characterize stratovolcanoes? Why are Hawaii's volcanoes so gently sloped in comparison?
2. When not actively erupting, which type of volcano presents a greater human hazard, a shield volcano or a stratovolcano? Why?

Answers to Review Questions

1. Describe the three different kinds of material that can erupt from a volcano.

ANS: Lava is molten rock, flowing out of the volcano in liquid state and cooling and solidifying on the ground. Pyroclastic debris forms when bodies of lava are shot into the atmosphere and cool during flight to form volcanic glass; pyroclastic debris ranges in size from ash to lapilli to larger pieces termed *bombs*. Blocks are fragments of pre-existing volcanic rock from older eruptions that are hurled by the force of eruption. Lastly, the primary gases that erupt from volcanoes are water vapor, carbon dioxide, sulfur dioxide, and hydrogen sulfide.

2. Contrast a pyroclastic flow with a lahar.

ANS: Pyroclastic flows are hot mixtures of suspended pyroclastic debris (ash and lapilli) and air that tumble down the sides of volcanoes at great speed. A lahar is a fast, liquid flow arising when a pyroclastic flow mixes with water from snowfields or nearby streams.

3. Describe the differences among shield volcanoes, stratovolcanoes, and cinder cones.

How can you explain these differences by the composition of their lava and other factors?

ANS: Shield volcanoes are gently sloped domes typically composed of basaltic volcanic

rock. The basaltic lava that forms this rock is of low viscosity, so it flows readily in response to gravity and attains a low profile on solidification. Cinder cones are radially symmetric tephra, with steeper slopes on the sides. Cinder cones form from fountains of lava, which squirt up and freeze in midair close to the volcanic vent. Pyroclastic tephra solidifies before reaching the ground and consequently cannot flow as basaltic lava will. Stratovolcanoes are large, conic volcanoes. The walls of stratovolcanoes are composed of alternating layers of tephra and lava rock. Stratovolcanoes are the result of multiple eruptions, which in turn have produced both effusive lava and explosive pyroclastics, whereas the smaller cinder cones represent single volcanic events. The high viscosity of andesitic lava yields the steep slope of stratovolcanoes.

4. Why do some volcanic eruptions consist mostly of lava flows, while others are explosive and do not produce flows?

ANS: Explosive eruptions are the result of a sudden release of accumulated gas pressure within the volcano. Lavas with high proportions of volatiles, such as water vapor, produce explosive eruptions in which the lava is blasted upward by explosively expanding gas, forming pyroclastic debris out of the lava that would otherwise have flowed down the slope of the volcano.

5. What processes may lead to hot-spot eruptions? How does an oceanic hot-spot volcano differ from a continental one?

ANS: Opinions among geologists vary concerning the genesis of hot spots. One school of thought proposes that they arise as plumes of very hot mantle rock from the base of the mantle (core-mantle boundary), which generate massive amounts of volcanism due to transfer of heat with surrounding rock. Another school argues that other circumstances are responsible for the copious melting seen at hot spots.

An oceanic hot spot volcano consists of a vast shield composed of basaltic lava flows. A continental hot spot volcano will produce more felsic melts and more pyroclastic debris, occasionally erupting with great force to form a caldera.

6. Why do some continental-rift eruptions yield flood basalts?

ANS: In a rift zone, basaltic magma may rise rapidly through fractures and may thus not

undergo substantial chemical change that commonly occurs when magma rises through continental crust. Erupting with low viscosity, basaltic lava spreads outward to form uniform sheets (similar to aqueous floods).

7. What are the characteristics of volcanoes erupting at volcanic arcs? How do they contrast with volcanoes erupting at mid-ocean ridges?

ANS: Volcanic arcs produce cone-shaped summits, including large stratovolcanoes in continental volcanic arcs. Mid-ocean ridge volcanism extrudes from fractures in the crust termed fissures, which extend parallel to the mid-ocean ridge axis.

8. Identify some of the major volcanic hazards, and explain how they develop.

ANS: Lava flows, poisonous volcanic gases, and pyroclastic ash and lapilli are the immediate products of eruption. Ash fall occurs due to the settling of fine pyroclastics out of the atmosphere. Pyroclastic flow occurs when pyroclastics are turbulently mixed with air and swirl down the slopes of a volcano due to gravity. Lahars occur when a pyroclastic flow obtains moisture from snow near the summit or stream water. Movement of magma generates earthquakes, which may trigger landslides; in coastal settings, a landslide or earthquake might generate a tsunami.

9. How do geologists predict volcanic eruptions?

ANS: Measured increases in heat flow, changes in the shape of volcanoes, and increasing incidence of earthquakes and gaseous emissions may signal that an eruption is imminent.

10. Explain how steps can be taken to protect people from the effects of eruptions.

ANS: Maps assessing volcanic hazards can be compiled and publicized. Plans for emergency evacuation can be developed. The direction of flowing lava can sometimes be diverted. Citizens can be educated concerning the hazards of living near volcanic summits and can receive incentives for relocating if practical.

On Further Thought

11. The Long Valley Caldera, near the Sierra Nevada range in California, exploded about 700,000 years ago and produced a huge ignimbrite called the Bishop Tuff. Mono Lake is found about 30 km to the northwest, with an island in the middle and a string of craters extending south from its south shore. Hot springs and tufa deposits can be found along the lake. You can see the lake on *Google Earth*TM at latitude 37° 59' 56.58" N, longitude 119° 2' 18.20" W. Explain the origin of Mono Lake.

ANS: The depression known as Mono Lake formed as a volcanic caldera that has infilled with water. Its islands and nearby domes imply resurgent volcanic activity.

12. Mount Fuji is a 3.6 km-high stratovolcano in Japan formed as a consequence of subduction. See it using *Google Earth*TM at latitude 35° 21' 46.72" N, longitude 138° 43' 49.38" E. You can see the volcano contains volcanic rocks with a range of compositions, including some andesitic rocks. Why do andesites erupt here? Very little andesite occurs on the Marianas Islands, which are also subduction-related volcanoes. Why?

ANS: Japan is not a classic volcanic island arc (rising above sea level solely due to eruptions triggered by subduction of one oceanic plate beneath another), but it represents a fragment of the Asian mainland that rifted and drifted eastward. Japan possesses characteristics of both continental and island arcs. As with continental arcs, magma from subduction-zone melting migrates upward through a thick continental sequence of intermediate to felsic rock and has opportunity to chemically evolve through fractional crystallization and assimilation. Magma beneath the Marianas Islands more rapidly migrates through a thin layer of mafic (basaltic) crust and is not as chemically altered by the time it erupts.

INTERLUDE B

A Surface Veneer: Sediments and Soils

Learning Objectives

1. Students should understand how rocks undergo weathering at and near the Earth's surface to produce sediment.
2. Students should be familiar with the difference between sediment and soil.
3. Students should know the factors that affect the character and thickness of soil.

Summary of the Text

Sediment consists of loose fragments derived from pre-existing rock, precipitated from water, or formed by the breakup of shells.

Rock at or near the Earth's surface weathers over time. Physical weathering breaks larger rock bodies into smaller pieces. Chemical weathering involves a variety of chemical reactions that dissolve and/or alter minerals.

Soil is a regolith that underwent change over time when water percolated down through it. Soil can be modified by interacting with organisms. The character of the soil depends on the composition of its source material, as well as on climate and time.

Soil is an essential resource to society, for it provides the basis for agriculture. Various phenomena, some caused by humans, can lead to the loss of soil.

Answers to Review Questions

1. Explain the difference between physical and chemical weathering.

ANS: Physical weathering involves processes that mechanically break rock into fragments. Chemical weathering involves chemical reactions between rock and either chemical solutions in water or chemicals in the air.

2. What processes can cause originally solid rock to break into pieces?

ANS: Rock can be broken by jointing from exhumation, frost wedging, animal attack, root wedging, salt wedging, and thermal expansion.

3. What are the various reactions that can contribute to chemical weathering?

ANS: Most chemical weathering is due to chemical reactions termed *dissolution*, *oxidation*, *hydrolysis*, and *hydration*.

4. Why doesn't weathering take place on the Moon?

ANS: The Moon has no atmosphere and no surface water, so there is no weathering on the Moon.

5. Explain the process of soil formation.

ANS: Soils form when surficial sediments are altered by the activities of organisms and chemical interaction with rainwater.

6. Why do soils develop distinct horizons?

ANS: Different levels within soil vary in moisture content and amount of organic matter. They are further differentiated by rainwater either dissolving or precipitating minerals locally.

7. What factors determine the character (e.g., thickness, texture, types of horizons, etc.) of a soil?

ANS: Important factors that determine soil character include climate, chemical nature of the substrate, moisture, steepness of the landscape, vegetation present, and the amount of time that has been available for weathering reactions.

8. How does a soil that forms in a tropical climate differ from one that forms in an arid climate?

ANS: In arid climates, soils develop slowly and retain soluble minerals, such as calcite. In a tropical climate, heavy rainfall and leaching remove nearly all but the most insoluble minerals, such as iron oxides and aluminum oxides.

9. Explain why soil erosion has been exacerbated by human activity.

ANS: Humans have deforested land and tilled soil to produce agricultural output, and these activities (plus grazing by livestock) have led to increased soil erosion.

CHAPTER 6

Pages of Earth's Past: Sedimentary Rocks

Learning Objectives

1. Students should know that although rare in the crust as a whole, sediments and sedimentary rocks are greatly abundant at the surface.
2. Students should be familiar with the sedimentary portion of the rock cycle, understanding weathering, erosion, transportation, deposition, and lithification.
3. Students should be able to distinguish among coarse- (gravel), medium- (sand), and fine-sized (mud) grains and to evaluate sorting, sphericity, and angularity among sediments and rocks.
4. Clastic sedimentary rocks are primarily classified on the basis of grain shape. Students should be able to recognize and characterize conglomerate, breccia, sandstone, mudstone, and shale.
5. Biologically mediated precipitation produces mineralized skeletons; these condense and lithify to form biochemical sedimentary rocks. Important examples are most types of limestone and bedded chert.
6. Organic sedimentary rocks include coal, which is the altered remains of trees and other plants that lived in swampy environments (which allow organic matter to accumulate without too much decay).
7. Chemical sedimentary rocks arise from physical precipitation. As with biochemical rocks, classification is primarily based on mineral content. An important subset are the evaporites, including rock salt (halite) and rock gypsum. Small amounts of carbonate sediment can also form as an evaporite. Chemical rocks can also form through the replacement of minerals during diagenesis.

8. The layering of rock is termed *stratification* (or bedding). Cross beds, dunes, and ripple marks signify deposition along a slope under the influence of a current. Other sedimentary structures of interest within sedimentary rocks include fossils, scour marks, and mud cracks.
9. The character of sedimentary rocks reflects their environments of deposition; students should be familiar with a few sedimentary environments (e.g., deltas, beaches, deep marine environments), as well as the characteristics of the sediments deposited in those realms. Locally, environments change over time; one source of these changes is the sequence of transgressions (rising local relative sea level) and regressions (falling local relative sea level).

Summary from the Text

Geologists recognize four major classes of sedimentary rocks. Clastic rocks form from cemented-together grains that were first produced by weathering and were then transported, deposited, and lithified; they are classified based on grain size. Biochemical rocks develop from the shells of organisms. Organic rocks consist of plant debris or of altered plankton remains. Chemical rocks precipitate directly from water, and they include evaporates that accumulate when salt water evaporates.

Sedimentary structures include bedding, cross bedding, graded bedding, ripple marks, dunes, and mud cracks. They serve as clues to depositional settings. Bedding, the fundamental layering in sedimentary strata, can be due to subtle or major changes in depositional conditions at a location.

The mineralogical composition (and, therefore, the chemical composition) is different for different types of sedimentary rocks. For example, limestone consists of calcite, chert of silica, coal of carbon, shale from clay, and sandstone from quartz grains.

Glaciers, streams, alluvial fans, deserts, rivers, lakes, deltas, beaches, shallow seas, and deep seas each accumulate a different, distinctive assemblage of sedimentary strata.

Therefore, study of sedimentary strata provides clues into the environment of a given location at times in the past.

Thick piles of sedimentary rocks accumulate in sedimentary basins, regions where the surface of the crust sinks or subsides over a long period of time. Such subsidence happens for a variety of reasons. The thickest sedimentary basins form along passive continental margins.

Transgressions occur when sea level rises and the coastline migrates inland. Regressions occur when sea level falls and the coastline migrates seaward.

Diagenesis involves processes leading to lithification and processes that alter sedimentary rock at temperatures lower than those that cause metamorphism.

Video and Animation Files

TRANSGRESSION AND REGRESSION

Number: Video 6.1

Length: 3 minutes, 34 seconds

Summary: This video shows how clastic rocks representing ancient environments that were laterally adjacent (such as beach sand environments and offshore mud environments) can come to be stacked atop one another vertically through marine regressions and transgressions. Further, it emphasizes the fact that a rock unit might have been deposited as sediment at different times in different places.

Classroom Use: This video could be shown in class to help students make sense of the seemingly inconsistent observation that vertically stacked strata represent environments that were laterally adjacent during deposition.

Review and Discussion Questions:

1. In the field, you see that a coal representing an ancient freshwater swamp overlies a sandstone representing an ancient beach. Is a transgression or a regression a better explanation for this observation?

2. In a complete sequence of strata documenting a regression, would offshore marine mudstones or terrestrial red beds be more likely to be found at the top of the sequence?

Answers to Review Questions

1. Describe how a clastic sedimentary rock forms from its unweathered parent rock.

ANS: First, physical and chemical weathering break up and alter the parent rock to form detrital fragments of parent material, dissolved ions, and clay. This sediment of weathered grains is then eroded from the parent surface and transported away from the source by water, wind, or glacial ice (or directly by gravity, in the case of large clasts on a slope). Ultimately, the sediment will settle out of the transport medium. Eventually, loose grains of deposited sediment may become buried under additional sediment, compacted, and cemented to form sedimentary rock.

2. Explain how biochemical sedimentary rocks form.

ANS: A variety of organisms in marine environments produce mineralized skeletons for their protection. When these organisms die, their skeletons often become fractured into grains by the activities of waves, currents, predators, and scavengers. Pieces of skeletal debris may accumulate on the sea floor, later to become buried and lithified through compaction and cementation.

3. How do grain size and shape, sorting, sphericity, and angularity change as sediments move downstream?

ANS: Mechanical forces such as tumbling and abrasion wear on sediments as they are transported downstream. Angular protuberances are especially likely to be broken off. As a result, grain size decreases, with grains becoming more spherical and more rounded (less angular). The speed at which the water in a stream is traveling decreases along its course, and the capacity of the stream to carry sediment is directly related to its rate of

flow. So larger grains are deposited upstream from finer grains (grains become sorted as they travel downstream).

4. Describe the two different kinds of chert. How are they similar? How are they different?

ANS: All chert is composed of microcrystalline (cryptocrystalline) quartz. Biochemical chert is derived from the siliceous skeletons of microorganisms (diatoms and radiolarians), which deposit in vast layers on the sea floor after the death of the organisms. Chert also occurs as a replacement mineral; groundwater may dissolve portions of limestone (when groundwater is undersaturated with respect to calcite) and fill in the resultant void space with microcrystalline quartz (with respect to which the groundwater is saturated). Bedding (layering) is absent in replacement chert.

5. Do all sedimentary rocks have same composition? What conditions produce evaporites?

ANS: Sedimentary rocks have diverse compositions. Evaporite formation requires a fluid with dissolved ions (typically seawater) to be evaporated to such an extent that the ions will precipitate out, typically as halide, carbonate, or sulfate minerals. Hot, dry conditions with extensive subaerial exposure are conducive to evaporite formation; these include warm, broad, shallow seas with little riverine influx and restricted circulation. Along coasts in regions with a hot, dry climate, evaporites are deposited in the supratidal (above the high tide limit) “splash zone,” where water washes up, becomes stranded (having lost contact with the cohesive ocean), and is evaporated by the heat of the Sun. Similarly, on the dry portions of continents, such as the western United States, isolated saline lakes and ephemeral streams produce evaporates when their water levels fall.

6. How does dolostone differ from limestone, and how does dolostone form?

ANS: Dolostone is composed of the mineral dolomite, $(Ca, Mg)CO_3$, whereas limestone is generally composed of calcite, $CaCO_3$. Dolostone contains more magnesium (a trace impurity in natural calcite) and has a different crystalline structure. Dolomite can form through chemical alteration of limestone by reaction with groundwater bearing magnesium.

7. What are cross beds, and how do they form? How can you use cross beds to read the current direction?

ANS: Cross beds form from sediment deposited on the lee (downcurrent) side of dunes and ripples. These angled beds dip downward in the downcurrent direction (parallel to the lee side of the dune or ripple).

8. Describe how a turbidity current forms and moves. How does it produce graded bedding?

ANS: Turbidity currents form when sediment becomes unstable on a subaqueous slope and tumbles downward, pulling a current of water with it. After a while, the velocity of the turbidity current slows. The heaviest (largest) particles settle out first, whereas smaller, lighter particles stay in suspension for longer periods. Ultimately, these smaller particles settle atop the coarser grains to produce graded bedding, a grain-sized gradient from coarse (near the base of the bed) to fine (at the top of the bed).

9. Compare the deposits of an alluvial fan with those of a deep-marine deposit.

ANS: Alluvial fans are wedge-shaped deposits occurring at the foot of an eroding mountain range. The sediments are typically coarse (sand, pebbles, or cobbles) and contain substantial amounts of feldspar (physically weathered from a typically granitic mountain source). Deep-marine deposits are dominated by the skeletons of planktonic microorganisms (chalk derived from foraminiferans, and bedded chert derived from diatoms and radiolarians) and clay (which settles to form finely laminated mudstone).

10. Why don't sediments accumulate everywhere? What types of tectonic conditions are required to create sedimentary basins?

ANS: In a majority of terrestrial environments, the rate of erosion meets or exceeds the rate of sedimentary deposition. Basin subsidence allows for the development and preservation of thick sedimentary sequences (including nonmarine deposits) but requires a locally sinking lithosphere. Sinking lithosphere is most often a consequence of tectonic rifting or collision, in which the lithosphere is either stretched and thinned or subjected to a load.

11. How is it possible for sandstone derived from sediment deposited in a beach environment to comprise a formation that blankets a broad region?

ANS: Sea level rises and falls overtime, shifting beach environments landward and seaward. Many areas in the region would have consisted of a beach environment at different times.

On Further Thought

12. Recent exploration of Mars by robotic vehicles suggests that layers of sedimentary rock cover portions of the planet's surface. On the basis of examining images of these layers, some researchers claim that the layers contain cross bedding and relicts of gypsum crystals. At face value, what do these features suggest about depositional environments on Mars in the past?

ANS: Mars once had surface water, including streams and lakes or seas subject to evaporation.

13. The Gulf Coast of the United States is a passive-margin basin that contains a very thick accumulation of sediment. Drilling reveals that the base of the sedimentary succession in this basin consists of redbeds. These are overlaid by a thick layer of evaporite. The evaporite, in turn, is overlaid by deposits composed of sandstone and shale. In some intervals, sandstone occurs in channels and contains ripple marks, and the shale contains mudcracks. In other intervals, the sandstone and shale contain fossils of marine organisms. Be a sedimentary detective, and explain the succession of sediment in the basin.

ANS: The redbeds suggest deposition in a subaerial, well-oxygenated environment. The continent was invaded by shallow seas that readily evaporated in the hot, arid climate to yield the thick evaporite sequence. A series of marine transgressions (leading to deposition of the units with marine fossils) and regressions (yielding the cross-bedded channel sandstones and shales bearing mudcracks) followed. The lack of arkose and conglomerate in the sequence suggests that at no time during deposition did any

collisional orogenic events take place.

14. Examine the Bahamas with *Google Earth*TM or NASA World Wind. (You can find a high-resolution image at latitude 23° 58' 40.98" N, longitude 77° 30' 20.37" W.) Note that broad expanses of very shallow water surround the islands, that white sand beaches occur along the coasts of the islands, and small reefs occur offshore. What does the sand consist of, and what rock will it become if it eventually becomes buried and lithified?

ANS: The Bahama sand consists of carbonate grains: fragments of coral and shells and physically precipitated ooids; when lithified, the rock would be (oolitic) limestone.

CHAPTER 7

Metamorphism: A Process of Change

Learning Objectives

1. Students should know that metamorphic rocks have been altered in the solid state due to environmental changes (typically, the addition of heat and/or stress).
2. Students should be familiar with the environments of metamorphic rock formation: dynamothermal (regional), thermal (contact), dynamic (fault zone/shear zone), burial, hydrothermal, and shock. In particular, they should understand why some environments yield both foliated and nonfoliated rocks, whereas others produce only nonfoliated rocks.
3. Metamorphism is induced by heat, pressure, differential stress, and chemical interaction. Heat can be added by burial depth or contact with hot groundwater. Pressure is added with depth. Differential stress arises at fault zones and over broad regions during mountain building.
4. Metamorphic effects include recrystallization, phase changes, metamorphic reactions (neocrystallization), pressure solution, and plastic deformation. Foliation involves the development of parallel alignment of mineral grains of preferred mineral associations (compositional banding).
5. Students should be familiar with the common pair of nonfoliated metamorphic rocks (quartzite, marble). They should also be able to recognize and describe the slate-phyllite-schist-gneiss series of foliated rocks, and they should know the nature of foliation present in each and the relative temperature at which each forms.
6. Protoliths affected by metamorphism can be of any type (igneous, sedimentary, or metamorphic).

Summary from the Text

Metamorphism refers to changes in a rock that result in the formation of a metamorphic mineral assemblage, and/or metamorphic texture, in response to changes in temperature and/or pressure, to the application of compression or shear, and the interaction with hydrothermal fluids (hot-water solutions).

Metamorphism involves recrystallization, phase changes, metamorphic reactions (neocrystallization), pressure solution, and/or plastic deformation. If hydrothermal fluids bring in or remove elements, we say that metasomatism has occurred.

Metamorphic foliation can be defined either by preferred mineral orientation (aligned inequant crystals) or by compositional banding. Preferred mineral orientation develops where compression and shearing take place.

Geologists separate metamorphic rocks into two groups—foliated rocks and nonfoliated rocks.

Foliated rocks include slate, phyllite, metaconglomerate, schist, and gneiss. Nonfoliated rocks include hornfels, quartzite, and marble. Migmatite is a mixture of igneous and metamorphic rock.

Rocks formed under relatively low temperatures are known as low-grade rocks, whereas those formed under high temperatures are known as high-grade rocks. Intermediate-grade rocks develop between these two extremes. Different metamorphic mineral assemblages form at different grades.

Geologists track the distribution of different grades of rock by looking for index minerals. An isograd indicates the location at which an index mineral first appears. A metamorphic zone is the region between two isograds.

A metamorphic facies is a group of metamorphic mineral assemblages that develop under a specified range of temperature and pressure conditions.

Thermal (contact) metamorphism occurs in an aureole surrounding an igneous intrusion. Burial metamorphism occurs at depth in a sedimentary basin. Dynamically

metamorphosed rocks form along faults. Dynamothermal (regional) metamorphism results when rocks undergo heating and shearing during mountain building. Hydrothermal metamorphism can take place due to the circulation of hot water in oceanic crust at mid-ocean ridges. Shock metamorphism happens during the impact of a meteorite.

We find belts of metamorphic rocks in mountain ranges. Blueschist forms in accretionary prisms. Shields expose broad areas of Precambrian metamorphic rocks.

Video and Animation Files

METAMORPHIC CHANGE

Number: Animation 7.1

Length: Length will vary based on student interaction.

Summary: This animation shows the major processes that form metamorphic rock, including compression, shear, pressure solution, recrystallization, neocrystallization, and phase change.

Classroom Use: This animation could be shown in lecture or assigned as visual homework.

Review and Discussion Questions:

1. If an elongate crystal grows within a metamorphic rock, would you expect its long axes to be aligned parallel to the direction of maximum compression, or perpendicular to it?
2. A sedimentary rock contains quartz, clay minerals, and iron oxides but no other silicate minerals. It is later metamorphosed without any change in whole rock chemistry, but now possesses garnet crystals. How is this possible?

Answers to Review Questions

1. How are metamorphic rocks different from igneous and sedimentary rocks?

ANS: Metamorphic rocks are the result of heat and stress causing an alteration of texture, mineralogy, or both within a pre-existing rock, without the rock having undergone melting. Many metamorphic (but no igneous or sedimentary) rocks possess foliation.

2. What two features characterize most metamorphic rocks?

ANS: Metamorphic mineral assemblages (minerals uniquely produced under the temperature and pressure regimes of metamorphism) and metamorphic texture (grain arrangement, often involving foliation, which is a preferred alignment of inequant grains or alternating light and dark mineral bands) are characteristic of most metamorphic rocks.

3. What phenomena can cause metamorphism?

ANS: Mountain building, plutonism, volcanism, faulting, meteoric impact, mantle convection, deep burial, and water-rock interactions all lead to metamorphism.

4. What is metamorphic foliation, and how does it form?

ANS: Foliation is the presence of parallel planar surfaces or layers in metamorphic rock. Under sufficient differential stress, platy or elongate grains are broken down and regrown in a preferred orientation perpendicular to maximum compressive stress.

5. How does slate differ from phyllite? How does phyllite differ from schist? How does schist differ from gneiss?

ANS: Slate and its characteristic slaty cleavage arise from the preferred orientation of clay minerals resulting from the relatively low-temperature and low-pressure metamorphism of a body of shale. Phyllite arises when significantly higher temperatures and pressures cause clay grains within slate to be recrystallized to form mica grains, which retain a preferred orientation. Unlike slate, which is rather dull, mica gives phyllite a silky luster. Schist differs from phyllite in that, as a result of greater heat and pressure, its mica grains are large, visible discrete plates, unlike the smooth sheen of tiny mica grains within phyllite. Gneiss is compositionally banded, with alternating bands or swirls

of light- and dark-colored minerals, including additional minerals besides mica (quartz, feldspar, amphibole).

6. Why is hornfels nonfoliated?

ANS: Hornfels forms through contact metamorphism, without the application of differential stress.

7. What is a metamorphic grade, and how can it be determined? How does grade differ from facies?

ANS: A *metamorphic grade* refers to a series of temperature and (to a lesser extent) pressure regimes under which metamorphism takes place. For example, high-grade metamorphism occurs under greater temperatures (and pressures) than does low-grade metamorphism. Metamorphic grade is usually assessed on the basis of the mineral assemblage making up the metamorphic rock, as well as its foliation and other textural clues (such as grain size). *Facies* is a more precise term used for a restricted range of temperatures and pressures defined by the presence of key minerals.

8. Describe the geologic settings where thermal, dynamic, and dynamothermal metamorphism take place, respectively.

ANS: Thermal metamorphism takes place in a zone of country rock surrounding a pluton, where the country rock's mineral assemblage becomes recrystallized. Dynamic metamorphism occurs in fault zones, where shearing force recrystallizes minerals at depth. Dynamothermal metamorphism occurs within the cores of mountain ranges, induced by increased heat and pressure associated with crustal thickening and the shear that arises from collision.

9. Why does metamorphism happen at the site of meteor impacts and along mid-ocean ridges?

ANS: At a meteor impact site, pressure on minerals rises sharply at the time of impact, producing conditions favorable for new minerals that would not otherwise be present. Mid-ocean ridge settings provide ample opportunity for relatively cool water to interact with hot, recently formed rock.

10. How does plate tectonics explain the peculiar combination of low-temperature but high-pressure minerals found in a blueschist?

ANS: Blueschists form at the base of thick accretionary prisms, sediments scraped off of the downgoing slab at subduction zones. Because the subducting slab is relatively cool, it adds little heat to the prism, allowing for the relatively high pressures but low temperatures in which the blueschist mineral assemblage is stable.

11. Where would you go if you wanted to find exposed metamorphic rocks, and how would such rocks have returned to the surface of Earth after being at depth in the crust?

ANS: You would go look for the site of an ancient, greatly eroded mountain range. Metamorphism is strongly active in the base of mountain ranges. As overlying layers of sediment and rock are weathered and eroded away, isostatic pressure causes the basement to be buoyed upward until these rocks are finally exposed at the surface.

On Further Thought

12. Do you think that you would be likely to find a long belt, hundreds of kilometers across and thousands of kilometers long, in which the outcrop consists of high-grade hornfels? Why or why not?

ANS: This scenario is unlikely; hornfels typically forms through thermal (contact) metamorphism, as an altered rind (aureole) of former shale that surrounded a cooling intrusion. These aureoles are never hundreds of kilometers wide. In the broader-scale regional (dynamothermal) setting, shale would be altered to form a variety of foliated rocks, such as slate, phyllite, schist, and gneiss.

13. Would we likely find broad regions of gneiss and schist on the Moon? Why or why not?

ANS: No. These dynamothermally altered rocks are ultimately products of horizontal stresses caused by plate tectonics, which the Moon lacks. Contact metamorphism was possible during lunar history, but not dynamothermal metamorphism.

14. Why don't builders use gneiss to make roof shingles?

ANS: Unlike slate, gneiss has no tendency to cleave on planar surfaces.

15. The geothermal gradient of Mars is $8^{\circ}\text{C}/\text{km}$, and the crust of Mars is 30 km thick. Do high-grade metamorphic rocks form in this crust?

ANS: No. The temperatures at the base of the crust (240°C) could only produce very low grade metamorphism.

16. Could you find a layer of metamorphic rock sandwiched between layers of sedimentary rock in a sedimentary basin? Why or why not?

ANS: Yes. You could, as a result of thermal metamorphism in aureoles above and below a sill that had intruded through the strata.

INTERLUDE C

The Rock Cycle

Learning Objectives

1. Students should understand that Earth rocks do not last forever because the Earth System is dynamic.
2. They should know why phenomena such as weathering, burial, heating, and/or melting can affect rock after it has formed.
3. Students should learn how components of a given rock may become incorporated in other rocks or even other rock classes, over time, in a progression of change called the rock cycle.
4. Students should learn why pathways through the rock cycle reflect geologic settings, interpretable in the context of plate tectonics.
5. They should know that steps of the rock cycle can happen at vastly different rates.
6. They should learn how energy from inside the Earth, from the Sun, and from gravity drives the rock cycle.

Summary of the Text

A given rock doesn't necessarily last forever. The atoms in a rock may, over time, be incorporated in different rock types. This transfer of atoms progressively from one rock type to another, over time, is the rock cycle.

Not all atoms follow the same path through the rock cycle. For example, an igneous

rock could later become eroded and turned into sediment, which becomes a sedimentary rock that may eventually be metamorphosed. Or the igneous rock could be metamorphosed directly.

The rock cycle happens because the Earth is dynamic, and internal and external sources of energy are driving melting, uplift, faulting, weathering, erosion, and burial.

The rock cycle is one of many cycles in the Earth System.

Answers to Review Questions

1. Once formed, does a rock necessarily last for all of Earth's history?

ANS: No. Earth is an active planet with plate tectonics, surface water, and an atmosphere. Uplift, weathering, heat, stress, and melting destroy rocks and allow Earth materials to be reused in the formation of new rocks.

2. Define the rock cycle, and give three examples of pathways through it.

ANS: The rock cycle is the name given to the transformation of Earth materials from one rock to another over time. Any rock from any of the three classes (igneous, sedimentary, metamorphic) may be altered to form a new rock from the same class or a new rock from a different class.

A first possible pathway through the rock cycle involves an igneous rock being uplifted, weathered to form sediment, and its sediments eroded, deposited, buried, and cemented to form sedimentary rock that is later metamorphosed.

A second possible pathway involves a metamorphic rock that is melted, with the melt solidifying later to form an igneous rock that is subsequently uplifted and weathered, with the sediment formed eroded, transported, buried, and cemented to form a sedimentary rock.

A third possible pathway involves a sedimentary rock that is melted, with the melt solidifying to form an igneous rock that is subsequently metamorphosed.

(Note: answers will vary.)

3. Have all rocks on Earth passed through the rock cycle the same number of times?

Explain your answer.

ANS: No. Rocks buried to critical depths within the continents may be protected from both surface weathering and heating from below for long spans of geologic time.

4. Is there a rock cycle on the Moon? Why or why not?

ANS: The Moon has no atmosphere, no surface water, and no great internal heat, so there is no lunar weathering, no plate tectonics, and no active igneous processes. Thus, there is currently no rock cycle on the Moon.

CHAPTER 8

A Violent Pulse: Earthquakes

Learning Objectives

1. Earthquakes are episodes of shaking within Earth. Most, though not all, earthquakes represent shock arising from displacement along a fault.
2. Strike-slip faults occur along nearly vertical planes; opposite sides are horizontally offset. Nonvertical fault planes give rise to a hanging wall and footwall (with the hanging wall vertically above the footwall at any point along the fault). If the foot wall slides up with respect to the hanging wall, the fault is termed *normal*. If the hanging wall slides up with respect to the footwall, the fault is termed *reverse* (or *thrust*, if the fault dips shallowly).
3. Students should know the four types of seismic waves, which two occur at the surface, which two travel through the interior, and which one travels fastest. They should be able to distinguish the difference between the compressional motion of the P-wave and the shear motion of the S-wave.
4. Students should know how a seismograph works in principle and how travel-time curves can be used from three stations to isolate the epicenter of an earthquake.
5. Students should understand distinctions among the Mercalli, Richter, and moment magnitude scales.
6. The coincident alignment between most belts of seismic activity and plate boundaries should be noted, with the understanding that intermediate- and deep-focus earthquakes occur only at convergent margins.
7. Earthquakes induce a variety of damaging hazards, including ruptured gas lines, fires, tsunamis, landslides, and sediment liquefaction.

Summary from the Text

Earthquakes are episodes of ground shaking. Earthquake activity is called seismicity.

Most earthquakes happen as a consequence of the slip on a fault. The place where rock breaks and earthquake energy is released is called the focus, and the point on the ground directly above the focus is the epicenter.

Active faults are faults on which movement is likely. Inactive faults ceased being active long ago, but they can still be recognized because of the displacement across them. Displacement on active faults that intersect the ground surface may yield a fault scarp.

During fault formation, rock elastically bends, then ruptures. When ruptures happen, the rock vibrates, and this event generates an earthquake.

Most earthquakes happen when stress overcomes friction on a pre-existing fault, and the fault slips again, again causing rocks to vibrate. Faults exhibit stick-slip behavior in that, once formed, stress builds up until they move in a sudden increment.

Earthquake energy travels in the form of seismic waves. Body waves, which pass through the interior of Earth, include P-waves and S-waves. Surface waves pass along the surface of Earth.

A seismometer can detect earthquake waves. Seismograms, records of earthquakes, demonstrate that different earthquake waves travel at different velocities. Using the difference between P-wave and S-wave arrival times, seismologists can pinpoint the epicenter location.

The Modified Mercalli Intensity Scale is based on documenting the damage caused by an earthquake and people's perception of the ground shaking. Earthquake intensity decreases with increasing distance from the epicenter.

Magnitude scales characterize the amount of energy released at the source and are based on measuring the amount of ground motion, at a reference distance, as indicated on a seismogram. There is one number for an earthquake magnitude for a given earthquake. The Richter scale is an early version of a magnitude scale. These days, seismologists

prefer to use the moment-magnitude scale.

A M_w 8 earthquake yields about 10 times as much ground motion as a M_w 7 earthquake and releases about 32 times as much energy.

Most earthquakes occur in seismic belts, of which the majority lie along plate boundaries. Intraplate earthquakes happen in the interior of plates.

Earthquake damage results from ground shaking, landslides, sediment liquefaction, fire, and tsunamis.

Seismologists predict that earthquakes are more likely in seismic belts than elsewhere, and they can determine the recurrence interval for great earthquakes. But it may never be possible to pinpoint the exact time and place at which an earthquake will happen.

Earthquake hazards can be reduced with better construction practices and zoning, and by educating people about what to do during an earthquake.

Video and Animation Files

EARTHQUAKE WAVES AND EPICENTER LOCATION

Number: Animation 8.1

Length: Length will vary based on student interaction.

Summary: This interactive animation allows students to determine the location of the epicenter of a fictional earthquake using data from three seismograms, taken from seismic stations of their choosing. After students determine the position of the epicenter, they are shown how to find the Richter magnitude for the earthquake.

Classroom Use: This animation would be a good homework assignment, allowing students to see how much we can learn from seismic data and how we can put this new knowledge to use in providing summary information for earthquakes. The instructor could provide a data table each student could fill it in, listing the locations of the chosen seismic stations, S–P travel times and distances for these seismic

stations, and their estimate of Richter magnitude for the quake.

Review and Discussion Questions:

1. Approximately how many earthquakes occur every year globally? Why don't most of these make the news?
2. If the difference between arrival times of the first S-wave and first P-wave of an earthquake is greater for a seismic station centered in Morgantown, West Virginia, than for a seismic station in Memphis, Tennessee, what do we know about the relative closeness of the epicenter to each of these cities?

TSUNAMI INITIATION AND ARRIVAL

Number: Animation 8.2

Length: 10 minutes, 56 seconds

Summary: The various processes and events that can trigger tsunamis are explored, and case studies of tsunamis from a variety of places around the globe are discussed.

Classroom Use: This animation could be used to reinforce differences between tsunamis and wind-blown storm waves, as well as to illustrate a variety of tsunami triggers.

Review and Discussion Questions:

1. List all of the possible events that could trigger a significant tsunami.
2. In all cases, what must necessarily happen for a tsunami to occur?

Answers to Review Questions

1. How do normal, reverse, and strike-slip faults differ from each other?

ANS: Normal and reverse faults occur on planes that are oriented at some angle between horizontal and vertical, whereas strike-slip faults are vertical. In a cross-sectional view, drawing a vertical line intersecting the fault plane illustrates the distinction between a hanging wall (block of material on one side of the fault, including the rock above the intersection of the fault plane and the vertical line) and a footwall (material on the opposite side of the fault, including rock below the intersection of the fault and the vertical line). In a normal fault, the hanging wall has slid downward with respect to the footwall (mnemonic phrase: “a hanging wall will normally fall”). In a reverse fault, the hanging wall has slid upward with respect to the footwall. For vertical strike-slip faults, offset consists of the blocks sliding past each other laterally, along the line of strike (intersection between the fault plane and ground surface).

2. Do all earthquakes require that a new fault initiate? Describe elastic-rebound theory and the concept of stick-slip behavior.

ANS: No; most earthquakes occur on previously established faults. When stress is applied to rock at a fault zone, and friction inhibits the rocks on opposite sides of the fault from sliding past each other, rock is deformed and stores up the energy produced by the stress. Ultimately, the rock will fail under stress, elastically returning to its prior shape and producing sudden slip along the fault plane. The release of this deformational energy produces the vibrational waves we sense as an earthquake. Many faults exhibit stick-slip behavior, meaning that most of the time, friction inhibits movement along the fault (the “stick” phase) and stress induces deformation of rock, which will ultimately lead to an earthquake (under the elastic-rebound model) and movement along the fault for a time (the “slip” phase) until friction again takes hold.

3. What is the difference between a body wave and a surface wave? How do P-waves and S-waves differ from each other? How do Rayleigh waves and Love waves differ from

each other?

ANS: Body waves travel through the Earth's interior; surface waves move only at the Earth's surface. P-waves are compressional waves, and S-waves are shear waves. Love waves are shear waves, and Rayleigh waves are rolling waves that have both shear and compressional components.

4. Explain how a seismometer detects the vertical and horizontal components of an earthquake are detected by a seismometer.

ANS: Vertical motions can be detected with a heavy weight suspended downward by a spring from a sturdy frame bolted into the ground, with a pen extending laterally and in contact with a rotating paper cylinder that is oriented vertically. Horizontal motion detectors have the weight attached to a bar that is free to rotate horizontally but not vertically, and a pen in contact with a horizontally oriented paper cylinder.

5. Explain the differences among the scales used to describe the size of an earthquake. Can more than one intensity number be assigned to a given earthquake? Why? Can there be more than one magnitude?

ANS: The Modified Mercalli Intensity Scale is a relative scale (I–XII) depicting a subjective assessment of ground shaking and damage inflicted by an earthquake on a given locality. The Richter scale is the magnitude of the largest S-wave oscillation as recorded by a seismograph situated 100 km away from the epicenter, as measured directly on a seismogram from this ideally situated seismic station. The moment magnitude scale is related to the amount of slip incurred along the fault during the earthquake and the area of the rupture.

Because damage and shaking decrease with increasing distance from the epicenter of an earthquake, a single quake produces more than one intensity level. However, magnitude measures total energy released during an earthquake, so only a single magnitude is possible.

6. How does seismicity on mid-ocean ridges compare with seismicity at convergent or transform boundaries? Do all earthquakes occur at plate boundaries?

ANS: At mid-ocean ridges, earthquakes associated with normal faults occur along the

ridge segments (strike-slip faulting occurs along the transform faults that connect them). All mid-ocean ridge earthquakes have shallow foci. At transform-plate boundaries, strike-slip faulting predominates, with uniformly shallow foci as well. At convergent boundaries (subduction zones), a variety of earthquakes occur. A subducting plate may be offset by both normal and thrust (reverse) faults, with the largest thrust faults arising at the contact plane between plates. The overriding plate develops reverse faults as well. The subducting slab may continue to generate earthquakes at depths considered intermediate and deep (up to 670 km). Earthquakes sometimes occur far from plate boundaries.

7. What is a Wadati-Benioff zone? Why can intermediate-focus and deep-focus earthquakes occur?

ANS: A Wadati-Benioff zone is an oblique band of earthquake foci that descend into the mantle along with a subducted lithospheric slab, extending down to a depth of 670 km. Intermediate- and deep-focus earthquakes can occur because subducting plates bring brittle crustal rock to unusually great depth, and because rock is such a strong thermal insulator that these subducting slabs remain cool enough to be sufficiently brittle so that they can experience earthquakes at these depths.

8. Describe the types of damage caused by earthquakes. Is all damage due to ground shaking?

ANS: The shaking of the ground due to surface waves can destroy buildings, bridges, and other constructions. Seismically induced water waves (seiches in lakes and tsunamis in the oceans) can destroy near-shore habitations. Earthquakes can trigger landslides, and earthquake damage may be locally aggravated if liquefaction of clay-rich soils occurs (seismic waves can cause coordinated water molecules within clay minerals to shake loose, forming a water and clay mixture that behaves as a liquid). Earthquakes can rupture gas lines to produce catastrophic fires and can cause unsanitary conditions that harbor disease. Thus, not all damage is due directly to ground shaking.

9. What is a tsunami, and why do tsunamis form? How do they differ from storm waves?

ANS: A tsunami is a powerful sea wave, usually generated by a deformation of the sea

floor during a coastal earthquake (most of these are due to faulting near an oceanic trench in a subduction zone). Some large examples can produce destruction across an entire ocean basin.

Tsunamis have much longer wavelengths than storm waves, and thus, they involve displacements of much greater volumes of water, and they crash on shore with much greater force and energy.

10. Explain how liquefaction occurs in an earthquake and how it can cause damage.

ANS: Seismic waves can cause coordinated water and mica-like molecules within clay minerals to shake loose, forming a water and clay mixture that behaves as a liquid.

Buildings with their foundations in clay that have been subjected to liquefaction may topple over or slide down if built on a slope.

11. How are long-term and short-term earthquake predictions made? What is the basis for determining a recurrence interval?

ANS: Long-term earthquake predictions are based on recorded earthquake occurrences. Within a designated time span, higher probabilities of future earthquakes are assigned to regions that have historically been seismically active, with smaller earthquakes being more frequent events than larger earthquakes. More specifically, within belts of seismicity, seismic gaps (sections within seismically active belts that have not experienced as many recent earthquakes) may be “due” for an earthquake. Short-term predictions are generally unreliable, but swarms of small earthquakes may be foreshocks for a coming event, and sudden deformation of rock (perhaps evidenced by a change in the water table) may forebode of an earthquake to come. Anecdotally, it has been reported that water levels in wells and changes in animal behavior may presage earthquakes, but these purported signals are rejected by most seismologists.

A recurrence interval is assessed using evidence of past earthquake activity (from seismogram records and geological evidence of faulting).

12. What types of structures are most prone to collapse in an earthquake? What types are most resistant to collapse? What causes most loss of life during an earthquake?

ANS: Unreinforced brick and concrete buildings are highly prone to collapse. Wood- and

steel-framed buildings and reinforced concrete buildings fare much better. Because most earthquakes do not generate great tsunamis, most loss of life is from the collapse of buildings and other structures.

On Further Thought

13. Is seismic risk greater in a town on the west coast of South America than on the east coast? Explain your answer.

ANS: Yes, the west coast of South America is a plate boundary (subduction zone), wherein the materials of the two opposed plates experience great stress associated with relative plate motion. Earthquakes can occur away from plate boundaries (the situation on the east coast), but they are far more rare.

14. The northeast-trending Ramapo Fault crops out north of New York City near the east coast of the United States. Precambrian gneiss forms the hills to the northwest of the fault, and Mesozoic sedimentary rock underlies the lowlands to the southeast. (You can see the fault on *Google Earth*TM by going to latitude 41° 10' 21.12" N, longitude 74° 5' 12.36" W. The fault trace follows a distinct escarpment.) Where the fault crosses the Hudson River, there is an abrupt bend in the river. A nuclear power plant was built near this bend on sediments deposited by the river. Imagine that you are a geologist with the task of determining the seismic risk of the fault. What evidence of prehistoric seismic activity could you look for?

ANS: Evidence of prehistoric seismicity includes slickensides (polished, grooved surfaces on faulted rock), fault gouge ("rock flour" that forms through physical weathering of rock by the faulting process), visible offset in rock layers, and doglegs in the course of streams. Based on the course of the Hudson River, ancient seismicity has taken place.

15. On the seismogram of an earthquake recorded at a seismic station in Paris, France, the

S-wave arrives 6 minutes after the P-wave. On the seismogram obtained by a station in Mumbai, India, for the same earthquake, the difference between the P-wave and S-wave arrival times is 4 minutes. Which station is closer to the epicenter? From the information provided, can you pinpoint the location of the epicenter? Explain.

ANS: The Mumbai station is closer to the epicenter (shorter S–P travel-time difference). Given distances between two seismic stations and the epicenter, the epicenter can be localized to one of two points on a map, but it cannot be precisely indicated until the information from a third seismic station is given.

16. Will the duration of shaking recorded at a seismic station be longer or shorter as the distance between the epicenter and the station increases?

ANS: Because seismic waves travel at a variety of different velocities, the total interval of observed shaking (first observed wave to last observed wave) will be longer with increasing distance from the epicenter. Wave arrival times will be more greatly spaced with increasing distance of travel.

INTERLUDE D

The Earth's Interior Revisited: Insights from Geophysics

Learning Objectives

1. Students should be familiar with how seismic waves behave as they pass through the Earth's interior.
2. Students should know what the study of seismic waves can tell us about layering inside the Earth.
3. They should know that Earth's gravitational attraction varies across with location and what these variations mean.
4. They should know why Earth's magnetic field exists and why its strength varies with location.

Summary of the Text

Details about the depth to Earth's internal layers, and about divisions within the layers, come from the study of seismic waves passing through the Earth. This is because waves refract and reflect at boundaries.

The Moho was discovered because seismic waves travel faster through the mantle than through the crust.

Seismic-velocity discontinuities define boundaries in the mantle. Several discontinuities occur in the transition zone.

Seismic shadow zones define the depth to the core. S-waves cannot pass through the core, so part of it must be liquid. The reflection of waves off the surface of the solid, inner core defines its depth.

Seismic tomography reveals that the onion-like model of the Earth's interior is an oversimplification because the layers are inhomogeneous. Modern EarthScope studies can outline subducted plates.

Seismic-reflection, using artificially produced seismic waves, allows geologists to identify layering and structures in the sedimentary strata of the upper crust.

The geoid, the representation of the surface on which the pull of gravity is the same, is not a perfect sphere. Local anomalies may indicate the presence of particularly dense rocks below the surface.

The elevation of the lithosphere's surface regionally reflects isostatic equilibrium. Local bending or loading, however, yields places that are not in equilibrium.

The Earth's magnetic dipole exists because of convective circulation in the outer core. Local anomalies may exist where rocks contain magnetic minerals.

Answers to Review Questions

1. What basic layers of the Earth were recognized before the use of seismology?

ANS: The crust, mantle, and core were recognized prior to the advent of seismology.

2. Do seismic waves travel at the same velocities in all rock types?

ANS: No. Seismic waves travel more rapidly through rock that is more densely packed and more rigid.

3. What is the difference between refraction and reflection of waves?

ANS: Refraction involves the bending of seismic-wave paths with depth; reflection occurs when waves bounce off boundaries between layers.

4. What observation led to the discovery of the Moho?

ANS: Seismic waves that travel over distances greater than 200 km to reach a seismic

station have substantially greater average velocities than those produced by local earthquakes. These more distant earthquakes send waves deep enough to travel through the mantle rather than just the crust. This observation led to the discovery of a seismic discontinuity at the crust-mantle boundary termed *the Moho*.

5. How and why do seismic waves bend as they pass through the mantle?

ANS: Seismic waves bend into arc-like paths due to the increasing velocity the waves experience with depth of travel in the mantle. Upon reaching material that permits faster travel, wave paths are bent so as to travel in a more lateral (less vertical) direction.

6. What are seismic-velocity discontinuities, and what do they tell us?

ANS: Seismic-velocity discontinuities are boundary surfaces within the Earth where the velocities of waves abruptly speed up or slow down rather than varying continuously with depth. They tell us that the materials the waves are passing through have changed in density, compressibility, or rigidity.

7. What are the P-wave and S-wave shadow zones, and what do they tell us?

ANS: The P-wave and S-wave shadow zones are areas at the surface where seismic stations will not receive either P-waves or S-waves, respectively. They tell us that there is a liquid layer, the outer core, beneath the mantle of the Earth and the depth of the boundary between the mantle and the outer core.

8. Is seismic velocity constant at a given depth? Explain how seismologists learned the answer to this question and what the answer tells us about the mantle.

ANS: No. Seismic tomography has illuminated areas within the mantle where velocities are greater or less than expectation based upon depth. Anomalous velocities may be associated with subducting plates, mantle upwelling, or mantle downwelling.

9. What can we learn from seismic-reflection surveys?

ANS: Reflection surveys show us boundaries between rock layers within the upper crust, revealing depth, thickness, and orientation of sedimentary strata. These profiles can be used to prospect for oil and other subsurface resources.

10. What is the principle of isostasy, and why is the lithosphere able to be in isostatic compensation, in general?

ANS: Isostasy is the tendency of pressure to equilibrate at depth in response to a surface load. The lithosphere can be isostatically compensated because the asthenosphere below is able to flow and allow a surface burden to partially subside.

11. Explain what the geoid is and why it is so bumpy. What is a gravity anomaly?

ANS: The geoid is a surface of equal gravitational potential across the surface of the Earth; it is bumpy because of the variability in density of materials near the surface. A gravity anomaly is a place where the gravitational potential is greater or less than expectation. Loads (mountains) supported by the lithosphere may lead to increased local potential (positive anomaly) because rock is denser than air. Trenches may show up as negative anomalies because seawater is less dense than rock.

12. Why might the Earth's magnetic field exist? What causes magnetic anomalies?

ANS: Turbulent motion in the liquid iron of the outer core is thought to produce a dynamo, with magnetism derived from the helical motion of electricity. Magnetic anomalies are caused by the presence of magnetic minerals in the rocks and sediments of the crust in places.

CHAPTER 9

Crags, Cracks, and Crumples: Crustal Deformation and Mountain Building

Learning Objectives

1. Students should understand normal, reverse, thrust, detachment, and right-lateral and left-lateral faults, including the orientation of the fault plane and sense of motion in each case. They should know how faults and joints differ, and be able to identify what evidence in the field is used to diagnose the presence of a fault.
2. Students should be able to recognize the four major folds (synclines, anticlines, domes, and basins) in both map view and cross-sectional view.
3. Students should be able to distinguish between brittle and ductile behavior, recognizing that faults exemplify the former and folds the latter. They should know that heat, pressure, and gradual application of stress favor ductile behavior in rocks.
4. Isostasy (isostatic equilibrium) denotes the balance between the weight of mountain ranges and the buoyant support they receive from the denser mantle below. Mountain ranges are underlain by thick crustal roots, just as most of an ice cube floats below the surface of water. As mountain ranges erode, their crustal roots are pressed upward.
5. The familiar montane topography is the result of erosion. Once the rate of uplift becomes less than the rate of erosion, the mountain range will begin to wear flat, a process that generally takes tens of millions of years.
6. Flat, low-lying regions that have not been exposed to orogenic deformation for more than 1 billion years are termed *cratons*. In the central portion of the craton, termed the *shield*, metamorphic rocks are exposed at the surface. The region on the flanks of the craton, where the metamorphics are overlain by sediments, is termed the *cratonic platform*.

Summary from the Text

Mountains occur in linear ranges called mountain belts or orogens. An orogen forms during an orogeny, or mountain-building event.

Mountain building causes rock to bend, break, shorten, stretch, and shear. Because of such deformation, rocks can change their location, orientation, and shape.

During brittle deformation, rocks break into pieces. During ductile deformation, rocks change shape without breaking.

Stress (force applied per unit area) can be compressional, tensional, or shear. Pressure refers to a condition in which a material feels the same amount of compression in all directions.

Strain refers to the way rocks change shape when subjected to a stress. For example, compression can cause shortening, and tension can cause stretching.

Deformation results in the development of geologic structures.

Joints are natural cracks in rock, formed in response to tension under brittle conditions. Veins develop when minerals precipitate out of water passing through cracks.

Faults are fractures on which there has been shear. Geologists distinguish among normal, reverse, strike-slip, and oblique-slip faults.

Folds are curved layers of rock. Anticlines are arch-like, synclines are trough-like, monoclines resemble the shape of a carpet draped over a stair step, basins are shaped like a bowl, and domes are shaped like an overturned bowl.

Tectonic foliation forms when grains flatten, rotate, or grow so that they align parallel with one another.

Mountain belts can form at convergent margins along continents, in collision zones, and in rifts. Convergent-margin and collisional orogenies, powerful forces that often deform and metamorphose rocks, can form fold-thrust belts. Rifting yields fault-block mountains.

Small crustal blocks that collide with plate margins become accreted terranes.

Accretion can add crust to a continent over time.

Large collisional mountain ranges are underlain by buoyant roots and contain folds, faults, and foliations.

With modern GPS technology, it is now possible to measure the slow shortening and uplift of mountains.

Uplift in mountains, over broad regions, is controlled largely by isostasy, meaning that the elevation of Earth's surface reflects the level at which lithosphere naturally floats.

Once uplifted, mountains are sculpted by erosion. When crust thickens during mountain building, the deep crust may eventually become weak, leading to orogenic collapse.

Cratons are the old, relatively stable parts of continental crust. They include shields and platforms. Broad regional domes and basins form in platform areas.

Video and Animation Files

CONTINENTAL COLLISION

Number: Video 9.1

Length: 3 minutes, 7 seconds

Summary: This video illustrates the transformation that occurs when subduction of oceanic lithosphere yields to collision of continents. Fold-and-thrust belts, at the periphery of the collision, are distinguished from the more highly deformed metamorphic core of the range. The Alps and Himalayas are used as modern examples of orogenic collision, and the valley-and-ridge topography of the Appalachians is revealed to be an ancient fold-and-thrust belt.

Classroom Use: This video might be useful to show in class to reinforce lecture on collisional orogeny due to its combination of animation and satellite imagery.

Review and Discussion Questions:

1. Why don't continents subduct deep into the mantle the way oceanic plates do?

2. Why do the Alps exist where they do?

DEFORMATION OF ROCK

Number: Animation 9.1

Length: 1 minute, 40 seconds

Summary: This animation contrasts the behavior of rock under elastic, brittle, and ductile deformation.

Classroom Use: This animation could be shown in class or assigned as a review for students.

Review and Discussion Questions:

1. Both elastic and ductile deformation involve change in the shape of rock. What is the major difference between them?
2. Is rock more likely to behave in a ductile manner if it is found close to the surface or if it is buried deep within the crust?

FAULTS: NORMAL, REVERSE, AND STRIKE-SLIP

Number: Animation 9.2

Length: 2 minutes, 47 seconds

Summary: Animation is used to convey the distinct sense of motion in each of three types of fault.

Classroom Use: This animation is highly recommended for classroom use, as it is difficult to convey motion on faults using only words and static pictures.

Review and Discussion Questions:

1. Both normal and reverse faults involve vertical motion of a hanging wall relative to a footwall. What is the difference between the two?
2. What is a thrust fault?

TYPES OF FOLDS

Number: Animation 9.3

Length: 1 minute, 49 seconds

Summary: This animation shows how anticlines, synclines, and monoclines are

formed.

Classroom Use: This animation could be used to help students visualize three-dimensional deformation that yields the most commonly seen folds.

Review and Discussion Questions:

1. Layered sedimentary strata are deposited as sediments with younger layers atop older layers. In the center of a syncline, would we expect to find the youngest or oldest layer present?
2. Would the youngest or oldest unit be found in the center of an anticline?

Answers to Review Questions

1. What changes do rocks undergo during formation of an orogenic belt such as the Alps?

ANS: In orogenic belts, rocks undergo deformation as a response to stress. Deformation can include faulting, jointing, folding, and the development of metamorphic foliation.

2. Contrast brittle and ductile deformation.

ANS: Brittle deformation involves fracturing of rock; ductile deformation involves rock bending or flowing without breaking.

3. What factors influence whether a rock will behave in brittle or ductile fashion?

ANS: Temperature, pressure, deformation rate, and lithology all influence the deformational behavior of rock under stress. Hot rocks are more likely to deform in a ductile manner than are cool rocks. Rocks under very high pressure will more likely undergo ductile deformation than those at low pressure. Sudden changes in stress, such as the rapid onset of great tensile stress, are more likely to produce brittle behavior than are gradual changes in stress. Some rocks, such as halite, are weaker than typical rocks and tend to exhibit ductile deformation.

4. How are stress and strain different?

ANS: Stress is applied force per unit area; strain is percent deformation in response to stress.

5. How is a fault different from a joint?

ANS: A fault is a fracture along which there has been displacement; a joint is a fracture without displacement.

6. Compare normal, reverse, strike-slip, and oblique-slip faults.

ANS: Along a normal fault, the hanging-wall block moves downward relative to the footwall block; along a reverse fault, the hanging-wall block moves upward relative to the footwall block. Normal and reverse faults both tend to form at an angle between vertical and horizontal. Both are termed dip-slip faults; motion is parallel to the dip direction of the fault plane.

A strike-slip fault is typically vertical in orientation; one block slides horizontally past the other, parallel to the strike direction of the fault plane.

An oblique-slip fault is one that is angled like a normal or reverse fault, but has more complicated motion that features a component parallel to dip and a component parallel to strike. (See Figure 9.8.)

7. How do you recognize faults in the field?

ANS: Offset of layers on opposite sides of the fault, the development of drag folds along the fault interface, the presence of an exposed fault scarp, shattered rock (fault breccia), powdered rock (fault gouge), and slickensides (polished fault surfaces) are all clues used to identify faults.

8. Describe the differences among an anticline, a syncline, and a monocline.

ANS: Anticlines (unless overturned) are convex-upward arches. Synclines (unless overturned) are concave-upward troughs. Monoclines are step-like folds.

9. Discuss the relationship between foliation and deformation.

ANS: Foliation is a layering resulting from the alignment of mineral grains or the development of compositional bands. Deformation involves folding and fracture of rock bodies. Both processes take place during orogenic events: foliation at microscopic scale,

and deformation at regional scale.

10. Discuss the processes by which mountain belts form in convergent margins, during collisions, and in continental rifts.

ANS: At convergent margins, if the overriding plate is a continent, a continental volcanic arc is formed. Collision may occur between the overriding continental plate and an exotic terrane (island arc or microcontinent), which will not subduct but merge into the continent, elevating the continental volcanic arc.

When continents collide, massive mountain ranges are produced. Thrust faulting at a fold-thrust belt loads the material from one continent above the other, leading to deep burial of rocks and regional metamorphism.

At continental rifts, the lithosphere is thinned by stretching, and the hot asthenosphere rises to compensate, heating the thinned lithosphere above and thereby making it less dense. Its reduced density causes the thin lithosphere to rise up to reestablish isostatic equilibrium. Normal faulting produces regions of relative uplift, termed fault-block mountains, to the sides of rift basins.

11. Describe the principle of isostasy.

ANS: Isostasy describes the balance between the downward force of gravity on an elevated load, such as a mountain range, and the buoyant supporting force of the asthenospheric mantle beneath it.

12. How are the structures of a craton different from those of an orogenic belt?

ANS: Orogenic belts feature the rugged topography of mountains, with folds, faults, and metamorphism visible at outcrop. The platforms of cratons are less deformed, but may feature broad domes and basins visible at map scale.

On Further Thought

13. Imagine that a geologist sees two outcrops of resistant sandstone, as depicted in the cross-section sketch. The region between the outcrops is covered by soil. A distinctive bed of cross-bedded sandstone occurs in both outcrops, so the geologist correlates the western outcrop (on the left) with the eastern outcrop. The curving lines in the bed indicate the shape of the cross beds. Keeping in mind how cross beds form (see Chapter 6), sketch how the cross-bedded bed connected from one outcrop to the other, before erosion. What geologic structure have you drawn?

ANS: The completed drawing will reveal an asymmetric syncline.

INTERLUDE E

Memories of Past Life: Fossils and Evolution

Learning Objectives

1. Students should know what a fossil is and how fossils form.
2. Students should know that it takes special conditions for an organism to be preserved as a fossil, so it's not surprising that the record of known fossils is very incomplete.
3. Students should know how fossils are classified, according to the rules of taxonomy, and the names of common fossils.
4. Students should know the fundamental principles of the theory of evolution by natural selection.
5. Students should know what extinction is, what mass extinctions are, and why mass extinctions take place.

Summary of the Text

Fossils form when organisms, or the traces of organisms (burrows or footprints), are buried and preserved in rock. Typically, the hard parts (shells or bones) of fossils are better preserved.

Examples of fossils include molds or casts of shells, bones, or footprints; permineralized wood or bones; carbonized impressions; preserved shells or bones; and bodies preserved in amber, tar, or permafrost. Certain distinctive molecules can serve as molecular fossils or biomarkers.

The fossil record is very incomplete, because preserved strata do not record all of geologic time, not all organisms have high preservation potential, and paleontologists have only found a tiny fraction of fossil species.

Fossils provide a record of life's evolution and a basis for geologists to determine the ages of rock layers relative to one another.

Fossil organisms can be classified using the same taxonomic concepts used to classify modern organisms.

Darwin proposed the theory of evolution by natural selection, which states that the fittest organisms survive and pass on their traits to their offspring. Over time, organisms become so different from their distant ancestors that they can be considered to be a new species.

When the last of a species dies out, the species goes extinct. At several times during Earth's history, a high percentage of genera went extinct. These events are called mass extinctions, and they may be a consequence of catastrophic events, such as meteorite impacts or unusually abundant volcanism.

Video and Animation Files

FOSSILS

Number: Animation E.1

Summary: This animation describes and explains the scarcity of fossil preservation and the factors that can improve the chances of a deceased organism entering the fossil record (mineralized hard parts and rapid burial). It then details how the various modes of preservation develop in fossils, including original preservation, recrystallization, carbonization, permineralization, replacement, and cast and mold formation.

Classroom Use: Instructors who are treating fossil preservation in lecture will want to use this animation in class. In particular, it will help students differentiate among external molds, internal molds, and casts. Alternatively, it could be used as a

homework activity, followed by a short summary quiz.

Review and Discussion Questions:

1. Which group of animals would have a better fossil record: clams or earthworms?

Why?

2. Clam and snail shells are typically made of calcite and aragonite, which are calcium carbonate minerals that effervesce (fizz) when a drop of dilute hydrochloric acid is placed on them. Would a recrystallized clamshell effervesce in weak acid?

How about a replaced snail shell?

Answers to Review Questions

1. What is a fossil? Give examples of various types.

ANS: Fossils are the remains and traces (indications of organism activity, such as footprints) of ancient living things preserved in the geologic record. Examples could include a dinosaur bone that has been permineralized, originally preserved bones and flesh of a mammoth in permafrost, a coral that had been chemically replaced, an impression (mold) of an ancient leaf, etc.

2. What are the various processes that can yield fossils?

ANS: Generally, organisms must be buried after death (often by flood deposition, mass movements, or marine storm waves) to be protected from scavengers and excessive decay in order to end up in the fossil record. If the organism possesses mineralized hard parts (such as our bony skeleton), then these portions might be preserved as original material after the burial sediment is lithified and eventually exposed at outcrop. Chemical interaction with pore water in sediment or rock may dissolve hard parts to leave an impression (mold) in the sediment, which preserves the shape of the organism. Chemical replacement of original material, and infilling of pore space with minerals, are also possible.

Preservation of soft tissues, such as flesh, feathers, or hair, is more rare and

generally requires very rapid burial in an oxygen-poor environment or entrapment in an airtight or very dry setting.

3. According to the fossil record, do strata of all ages contain the same fossils?

ANS: No. Species have finite lifetimes and will only be found in strata deposited while they were extant. Strata of different ages thus have distinctly different fossils in them.

4. What conditions can lead to preservation of an organism as a fossil?

ANS: Organisms with robust, mineralized skeletons that live (and tend to die) in environments where sediments are deposited, leading to rapid burial, are those with the greatest chances of becoming fossilized. There are some exceptional settings where extremely rapid burial in an oxygen-poor environment has allowed soft-tissue preservation. There are even rare cases (ice, amber) where conditions allow complete preservation of bodies in three dimensions.

5. Is the fossil record complete? Why or why not?

ANS: The fossil record is highly incomplete. Only a small fraction of ancient environments are preserved in the rock record and exposed at outcrop somewhere on land. Even within the record of outcropping strata, some fossiliferous rocks have not yet been collected due to their remote or otherwise inaccessible location. Furthermore, fossils at outcrops may be lost to weathering because of the limited number of humans actively collecting fossils. Additionally, most organisms do not have a robust, mineralized skeleton possessing a reasonable chance of remaining intact before and after burial. Many organisms are consumed upon death, or otherwise do not live in environments conducive to fossilization.

6. Describe the basic principles of the theory of evolution by natural selection.

ANS: Within populations, many more individuals are born than will survive to reproduce. There is variability among offspring, and much of this variability is heritable (genetically induced) and can thus be passed down to future generations. Individuals with traits that cause them to be relatively fit (adapted to their environment) are more likely to survive and reproduce, and thus, pass down these favorable traits. Therefore, over time,

populations tend to become better adapted to their environment and distinct from earlier ancestral populations.

7. Explain different ideas characterizing the rate of evolution.

ANS: Gradualism is the idea that change in the fossil record is generally slow and steady. Punctuated equilibrium is the idea that rates of evolutionary change are highly variable, with stability or mild fluctuation during most spans of time, punctuated by abrupt events of massive change.

8. What phenomena may cause extinction?

ANS: Species may become extinct if a vital resource (such as food or shelter) disappears from the environment, if a superior predator or competitor species arises, or if the environment changes too suddenly to allow for adaptation, as might occur as a result of a massive meteorite strike, an extreme volcanic episode, or sudden, rapid climate change.

9. What is a mass-extinction event, and why might such an event take place?

ANS: Mass-extinction events are abrupt, worldwide declines in numbers of species or genera (closely related groups of species). These events might be triggered by sudden climate change, massive volcanic eruptions, or meteorite impacts. Based on measured rates of extinction, it has recently been established that we currently live in a time of mass extinction, most likely driven by human habitat destruction, overhunting, and pollution.

CHAPTER 10

Deep Time: How Old Is Old?

Learning Objectives

1. Students should become familiar with the geologic time scale, including the ordered sequence of eons—Hadean, Archean, Proterozoic, and Phanerozoic—and the ordered sequence of eras within the Phanerozoic Eon: Paleozoic, Mesozoic, and Cenozoic.
2. Students should be familiar with the distinction between relative (ordinal) age, represented by the names of eras and periods; and numerical age, represented by dates measured in (typically millions of) years. Relative ages are primarily determined through superposition, cross-cutting relations, inclusions, and fossil succession. Numerical ages for boundaries on the time scale require radiometric dates for igneous rocks (lava flows and ash layers are particularly helpful) combined with the observation of spatial relationships between these rocks and sedimentary strata.
3. Similarly, students should be able to understand and apply the principles that can be used to interpret the order of events that resulted in a given sequence of rocks (Steno's lateral continuity, original horizontality, and superposition, as well as cross-cutting relations, baked contacts, and inclusions).
4. Uniformitarianism ("the present is the key to the past") was an important step forward in geological thinking. Observing modern rates of deposition, erosion, and volcanic extrusion provides a first approximation for understanding ancient Earth conditions and further implies that Earth must be very ancient (given the complexities of many outcrops and the diversity of strata across Earth). Modern geologists nevertheless understand that rates of processes may have changed over time, and that rare catastrophic impacts and volcanic eruptions have occurred in the past.
5. Fossil succession allows relative ages to be produced for many fossiliferous

sedimentary rocks, regardless of their spatial contexts. This succession allows for temporal correlation of widely separated strata on the basis of fossil content. Students should be able to produce overlap ranges (last origination–first extinction) for suites of long-ranging fossil species so as to provide maximum constraint on the ages of the strata that contain them.

6. The constancy of a half-life for any given unstable isotope implies that radioactive decay occurs at a constant exponential rather than linear rate. Isotopic (radiometric) dating applied to ancient rocks does not entail the use of radiocarbon (^{14}C) because of its short half-life. Isotopes of elements such as uranium, rubidium, potassium, and samarium, which have half-lives on the order of millions and billions of years, are employed.
7. Earth is a geologically active planet; Earth materials are continually recycled, so the age of Earth is likely significantly older than the oldest known rocks (~ 4 giga-anni [Ga]). The widely cited 4.57 Ga age of Solar System formation arises from radiometric dating of meteorites (orbital characteristics of the Solar System imply contemporaneous formation of the Sun, planets, and asteroids).

Summary from the Text

Geologic time refers to the time span since the Earth's formation.

Relative age specifies whether one geologic feature is older than or younger than another; numerical age (absolute age) provides the age of a geologic rock or feature in years.

Using such principles as uniformitarianism, original horizontality, superposition, and cross-cutting relations, we can construct the geologic history of a region.

The principle of fossil succession states that the assemblage of fossils in strata changes from base to top of a sequence. Once a species becomes extinct, it never reappears higher in the sequence.

Strata are not necessarily deposited continuously at a location. An interval of nondeposition and/or erosion produces an unconformity. Geologists recognize three kinds: angular unconformity, nonconformity, and disconformity.

A stratigraphic column shows the succession of strata in a region. A given succession of strata that can be traced over a fairly broad region is called a stratigraphic formation.

The process of determining the relationship between strata at one location and strata at another location is called correlation. A geologic map shows the distribution of formations, as well as of geologic structures.

A composite chart that represents the entirety of geologic time is called the geologic column. The column's largest subdivisions are eons. Eons are subdivided into eras, eras into periods, and periods into epochs.

The numerical age of rocks can be determined by isotopic (radiometric) dating. This determination is because radioactive elements decay at a rate characterized by a known half-life.

The isotopic age of a mineral specifies the time at which the mineral cooled below a closure temperature. We can use isotopic dating to determine when an igneous rock solidified and when a metamorphic rock cooled. To date sedimentary strata, we must examine cross-cutting relations with dated igneous or metamorphic rock.

Other methods for dating materials include counting growth rings in trees and seasonal layers in glaciers.

Isotopic dating indicates that the Earth is 4.54 billion years old. This date represents the time when the planet internally differentiated into a core and a mantle. A rock record of the first half billion years of Earth history doesn't exist, for the oldest dated whole rock is about 4 Ga.

Video and Animation Files

RELATIVE AGE DATING

Number: Animation 10.1

Length: 7 minutes, 35 seconds

Summary: This animation shows students how to use the principles of relative age dating to unravel the sequence of geologic events that produce cross-sections of varying complexity. For each of five levels of difficulty, a finished block diagram is shown and then the sequence of events necessary to produce the final geology is demonstrated, step by step.

Classroom Use: This animation could be assigned as a study aid prior to a quiz or examination covering reconstruction of Earth history.

Review and Discussion Questions:

1. In the Moderate Level module, at the end of the animation, we see a basalt dike that is younger than a normal fault with which it intersects. If the dike were older than the fault, how would the picture look different?
2. In the Difficult Level module, at the end of the animation, we see multiple unconformity surfaces in cross-sectional view on the front face of the block diagram. Which type of unconformity is represented by the uppermost unconformity in the sequence: disconformity, angular unconformity, or nonconformity?

UNCONFORMITIES

Number: Animation 10.2

Length: 3 minutes, 48 seconds

Summary: The three types of unconformities are named and defined, with step-by-step animation used to show how each is formed.

Classroom Use: This animation could be used either in class to explicate formation of each type of unconformity or as a recommended study aid.

Review and Discussion Questions:

1. Of the three types of unconformity, which would most likely represent the least amount of missing time in the rock record, perhaps just tens of thousands of years of sea level rise and fall?
2. Beneath a sandstone layer at outcrop, you see a buried erosional surface atop a body of diorite. Which type of unconformity have you just observed?

Answers to Review Questions

1. Explain the concept of uniformitarianism.

ANS: Uniformitarianism is sometimes summarized by the statement “the present is the key to the past.” Ancient geological events are thought to have been similar to those that have been historically recorded because there is no reason to assume that the laws of nature have changed over time. For example, great bodies of mudstone preserved in the rock record are the result of long-term, slow (on a human scale) deposition of muddy sediment at the surface. Muddy (or sandy or pebbly) strata do not intrude from below the surface, and it is clear that this has always been the case given our present knowledge of Earth’s interior.

Modern understanding of uniformitarianism does not mean, however, that all processes have occurred at the same rate throughout Earth history, nor that there have not been unique events in the history of the Earth.

2. Compare the numerical age (absolute age) of a rock to the relative age of the rock.

ANS: Numerical age for a rock is a number estimating the time of the rock’s formation in years before the present. Relative age is a statement of ordinal timing; for example, Ordovician sedimentary rocks were deposited after those of the Cambrian, but before those of the Silurian.

3. Describe the principles that allow us to determine the relative ages of geologic events.

ANS: Along with uniformitarianism (Review Question 1) and fossil succession (Review Question 4), there are six physical principles:

Superposition—In an undisturbed sequence of sedimentary rocks, younger layers are deposited on top of older layers.

Original horizontality—Sediments are deposited in horizontal layers; variance from this implies post-depositional deformation.

Lateral continuity—Spatially isolated bodies of sedimentary rock of identical lithology were once physically connected. Isolation resulted from erosion of a previously continuous planar bed.

Cross-cutting relations—Features can only disrupt other features that are older than themselves: (a) Igneous intrusions are younger than the rocks they intrude; (b) Faults are younger than the rocks and surfaces they offset; and (c) Erosional surfaces are younger than the rocks into which they cut.

Inclusions—If a rock contains pieces of another body of rock, then it must be younger than the donor rock.

Baked contacts—If a rock is in places metamorphosed as a result of contact with a hot body of magma or lava (which later crystallized to form igneous rock), the metamorphosed rock must have existed (as unaltered rock) prior to the metamorphic event.

4. How does the principle of fossil succession allow determination of relative ages of strata?

ANS: Species originate within geologically brief time frames, few species persist for more than a few million years, and extinction is permanent. Fossils that are, for example, uniquely found within Upper Triassic rocks can be used to illustrate temporal equivalence of isolated strata that bear these same fossil assemblages. Thus, physically isolated sedimentary sequences can be temporally correlated in the absence of datable igneous intrusions. Additionally, strata containing characteristically Lower Jurassic assemblages must be younger than those with Upper Triassic fossils.

5. How does an unconformity develop? Describe the differences among the three kinds of

unconformities.

ANS: An unconformity occurs when sedimentary layers are deposited on top of a surface of erosion or nondeposition. Three kinds of unconformities are recognized:

nonconformities, disconformities, and angular unconformities. Nonconformities arise when sedimentary strata are deposited on top of crystalline (metamorphic or igneous) rock. Disconformities occur when strata are deposited on top of an erosional surface that was horizontal at the time, so that layers above and below the unconformity are parallel. Angular unconformities arise when the new strata are deposited on top of older layers that have been tilted out of horizontality, so that, regardless of future tilting, layers on opposite sides of the unconformity are not parallel.

6. Describe two different methods of correlating rock units. How was correlation used to develop the geologic column?

ANS: Lithologic correlation is the use of physical and chemical characteristics of rocks to determine that spatially isolated strata were once continuous (through original lateral continuity). Fossil correlation uses fossils with known stratigraphic ranges to determine the approximate temporal equivalence of two bodies of rock (which may be of disparate lithologies). Because a single locality does not provide strata that span in age throughout Earth's history, fossil correlation was required to provide time equivalence for units that are geographically isolated. With successful correlation, rock sequences from all parts of the world could be brought together to form an accurate sequence of relative time: the geologic column.

7. What is a stratigraphic formation, and how is a stratigraphic formation depicted on a geologic map?

ANS: A stratigraphic formation is a recognizable layer of a specific (usually sedimentary) rock type, or set of types, that was deposited within a certain time interval and can be traced over a broad region. The presence of a formation at the surface would be depicted on a geologic map by a unique color shade distinct from that used for other formations.

8. Is there one place on Earth where we can see the complete geologic column?

ANS: No. The geologic column was pieced together by assessing information provided by many outcrops worldwide.

9. What does the process of radioactive decay entail?

ANS: Radioactive decay is the nuclear breakdown of unstable isotopes in mineral crystals to form new (daughter) isotopes over time.

10. How do geologists obtain an isotopic date? What are some of the pitfalls in obtaining a reliable one?

ANS: Geologists obtain an isotopic date by first observing the ratio of unstable parent isotope to the stable daughter product of the reaction within a mineral extracted from the rock of interest and then comparing this ratio to the known half-life for the nuclear reaction.

Problems encountered in the quest to obtain an accurate isotopic date include the fact that different minerals within the rock may have different closure temperatures and thus give slightly different ages for the rock. The isotopic system used in dating must have a sufficiently long half-life, so that parent isotopes will remain in the crystals being dated. There is also some uncertainty in the half-life of the isotope systems used in geology. Clastic sedimentary rocks generally cannot be accurately dated, as they are always younger than any dates acquired from their constituent grains due to the principle of inclusions.

11. Why can't we date sedimentary rocks directly? Why don't periods on the geologic column have the same duration?

ANS: Isotopic dates provide ages of minerals (grains or crystals) within rock. Igneous rocks form at the same time as their component minerals and are thus datable.

Sedimentary rock grains, such as sand, mud, and gravel, derive from the physical and chemical weathering of preexisting rocks at relatively low temperatures. The mineral components within sedimentary rocks are generally much older than the rocks themselves (principle of inclusions).

Boundaries between periods on the geologic column are assigned based on mass extinctions and other developments in the fossil record. These are episodic rather than

periodic.

12. What is the age of the oldest rocks on Earth? What is the age of the oldest rocks known? Why is there a difference?

ANS: The oldest rocks on Earth are about 4 Ga. Moon rocks are as old as 4.5 Ga, and meteorites are as ancient as 4.57 Ga.; this last date is likely the age of the beginnings of the formation of the Solar System (including Earth). Earth itself formed as a planet shortly thereafter, at about 4.54 Ga. No Earth rocks are likely to be found yielding 4.54 Ga dates because Earth was initially too hot (with heat derived from initial accretion; collisions with other Solar System bodies; and differentiation to form the core, mantle, and crust, as well as radioactivity) to sustain solid rock at the surface for any great length of time. Even today, Earth is geologically active in comparison to other bodies in the Solar System. Erosion, subduction, and melting are processes that actively destroy rock, so the oldest rock preserved on Earth is younger than the oldest rock ever formed in the Solar System.

On Further Thought

13. Imagine an outcrop exposing a succession of alternating sandstone and conglomerate beds. A geologist studying the outcrop notes the following:

The sandstone beds contain fragments of land plants, but the fragments are too small to permit identification

A layer of volcanic ash overlies the sandstone beds. Isotopic dating indicates that this ash is 300 Ma.

A paleosol (preserved ancient soil) occurs at the base of the ash layer.

A basalt dike, dated at 100 Ma, cuts both the ash and the sandstone-conglomerate sequence.

Pebbles of granite in the conglomerate beds yield radiometric dates of 400 Ma.

On the basis of these observations, how old is the sandstone and conglomerate? (Specify both the numerical age range and the period or periods of the geologic column during

which it formed.)

ANS: The sandstone-conglomerate sequence was deposited sometime after 400 Ma (the age of granite clasts in the conglomerate) and before 300 Ma (the age of the ash layer stratigraphically above the sequence). This numerical time range corresponds to the Devonian and Carboniferous periods.

14. Examine the photograph and the What a Geologist Sees interpretation of an outcrop in eastern New York state, shown below. Write a brief geologic history that explains the relationships displayed in this outcrop. The strata above the unconformity are Late Silurian (Rondout Formation) and Early Devonian (Helderberg Group), whereas the strata below the unconformity are Middle Ordovician (Austin Glen Formation).

ANS: The first traceable event was the 470 Ma deposition of the Middle Ordovician Austin Glen Formation sediments. These were tilted out of their original horizontality and the tops of the beds eroded. By 420 Ma, the erosional surface was buried by the sediments that form the Rondout Formation and later the slightly younger Devonian Helderberg Group sediments, producing an angular unconformity. Later, the Rondout and Helderberg beds were tilted out of their original horizontality. The sequence of rock was then weathered, eroded, and vegetated.

CHAPTER 11

A Biography of Earth

Learning Objectives

1. Students should know the approximate age of Earth, how this date was obtained, and why the Earth is substantially older than the oldest known rocks.
2. Students should have a general idea about Hadean temperatures; the potential sources of heat early in Earth's history; and the thin, transient nature of the earliest crust. They should be able to distinguish the early volcanically dominated atmosphere from today's atmosphere.
3. Students should know and understand the following:
 - a. the contrast between early Archean tectonics (microcontinents surrounded by seas) and Proterozoic conditions (development of larger oceanic plates and extensive stable cratons)
 - b. the appearance of the first life on Earth (3.8–3.5 Ga), and the geological importance of cyanobacteria (stromatolite formation, oxygenation of the oceans and, ultimately, the atmosphere)
 - c. the formation of supercontinents Rodinia (1 Ga) and Pangaea (roughly 300 Ma), and evidence of worldwide glaciation in the late Proterozoic
 - d. the Cambrian explosion of animal life, and the development of a complex food web with filter feeders, bottom (deposit) feeders, and predators
 - e. the timing of orogenic events that produced the Appalachians and Rockies
 - f. major events in the history of life (from an admittedly biased vertebrate perspective): first fishes, first terrestrial vertebrates, the age of dinosaurs, the origin of birds (Jurassic), and the appearance of early mammals (Late Triassic).

Summary from the Text

Earth formed about 4.54 billion years ago. There is no rock record of its first half billion years, the Hadean Eon, even though the planet probably had a solid skin of ultramafic rock. It may even have hosted liquid water for part of this time, perhaps because it was intensely bombarded by meteorites.

The Archean Eon began about 4.0 Ga, with the formation of the first rocks that still survive. Once plate tectonics started, early continental crust assembled out of volcanic arcs and hot-spot volcanoes that were too buoyant to subduct. The atmosphere contained little oxygen, but the first life forms—bacteria and archaea—appeared.

In the Proterozoic Eon, which began at 2.5 Ga, Archean cratons sutured together to form large cratons. Photosynthesis added oxygen to the atmosphere. By the end of the Proterozoic, soft-bodied marine invertebrates populated the planet, and continental crust had accumulated to form a supercontinent.

As the Paleozoic Era began, rifting yielded several separate continents. Sea level rose and fell, depositing sequences of strata in continental interiors. Continents coalesced again to form another supercontinent, Pangaea. Early Paleozoic evolution produced many invertebrates with shells, and jawless fish. Land plants and insects appeared in the middle Paleozoic, and by the end of the eon, there were land reptiles and gymnosperm trees.

In the Mesozoic Era, Pangaea broke apart, and the Atlantic Ocean formed. Convergent-boundary tectonics dominated along the western margin of North America, and dinosaurs became prominent land animals. During the Cretaceous Period, the continents flooded, and angiosperms appeared along with modern fish. A huge mass-extinction event wiped out the dinosaurs at the end of the Cretaceous, probably due to the impact of a large meteorite.

In the Cenozoic Era, the collision of Africa and India with Asia and Europe formed the Alpine-Himalayan orogen. Convergent tectonics persisted along the margin of South America, forming the Andes, but ceased in North America as the San Andreas Fault initiated. Rifting in the western United States produced the Basin and Range Province.

Mammals filled niches left vacant by the dinosaurs, and the human genus, *Homo*, appeared and evolved through the Pleistocene Ice Age.

Video and Animation Files

BIOSTRATIGRAPHY

Number: Animation 11.1

Length: 3 minutes, 34 seconds

Summary: This interactive animation introduces students to the work of William Smith in developing the principle of fossil succession, and then it lets them see if they can use its logic to put together the geologic column for a fictional land in proper relative sequence using simple shapes as proxies for fossil organisms.

Classroom Use: This animation could be assigned as homework.

Review and Discussion Questions:

1. Who is credited with the discovery of the principle of fossil succession, and thus considered the father of biostratigraphy?
2. In the Expert Level activity, describe the appearance of the uppermost fossil (shape) in the completed column.

Answers to Review Questions

1. Why are there no rocks on Earth that yield isotopic dates older than 4 billion years?

ANS: Earth is a geologically active planet. Subduction, erosion, metamorphism, and melting destroy rocks.

2. Why can we find mineral grains that are older than the oldest whole rocks?

ANS: Hadean zircon crystals have survived the ravages of the rock cycle long after the igneous rocks in which they formed were destroyed. They have since been incorporated into sandstones. These crystals have been isotopically dated to more than 4 Ga, but the sandstones in which they are found must be younger than this, due to the principle of inclusions.

3. Describe the condition of the crust, atmosphere, and oceans during the Hadean Eon.

ANS: The crust would have been largely ultramafic magma and rock (which may have been subject to remelting). The atmosphere lacked free oxygen and would have been dominated by volcanically emitted gases (including water vapor, nitrogen, and carbon dioxide). For at least part of the Hadean, temperatures were likely too hot to sustain a liquid ocean.

4. Describe how the first continental crust might have formed, and when plate tectonics started.

ANS: The first continental crust might have formed from collisions of volcanic arcs that became buoyant due to partial melting. Plate tectonics is thought to have started by 3.2 Ga (middle of the Archean) as mantle lithosphere had cooled enough at this point to allow for subduction.

5. How did the atmosphere and tectonic conditions change during the Proterozoic Eon?

ANS: The atmosphere became oxygenated (and depleted of some carbon dioxide) as a result of photosynthesis. Plate-tectonic conditions became more similar to what is observed today, with larger oceanic plates and the development of broad, stable cratons in continental interiors.

6. What evidence do we have that Earth nearly froze over during the Proterozoic Eon?

ANS: Glacial deposits have been found in sedimentary rocks representing sea-level environments along the paleoequator.

7. Did supercontinents form in the Proterozoic?

ANS: Yes. Late in the Proterozoic, a global supercontinent called Rodinia had

assembled.

8. How did the Cambrian explosion of life change the nature of the living world?

ANS: These first abundant animals complicated the world food web through the introduction of more abundant filter and bottom (deposit) feeders, as well as large, mobile predators and the first biogenic reefs.

9. Were there multicellular organisms before the Cambrian?

ANS: Yes. The Ediacaran faunas preserve a diversity of multicellular animals.

10. How did the Alleghanian and Ancestral Rockies orogenies affect North America?

ANS: The Alleghanian orogeny provided the final uplift to produce the Appalachian Mountains. This powerful collision between Laurentia and Gondwana influenced fault movement in what is now western North America. Uplifted western blocks (the Ancestral Rockies) are the first tectonic events in the region of the modern Rocky Mountains.

11. What major types of organisms first appeared in the Paleozoic, and in what sequence?

ANS: In the early Cambrian, diverse marine invertebrates appeared including mollusks, brachiopods, trilobites, and echinoderms. The first jawless fishes appear by the Ordovician. Vascular plants appear on land in the Silurian, and forests of large trees had developed by the Devonian. Alongside early plants, invertebrates such as spiders, scorpions, and insects colonized land. By the end of the Devonian, some specialized lobe-finned bony fishes, the first vertebrates to walk on land, had appeared. The Carboniferous saw the advent of widespread coal swamp forests, along with early amphibians and reptiles.

12. What supercontinent formed at the end of the Paleozoic, and what ocean formed when it broke apart?

ANS: Pangaea formed at the end of the Paleozoic. Its breakup in the Mesozoic produced the Atlantic Ocean basin.

13. Describe the plate-tectonic conditions that led to the formation of the Sierran arc and the Sevier thrust belt. How did deformation during the Laramide orogeny differ from that

of the Sierran/Sevier orogeny?

ANS: North America had a convergent-plate boundary to the west that induced collisions with microcontinents and caused subduction of oceanic crust, which partially melted to form the Sierran volcanic arc. Compression induced the folds and thrust faults just interior to the arc itself. Faulting associated with the Laramide orogeny uplifted deep basement rock to produce the Rocky Mountains, whereas earlier orogenies produced only the more superficial faults of the fold-thrust belts behind the arc. Changes from the Sevier-style orogeny may have been a result of a shallowing dip of the subducting slab.

14. What life forms appeared during the Mesozoic?

ANS: Dinosaurs, mammals, birds, large swimming reptiles, and pterosaurs are a few examples.

15. What may have caused the flooding of the continents during the Cretaceous Period?

ANS: Rapid Cretaceous rates of submarine volcanism thickened the mid-ocean ridges and produced numerous hot spots, which displaced water onto the continents. Additionally, glacial ice could not accumulate anywhere on Earth in the associated greenhouse warmth.

16. What could have caused the K-T (K-Pg) extinctions?

ANS: The extraterrestrial impact that produced the Chicxulub crater was likely a factor. (The Deccan Traps flood basalt eruption is another, unmentioned in the text.)

17. What could have caused the extinction at the end of the Paleozoic?

ANS: An immense eruption of basalt and greenhouse gases took place at this time, forming the Siberian traps.

18. What continents formed as a result of the breakup of Pangaea?

ANS: North America, South America, Africa, Eurasia, Australia, Antarctica, and the microcontinents Madagascar and New Zealand are examples (answers may vary).

19. What caused the Himalayas and Alps to form?

ANS: The Alps arose from Europe's collision with Africa; the Himalayas arose from

India's collision with Asia.

20. What major tectonic provinces formed in the western United States during the Cenozoic?

ANS: The Basin and Range Province and the Snake River Plain Province are two important examples.

21. What major climatic and biologic events happened during the Pleistocene?

ANS: Much of the northern hemisphere was in the grip of a glaciation (ice age), and numerous extinctions of large animals occurred toward the end of the glaciation.

On Further Thought

22. Geologists have concluded that 80% to 90% of Earth's continental crust had formed by 2.5 Ga. But if you look at a geological map of the world, you find that only about 10% of Earth's continental crustal surface is labeled "Precambrian." Why?

ANS: In most places, the Precambrian is overlain by younger rocks and is not visible at the surface.

Chapter 12

Riches in Rock: Energy and Mineral Resources

Learning Objectives

1. Students should know the major energy resources found within rocks and sediment (oil, natural gas, coal, and uranium), how they form, how they are recovered, and how they are utilized for our energy needs.
2. Oil and gas are commonly produced together in the heat of burial as a result of the alteration of black shale, which is rich in organic matter. The organic matter within the shale is derived from the remains of plankton, which settled to the bottom of the water in an oxygen-poor environment (retarding bacterial decay). Gas (a short-chain hydrocarbon) is less dense and more volatile than oil (which is composed of longer carbon chains) and forms at somewhat higher temperatures (and thus is found in the absence of oil at greater depths and temperatures).
3. A recoverable quantity of oil requires that an organic-rich source rock be subjected to temperatures within the oil window. Additionally, at least two other bodies of rock must be present in conventional oil recovery. Directly above the source rock, a highly permeable reservoir rock must reside. Oil from the source will migrate upward through the pores of the reservoir rock because it is less dense than the water that is also found within the pores. An impermeable seal rock must lie above the reservoir rock to keep the oil from escaping to the surface. Further, economically feasible bodies of oil require a geometric configuration that allows oil to pool in a restricted space, bounded by seal rock so that it cannot reach the surface. Together, this configuration and the seal rock form what is termed an *oil trap*.
4. Oil and gas production in the United States have recently increased substantially due to hydrofracking, in which water, sand, and chemicals are injected into organic-rich shale source rocks, opening and propagating fractures within them. This allows the source rock to serve as a reservoir, with oil and/or gas extracted directly from source

rocks. Hydrofracking has been an economic boon for energy companies and has helped reduce our need for oil imports, but it has been implicated in groundwater contamination and in triggering numerous small earthquakes.

5. Coal is the altered remains of ancient plants that lived in swampy environments. The acidic water of swamps retards decay, allowing wood and leafy matter to accumulate and be compressed to form peat. Later, deep burial of peat at great temperatures burns off volatile materials to leave behind greater amounts of organic carbon. Grades of coal are ranked, on the basis of their carbon content, from lignite (low rank) through bituminous to anthracite (high rank), which has the greatest proportion of carbon and produces the greatest amount of heat per unit volume of material burned. Problems associated with coal mining include the incidence of acid mine drainage, because most coal contains sulfur and is found in association with pyrite (iron sulfide). Burning of fossil fuels contributes carbon dioxide to the atmosphere, adding to current global climatic warming, as well as sulfur dioxide, which contributes to the problem of acid rain.
6. Most mined uranium has been concentrated by hot, circulating groundwater in veins within granite plutons. The isotope used in fission reactors is relatively sparse within naturally occurring ore (uranium oxide) and must be enriched (concentrated). Fission reactors provide abundant energy, but the storage of radioactive waste is a major environmental concern.
7. The world's supply of oil, a nonrenewable fossil fuel, is finite, and at current rates of use will last for only a couple of centuries under even the most optimistic scenarios. Alternative sources of energy (geothermal, wind, solar, and, in some scenarios, nuclear energy and perhaps even coal) will see expanded use in the not-too-distant future.
8. Students should know a few important precious metal (gold, silver), base metal (copper, lead, iron), and nonmetallic mineral resources (dimension stone, quartz sand) and their uses. Strategic minerals are important and useful minerals (including ores of many metals) that are found in countries that are currently, or may become, unreliable trading partners with our nation.
9. Metals in nature are most commonly combined with nonmetals to form ore minerals,

which must be smelted to separate metal from nonmetal.

10. Students should know the seven types of deposits that concentrate ore minerals (magmatic, hydrothermal, secondary-enrichment, Mississippi Valley-type ([MVT),], sedimentary, residual mineral, and placer) and how each forms.

Summary from the Text

Energy resources come in a variety of forms: energy directly from the Sun; energy from tides, flowing water, or wind; energy from chemical reactions; energy from nuclear fission; and energy from Earth's internal heat.

Oil and gas are hydrocarbons formed from the organic remains of plankton, which settle out and become incorporated in black organic shale. Chemical reactions at elevated temperatures convert the organic matter to kerogen and then to oil.

To form a conventional oil reserve, oil must migrate from a source rock into a reservoir rock. The subsurface configuration of strata that holds oil is called an oil trap.

Substantial volumes of hydrocarbons also exist in nonconventional reserves. These include shale gas and shale oil, tar sand, and oil shale. Extraction of unconventional reserves has increased dramatically in recent years due to the development of directional drilling and hydrofracturing.

For coal to form, abundant plant debris must be deposited in an oxygen-poor environment. Compaction changes the debris to peat that, when buried deeply and heated, transforms into coal.

Geologists distinguish among three ranks of coal, based on the amount of carbon the coal contains. Coal occurs in beds, and can be mined by either strip mining or underground mining.

Nuclear power plants generate energy by using the heat released from the fission of uranium.

Nuclear reactors must be carefully controlled to avoid overheating or meltdown. The disposal of radioactive nuclear waste can create environmental challenges.

Geothermal energy uses Earth's internal heat to transform groundwater into steam

that drives turbines; hydroelectric power uses the potential energy of water; and solar energy uses solar cells to convert sunlight to electricity.

We now live in the Oil Age, but oil supplies may last only for another century, and the production and use of energy resources have many environmental consequences.

Industrial societies use many types of minerals, all of which must be extracted from the upper crust.

Metals come from ore. An ore is a rock containing native metals or ore minerals in sufficient quantities to be worth mining.

Magmatic ore deposits form when ore minerals grow during solidification of melt. In hydrothermal deposits, ore minerals precipitate from hot-water solutions. Secondary-enrichment deposits and MVT deposits precipitate from groundwater. Sedimentary deposits settle out of water, residual mineral deposits are the result of soil formation, and placer deposits develop when metal grains accumulate in sediment.

Nonmetallic resources include dimension stone, crushed stone, clay, sand, and many other materials. A large proportion of materials in your home have a geological ancestry.

Mineral resources are nonrenewable. Many, including strategic minerals, are now or may soon be in short supply.

Video and Animation Files

HYDROFRACKING

Number: 12.1

Length: 3 minutes, 6 seconds

Summary: The video uses animation to illustrate how the techniques of horizontal drilling and hydrofracturing (“fracking”) are used to recover natural gas from shale. A flexible drill bit assembly is guided into a shale body and excavates a borehole within the shale. The borehole is sealed laterally by strong, inflatable stoppers. Water, sand, and chemicals are injected at high pressure to expand microfractures within the shale and open new fractures. Gas then migrates to the borehole and is extracted.

Classroom Use: This video is strongly recommended for classroom and online use because the subject matter is both topical and difficult for new students to grasp. Further development and discussion could focus on the nature and purpose of specific injected chemicals (briefly flashed on the screen). Discussion would also likely address potential negative environmental consequences of fracking and the recent legal response to these concerns made by state and local governments.

Review and Discussion Questions:

1. Why is sand injected into the shale beds along with fracking fluid?
2. Is natural gas more likely to escape from a fracking site laterally or vertically?

FORMATION OF AN ORE DEPOSIT

Number: 12.2

Length: 3 minutes, 6 seconds

Summary: The video defines ore minerals and ore deposits and explains how metals can come to be concentrated in economically useful deposits, using animation and photography of mining activity and ore minerals themselves.

Classroom Use: This video could be shown to reinforce understanding of the geological circumstances necessary to produce an economically viable deposit of ore and the smelting techniques necessary to extract metals from ore minerals. Further discussion might focus on historical use of metals, including reasons why the Copper Age necessarily preceded the Bronze Age, which in turn preceded the Iron Age.

Review and Discussion Questions:

1. What is a placer deposit, and how have these deposits been historically exploited?
2. What influence have placer deposits had on American history?

MINERALS

Number: Animation 12.3

Summary: This animation explains the many criteria that must be met in order for a substance to be considered a mineral. Minerals are naturally occurring, generally inorganic solids with a fixed crystalline structure and a definable chemical composition that form through geologic processes. Each part of the definition is broken down for easier memorization. Students should be able to apply this definition to distinguish minerals from nonminerals.

Classroom Use: This animation could be shown in class as a visual aid when the instructor is introducing the definition of a mineral.

Review and Discussion Questions:

1. Both glass and quartz sand are primarily made of silicon dioxide, SiO_2 . Why is quartz considered a mineral, but glass is not?
2. Could glacial ice be considered a mineral? Think carefully through all parts of the definition.

Answers to Review Questions

1. What are the fundamental sources of energy?

ANS: According to the text, the seven fundamental sources are solar energy, gravitational energy, energy from the interaction of solar and gravitational energy (wind and water energy), energy from photosynthesis, energy from fossil fuels, energy from inorganic chemical reactions, energy from nuclear fission, and energy from Earth's internal heat.

2. What is the source of the organic material in oil and how is it transformed into oil?

ANS: Ancient plankton, including algae, are the source of organic matter in oil. When these plankton die and are buried in an oxygen-starved setting, they become incorporated into organic-rich mud. With further burial, the sediment forms shale and the organic matter may be transformed by heat into first kerogen and then hydrocarbons (oil and gas).

3. What is the oil window, and what happens to oil at temperatures higher than the oil window?

ANS: The oil window is the range of temperatures in which oil forms from organic matter. At temperatures above the oil window, oil is converted to gas.

4. Explain how a conventional oil or gas reserve forms.

ANS: When organic matter derived from the remains of plankton are heated at depth, oil and/or gas is formed. Oil and gas are both less dense than water (which coexists with the oil in subterranean pores within rocks and sediments), so they will migrate upward to the surface. In order to produce an oil or gas reserve field that can be commercially exploited, a porous and permeable rock (termed a *reservoir*) such as sandstone must reside above the source rock (oil- or gas-producing shale). The shales that produce oil or gas do not conduct liquids rapidly, hence the need for a separate reservoir into which the hydrocarbons will flow. In order to keep the hydrocarbons from escaping to the surface, a trap is necessary. A trap consists of an impermeable seal rock (such as shale) to block the flow of hydrocarbons, along with a geometric configuration (such as an anticline, salt dome, fault, or stratigraphic pinch-out) that causes the hydrocarbons to migrate into a relatively confined space.

5. What are unconventional hydrocarbon reserves, and how can hydrocarbons be extracted from them?

ANS: Tar sand is sand or sandstone filled with viscous, long-chain hydrocarbons. Tar sands are mined from the surface and heated to separate hydrocarbons from sand. Oil shale is shale rich in organic matter that has been insufficiently heated (with regard to oil formation); its organic content is primarily kerogen. Oil shale can be heated to produce oil.

Shale oil and shale gas are hydrocarbons trapped in impermeable source rocks. Hydrofracking involves the injection of water, sand, and chemicals into these source rocks to open fractures, allowing hydrocarbon extraction.

6. Where is most of the world's oil found? At present rates of consumption, how long will oil supplies last?

ANS: The majority of oil is found in the Persian Gulf region of the Middle East. It might last for a century or perhaps as long as two centuries.

7. How is coal formed, and in what class of rocks is coal considered to be?

ANS: Coal represents the remains of plants that lived and died in moist or swampy environments in which there was little bacterial decay. As trees and other plants died, their organic matter accumulated, and burial compaction eliminated some of the volatile materials, forming peat from the remains. With additional heat and pressure derived from later, deeper burial under layers of sediment and rock, lignite, bituminous, and occasionally anthracite coal were produced. Each successively higher rank of coal is richer in carbon. Coal is sedimentary rock.

8. What determines the rank of coal?

ANS: Higher ranks of coal contain more carbon and fewer volatiles than lower ranks. Heat and pressure during burial burn off volatile matter, which is most abundant in peat and least abundant in anthracite.

9. How is electricity generated by a nuclear power plant?

ANS: A neutron is struck against an unstable uranium isotope (^{235}U) within uranium oxide inside a fuel rod, inducing fission of the uranium atom, which emits three additional neutrons that then strike other ^{235}U atoms, which release yet more neutrons, forming a chain reaction. The reaction is controlled by keeping the quantity of uranium within the fuel rods below a critical mass and by surrounding the rods with cool, circulating water and inserting control rods that absorb neutrons as needed. Heat from the fission reaction is used to boil water to generate steam that drives a turbine, which in turn drives a generator (spinning magnet), producing a flow of electricity.

10. Where do uranium deposits form in the Earth's crust?

ANS: Uranium is incorporated into magmas, which rise up through the crust, cooling to form granite plutons. Hot groundwater dissolves the uranium scattered throughout the plutons. The uranium then precipitates in higher concentrations in veins within the plutons.

11. What are some of the drawbacks of nuclear energy?

ANS: The primary drawbacks of nuclear energy are the possibility of meltdown (fuel becoming too hot and melting through some of the architecture of the power plant), as occurred at Chernobyl in Ukraine in 1986 and Fukushima in Japan in 2011, and the difficulties associated with nuclear waste disposal. Waste must be disposed of in a way that will ensure that radioactive isotopes will not be carried by surrounding groundwater into aquifers.

12. Define geothermal energy, and describe the ways that it can be used. Can geothermal energy be used to generate energy economically everywhere?

ANS: Geothermal energy is the internal heat of the Earth. In places of high heat flow, rising steam or hot water can be withdrawn and used to generate electricity. Hot water can also be piped directly into homes, conserving electricity or other sources of energy that otherwise might be used to heat water. There are few places on Earth where hot groundwater rises naturally to sufficiently shallow depths so that its heat can be readily exploited.

13. What is the difference between renewable and nonrenewable resources?

ANS: Renewable resources are those that are naturally replenished at sufficient rates to offset current use of the resource. Nonrenewable resources are used more rapidly than they are replenished and thus have a finite lifetime.

14. What is the likely future of hydrocarbon production and use in the 21st century?

ANS: Conventional oil reserves will become drastically depleted by the end of the century at current rates of use. As oil becomes more scarce in the future, its price will undoubtedly go up; we will see more unconventional production of oil, and alternative sources of energy will have to be exploited. We have greater reserves of natural gas globally and nationally and will likely be using more of this fuel in the future unless the use of nuclear and renewable sources is greatly expanded in the next few decades.

15. Why don't we use an average granite as a source for metals?

ANS: The metals are too scarce within the rock and too diffusely spread among its

constituent minerals for an average granite to be an economically viable source of metals.

16. Describe various kinds of economic mineral deposits and how they form.

ANS: Magmatic deposits form when ore minerals grow during the solidification of a melt; an example is a deposit of sulfide ore minerals at the base of a pluton. In hydrothermal deposits, ore minerals precipitate from hot-water solutions; gold flakes among quartz within veins of granite are an example. Secondary-enrichment deposits and MVT deposits precipitate from groundwater; they include the lead-rich deposits along the Mississippi River valley for which MVTs are named. Sedimentary deposits settle out of water; the prime example is the abundant banded iron formations found in outcrops of Proterozoic rock worldwide. Residual mineral deposits are the result of soil formation, typified by the bauxite ores of aluminum derived from ancient, highly weathered tropical soils. Placer deposits develop when metal grains accumulate in sediment, as when eroded gold nuggets and flakes become trapped within streambeds.

17. What procedures are used to locate and mine mineral resources today?

ANS: In settings deemed likely sites for ore deposits, the local strength of Earth's gravitational and magnetic fields is assessed (ores are relatively dense and have high concentrations of magnetic minerals as compared to silicate rock). Rocks, soils, and plants are chemically analyzed to determine if unusually high metal concentrations are present. If a site looks promising for subsurface ore, geologists may drill test holes to sample the rock below. If the mineral resource is close to the surface, explosives may be used to produce an open pit mine. Deeply buried minerals require the construction of an underground mine through boring.

18. How is stone cut from a quarry?

ANS: Stone is cut from a quarry by hammering with wedges, cutting with a braided wireline saw, blasting the rock with jets of water, or heating the rock with a thermal lance.

19. What are the ingredients of concrete and brick, and where do they come from?

ANS: Concrete consists of gravel, sand, and cement. Gravel and sand are quarried;

cement is a mixture of lime, silica, iron oxide, and aluminum oxide, all of which are sourced from rocks, primarily limestone (cement is two-thirds lime). Bricks are made from clay minerals, which are abundant in rocks and sediments near the surface because they form through the weathering of abundant silicate minerals.

20. Will the supply of mineral resources run out? Can a country survive without importing minerals?

ANS: Mineral resources are nonrenewable, and thus they have finite lifetimes. Every nation must import at least some of the mineral resources they need.

21. What are some environmental hazards of mining?

ANS: Mining creates holes in the surface with associated tailing piles; mine waste may react with water to produce acid runoff. The chemical treatment of ore at the mine site and at smelters can lead to air pollution and water pollution.

22. Name materials in your home that come from mineral resources.

ANS: Answers will vary but may include metal pipes, pencil “lead,” coins and gold jewelry, bricks, and so on.

On Further Thought

23. Do you think it would make sense for an energy company to drill for oil in a locality where beds of anthracite occur in the stratigraphic sequence? Explain your answer.

ANS: It is not sensible to expect to find anthracite and oil to co-occur. Anthracite forms at temperatures above 200°C, which is hotter than the oil window. Any oil that had formed would have been cooked off.

24. An ore deposit at a location in Arizona has the following characteristics: One portion of the ore deposit is an intrusive igneous rock in which tiny grains of copper sulfide minerals are dispersed among the other minerals of the rock. Another nearby portion of the ore deposit consists of limestone in which malachite fills cavities and pores in the rock. What types of ores are these? Describe the geologic history that led to the

formation of these deposits.

ANS: The first portion is a disseminated hydrothermal deposit. Hot groundwater dissolved copper and sulfide and redeposited it at scattered sites within the intrusion. The second portion represents a secondary-enrichment deposit. Copper was likely dissolved from the disseminated deposit by hot groundwater and transported to the limestone, where it combined with dissolved carbonate from the limestone to form malachite in the veins and pores.

INTERLUDE F

An Introduction to Landscapes and the Hydrologic Cycle

Learning Objectives

1. Students should be familiar with what a landscape is and what questions geologists ask about landscapes.
2. Students should know the difference between uplift and subsidence and the forces that drive them.
3. Students should know the contrasts between internal and external energy in the Earth System.
4. They should be familiar with how erosional and depositional landscapes differ.
5. They should know the reservoirs and exchange processes of the hydrologic cycle.

Summary of the Text

The character and shape of the land surface in a region is a landscape. Individual shapes are landforms. Topographic maps, shaded-relief maps, and DEMs (digital elevation models) can portray the shape of landscapes.

Land can undergo uplift or subsidence, to yield relief. Rock, as well as debris formed by weathering, eventually undergoes downslope movement and collects in lower areas.

The energy driving landscape evolution comes from three sources: Earth's internal

energy, gravitational energy, and energy radiating from the Sun.

The nature of a landscape depends on climate, time, relief, slope angles, elevation, the activity of organisms, substrate composition, and the rate of tectonic movement.

Water is the dominant agent of erosion on the Earth. Driven by gravity and by energy from the Sun, water moves among various reservoirs (such as the ocean, the atmosphere, the land surface, the subsurface, and life) during the hydrologic cycle. Landscapes on other planets differ markedly from those on Earth. Researchers are working hard to understand how water played a role in forming Martian landscapes, and if water remains on the planet today.

Answers to Review Questions

1. What is the difference between uplift and subsidence?

ANS: Uplift is raising of the land surface; subsidence is sinking of the land surface.

2. Why do landscapes on the Earth change over geologic time, while they remain static on the Moon?

ANS: Earth has plate tectonics, an active hydrologic cycle, and a windy atmosphere; the Moon lacks these.

3. What is topography, and how can we portray it on a sheet of paper?

ANS: Topography is variability in the elevation of the land surface. We can portray it on a topographic map with contour lines connecting points of equal elevation, or, less precisely, through shading.

4. What are the principal agents of erosion on Earth?

ANS: The principal agents of erosion are wind, running water, and ice.

5. What factors affect the character of erosional or depositional landforms that develop in a region?

ANS: These landforms are affected by agents of erosion and transportation, relief,

climate, composition of the substrate, organism activity, and the passage of time.

6. Explain the steps in the hydrologic cycle.

ANS: Evaporation occurs when solar radiation converts liquid water (primarily in the ocean) into atmospheric water vapor. Condensation of atmospheric water vapor forms droplets of liquid water that may precipitate (rain down) to the surface (alternatively, ice crystals may form in clouds and may fall as snow). Precipitation that falls on the land may run off into a surface body of water, infiltrate into the groundwater system, or evapotranspire. Groundwater commonly flows into surface streams and lakes. Surficial streams typically transport water to lakes or the ocean.

7. How do landscapes of other planets differ from those of Earth?

ANS: Although they do show evidence of ancient plume-based volcanism, Mars and Venus do not have a system of plate tectonics. They thus lack mountain belts and volcanic arcs, and their primary features consist of impact craters, extinct volcanoes, and ancient basalt flows. Mars does produce winds that shift sediment into dunes and ancient stream channels indicating a wetter past.

CHAPTER 13

Unsafe Ground: Landslides and Other Mass Movements

Learning Objectives

1. Students should be able to differentiate the major types of subaerial (creep, solifluction, slump, mudflow, debris flow, lahar, rockslide, debris slide, avalanche, rockfall, debris fall) and submarine (slump, debris flow, and turbidity current) mass movements on the basis of coherence, geometry, velocity, and other physical characteristics. Although the term “landslide” is used colloquially for any sudden, subaerial mass movement, geologists reserve this term exclusively for rockslides and debris slides.
2. Students should be aware of the major factors that favor mass movement: steep slopes, addition of mass upslope, excavation downslope, saturation of pore space, barren hillsides, and earthquakes.

Summary from the Text

Rock or regolith on unstable slopes has the potential to move downslope under the influence of gravity. This process, called mass movement, or mass wasting, plays an important role in the erosion of mountains.

Slow mass movement, caused by the freezing and thawing of regolith, is called

creep. In places where slopes are underlain with permafrost, solifluction causes a melted layer of regolith to flow down slopes. During slumping, a semicoherent mass of material moves down a spoon-shaped failure surface. Mudflows and debris flows occur where regolith has become saturated with water and moves downslope as a slurry.

Rockslides and debris slides move very rapidly down a slope; the rock or debris breaks apart and tumbles. In a debris fall or rockfall, the material free falls down a vertical cliff. During avalanches, snow or debris mixes with air and moves downslope as a turbulent cloud.

Large mass movements can take place on underwater slopes. Some may generate tsunamis.

Intact, fresh rock is too strong to undergo mass movement. Thus, for mass movement to be possible, rock must be weakened by fracturing or weathering.

Unstable slopes start to move when the downslope force exceeds the resistance force that holds material in place. The steepest angle at which a slope of unconsolidated material can remain without collapsing is the angle of repose.

Downslope movement can be triggered by shocks and vibrations, a change in the steepness of a slope, removal of support from the base of the slope, changes in the strength of a slope, deforestation, weathering, or heavy rain.

Geologists can sometimes detect unstable ground before it begins to move, and they produce landslide-potential maps to identify areas susceptible to mass movement.

Engineers can help prevent mass movements by using a variety of techniques to stabilize slopes.

Video and Animation Files

DEVELOPING AND DETECTING SLUMPS

Number: Video 13.1

Length: 2 minutes, 21 seconds

Summary: This video defines slumps, details the anatomy of a slump, and shows how slumps propagate through time. Students are shown how small-scale slumping can be detected visually and with specialized equipment.

Classroom Use: This video could be shown in lecture or serve as a portion of a homework assignment.

Review and Discussion Questions:

1. How can small slumping movements be detected, even if no scarps are evident?
2. Why is it important that we be able to detect such small-scale movements?

Answers to Review Questions

1. What factors do geologists use to distinguish the various types of mass movements?

ANS: Mass movements are distinguished on the basis of the material that is moving, its rate of movement, the physical character of the moving mass (rigidity, viscosity), and the environment through which it is moving (subaerial or submarine).

2. Explain how soil creep operates.

ANS: Soil creep is a gradual downhill movement of regolith that is most often caused by the expansion and contraction of regolith in response to freezing and thawing. In winter, frozen regolith expands outward (perpendicular to the slope surface) as ice takes up more volume than liquid water. When warmer conditions return, the ice within the regolith melts and gravity pulls the now loosened soil slightly downslope.

3. Identify the key differences between a slump, a debris flow, a lahar, an avalanche, a rockslide and a rockfall.

ANS: A slump is an event in which sedimentary material breaks off an elevated slope and slides downward as a coherent mass along a curved surface. Debris flows are slurries of water and larger sediment grains that flow downhill more chaotically. Lahars are wet mudflows mixed with volcanic ash. An avalanche is a mass of turbulent air mixed with

snow or mineral debris. A rockslide involves rocky material moving down a nonvertical slope. A rockfall is a vertical drop of boulders or other rock fragments from a fracturing cliff.

4. Why is intact bedrock stronger than fractured bedrock? Why is it stronger than regolith?

ANS: Fractured bedrock is more readily pulled apart than bedrock that is solidly lithified throughout. Regolith is unlithified, and it is thus relatively easy for the force of gravity or vibrations to displace grains from one another.

5. Explain the difference between a stable and an unstable slope. What features are likely to serve as failure surfaces?

ANS: A stable slope is one that is unlikely to experience rapid mass movement in the near future; an unstable slope is one that is at risk for mass movements. Fractures, wet clays, and any weak layers of rock or sediment are likely to form failure surfaces.

6. Discuss the variety of phenomena that can cause a stable slope to become so unstable that it fails.

ANS: A stable slope can be destabilized by vibrations (as from seismic waves), an increase in slope, an increase in the load at the top of the slope, excavation of the hillside downslope, removal of vegetation, rise or fall of the water table, and saturation due to intense rainfall or snowmelt. Any of these may trigger mass movement downslope.

7. Discuss the role of vegetation in slope stability. Why can fires and deforestation lead to slope failure?

ANS: The branching nature of plant roots anchors in the sediment, reducing erosion and the chance of mass wasting. Fire and deforestation strip slopes of their vegetation and leave the regolith more vulnerable to relative motion, sliding, and slumping.

8. What factors do geologists take into account when producing a landslide-potential map, and how can geologists detect the beginning of mass movement in an area?

ANS: Locally, geologists assess the risk of mass movement by looking for sedimentary evidence of past events such as head scarps, tilted trees and bends within tree trunks.

They will take precise and accurate surveys of the area, and look for cracks in roads or pipes, which may indicate the coming onset of mass movement. Over broader regions, geologists assess slope steepness, strength of the substrate, vegetation, water saturation, and seismic risk.

9. What steps can people take to avoid landslide disasters?

ANS: Apart from relocating to flatter terrain, people can avoid landslides by helping to stabilize slopes via planting vegetation, reducing slope steepness, preventing undercutting by streams or crashing waves, and developing structures (such as meshwork) that artificially stabilize slopes.

On Further Thought

10. Imagine that you have been asked by a nongovernmental organization (NGO) to determine whether it makes sense to build a dam in a steep-sided, east-west-trending valley in a small central Asian nation. The local government has lobbied for the dam because the climate of the country has gradually been getting drier, and the farms of the area are running out of water. The NGO is considering making a loan to finance construction of the dam, a process that would employ hundreds of now-jobless people. Initial investigation shows that the rock of the valley floor consists of schist containing a strong foliation that dips toward the valley and is parallel to the valley wall. Outcrop studies reveal that abundant fractures occur in the schist along the valley floor; the surfaces of most fractures are coated with slickensides. Moderate earthquakes have rattled the region. How would you advise the NGO, and why? Explain the hazards and what might happen if the reservoir were filled.

ANS: The NGO should not fund this project. There are significant hazards associated with earthquakes and rockslides in this area. If the reservoir were filled, there would be a substantial chance of repeating the disaster that struck Vaiont Dam in Italy. The dip

direction of the foliation planes would likely lead to rockslide rubble splashing down into the reservoir. A large slide could displace water over the dam and destroy any dwellings downstream.

CHAPTER 14

Streams and Running Water

Learning Objectives

1. Students should be familiar with stream channels and be able to label a diagram of a stream channel and adjacent floodplain, locating point bars, cut banks, oxbow lakes, meander necks, and the thalweg. They should know how meanders form and migrate. They should understand the process of cutoff route formation causing meanders to become isolated oxbow lakes. Relationships among erosion, deposition, and current velocity should be understood, as well as geometrical differences between braided and meandering streams; they should understand how streams become braided.
2. Students should be able to identify the major drainage networks (dendritic, radial, rectangular, trellis, and parallel) and understand the conditions that give rise to each.
3. Rivers carry a sediment load in three components: dissolved ions, suspended grains, and bed load (larger grains that tumble along the stream bottom). Stream competence refers to the largest particle size a stream can carry; the total volume of sediment carried by a stream is its capacity.
4. The total volume of water passing by a fixed point in one second is its discharge; the Amazon has by far the greatest discharge of any river on Earth. In moist climates, discharge increases downstream with the addition of tributaries and rainfall; however, in arid climates, discharge may decrease downstream because of evaporation and infiltration (and human use in agriculture).
5. The farthest that a stream can downcut into underlying sediment or rock is termed the base level. Sea level is the ultimate base level, but resistant rock and lakes may locally raise the base level substantially.
6. Streams are important agents of erosion, carving out steep-walled canyons and more

gently sloped valleys. Water itself is not especially abrasive, but the sediment that it carries is highly so.

7. When rivers meet the sea (or a lake), their velocity and competence decrease, and they deposit sediments, which form wedge-shaped bodies termed deltas. The shape of ocean deltas is variable.
8. Floods may be seasonal or episodic; they may arise suddenly or gradually (in the floodplains of major river systems). Large, catastrophic floods are less common than small floods, and so floods of various magnitudes have been assigned estimated recurrence intervals (average waiting times between floods of a specific magnitude over very long time periods). For example, a flood with a 100-year recurrence interval has a 1% chance of occurring within a given year.
9. Streams are not purely natural environments. They have been influenced by pollution, dam construction, overuse of water, urbanization, and agriculture.

Summary from the Text

Streams are bodies of water that flow down channels and drain the land surface. They grow by downcutting and headward erosion. Streams carry water out of a drainage basin; a drainage divide separates two adjacent basins. Drainage networks consist of many tributaries that flow into a trunk stream.

Permanent streams exist where the water table lies above the bed of the channel or when large amounts of water enter the channel from upstream. Where the water table lies below the channel bed, streams are ephemeral.

The discharge of a stream is the total volume of water passing a point along the bank in a second. Most streams are turbulent, meaning that their water swirls in complex patterns.

Streams erode the landscape by scouring, lifting, abrading, and dissolving. The resulting sediment provides dissolved loads, suspended loads, and bed loads. The total

quantity of sediment carried by a stream is its capacity. Capacity differs from competence, the maximum particle size a stream can carry. When stream water slows, it deposits alluvium.

The longitudinal profile of a stream is concave up, meaning that a stream has a steeper gradient at its headwaters than near its mouth. The depth of downcutting is limited by the base level.

Streams cut valleys or canyons, depending on the rate of downcutting relative to the rate at which the slopes on either side of the stream undergo mass wasting. Where a stream flows down steep gradients and has a bed littered with large rocks, rapids develop, and where a stream plunges off a vertical face, a waterfall forms.

A meandering stream wanders back and forth across a floodplain. It erodes its outer bank and builds out sediment into a point bar on the inner bank. Eventually, a meander may be cut off and turn into an oxbow lake. Natural levees form on either side of the river channel.

Braided streams form where a stream that carried abundant sediment during floods slow, so the flowing water divides among many entwined channels.

Where streams or rivers flow into standing water, they deposit deltas. Different deltas have different shapes.

Fluvial erosion can bevel landscapes to a nearly flat plain. If the base level drops or the land surface rises, stream rejuvenation takes place. The headward erosion of one stream may capture the flow of another.

If an increase in rainfall or spring melting causes more water to enter a stream than the channel can hold, a flood results. Some floods are seasonal and submerge floodplains or delta plains. Flash floods happen very rapidly. Officials try to prevent floods by building reservoirs and levees.

Rivers are becoming a vanishing resource because of pollution, damming, and overuse of water.

Video and Animation Files

RIVER MEANDERS

Number: Video 14.1

Length: 3 minutes, 42 seconds

Summary: This video shows and labels the major features of meandering streams and their floodplains before using animation to show how these systems evolve over time through cutbank erosion, point-bar deposition, and cutoff route development.

Classroom Use: This video features eye-catching animation that would be a good addition to lecture.

Review and Discussion Questions:

1. We see a meandering stream. If we were to revisit this stream 50 years into the future, how and why might it look different?
2. Why do we see erosion on the outer banks of meanders and deposition on the inner banks?

Answers to Review Questions

1. What role do streams serve during the hydrologic cycle?

ANS: Streams conduct water from elevated regions of the continent down to the sea.

2. Describe the five different types of drainage networks. What factors are responsible for the formation of each?

ANS: Dendritic drainage networks look similar to a branching tree and occur when streams cut through uniform material with a relatively constant slope. Radial drainage resembles the spokes of a wheel and occurs when streams drain a central, conical mountain. Rectangular drainage networks consist of streams that make right-angle turns, with multiple streams commonly traveling in parallel; they occur in areas where

perpendicular sets of joints present paths of least resistance to flow. Trellis drainage occurs in valley and ridge topography, with major tributaries inhabiting the valleys and traveling parallel to the ridges, and minor tributaries draining the hillsides transversely before their flows join the valley streams. Parallel networks look like parallel lines; they form when streams flow down uniform, steep slopes.

3. Distinguish between permanent and ephemeral streams, and explain why the difference exists.

ANS: Permanent streams feature a continuous discharge of flowing water. Ephemeral streams are dry except after heavy rainfall or snowmelt. In moist climates, streams are typically permanent and gaining because the water table in nearby sediment is above the level of the stream floor; in dry climates, the water table sinks lower, and streams may be permanent but losing or may even be ephemeral

4. Why does the velocity of a stream vary with location, in a given reach of the stream?

ANS: Friction with sediment lining the channel tends to slow the velocity of flow along the sides and bottom. Fastest flow tends to be near the center of the surface of the stream. Turbulence in flow also locally reduces velocity.

5. Describe how streams erode the Earth's surface.

ANS: Running water can break and lift particles off the stream bottom and also use these particles as abrasive tools to scratch away additional sediment. Water can dissolve some minerals within the streambed.

6. What are three components of sediment load in a stream, and how do competence and capacity differ?

ANS: Dissolved load (ions), suspended load (small, floating grains), and bedload (larger grains moving along the stream bottom) are three components of sediment.

Competence is a measure of stream energy and refers to the largest particle size that a stream can carry; capacity is the volume of sediment that a stream can carry.

7. Describe how the character of a drainage network changes along its length.

ANS: Drainage networks near their source consist of many small tributary channels.

With increasing distance from the source, these channels merge to form a single main channel. Near the delta of a river, the main channel becomes choked with sediment and is broken into many distributary channels that conduct water and sediment into the ocean.

8. What is the difference between a local base level and the ultimate base level of a stream?

ANS: Base level is the lowest level to which a stream can downcut. Generally, the ultimate base level is sea level, but many factors may cause a stream to be subject to a local base level that is higher in elevation. This local base level may arise due to the presence of a natural lake or artificial reservoir, resistant rock layers (forming waterfalls), or large rivers, into which tributaries flow.

9. Why do some streams become braided?

ANS: Braids form when streams are choked with relatively coarse sediment; they readily spill through their banks to form numerous, subparallel braided channel strands. One cause of braiding is variable discharge; large sediment volumes are transported during flood stage, but they cannot be accommodated during normal flow.

10. Describe how meanders form, develop, are cut off, and then are abandoned. What is a floodplain?

ANS: All streams will waver from a straight line at some point. When they do, the outer bend of a turn has relatively fast flow (becoming a site of erosion), as compared to the inner bend (which becomes a site of point-bar deposition). Meanders are thus a system of positive feedback, as subsequent erosion and deposition push the stream channel farther and farther off a straight course. However, surrounding cut banks can encroach upon each other over time, and streams can change course due to earthquakes or floods. These changes yield a shorter, straighter segment that draws flow away from the meander and isolates it, forming an oxbow lake. Over time, oxbow lakes will either dry up (arid climate) or infill with flood sediment (wet climate) to form abandoned meanders.

A floodplain is a broad, flat region surrounding a stream channel. As the name suggests, the floodplain becomes inundated when its stream enters flood stage.

11. Describe how deltas grow and develop. How do they differ from alluvial fans?

ANS: Rivers carrying sediment meet an ocean or large lake in which the water is stagnant. Flow velocity is slowed dramatically at the interface, and the stream loses its competence as its sediment load falls out to form a wedge. Alluvial fans form at the foot of a mountain range, often from the deposits of ephemeral streams. The sediments of an alluvial fan are generally coarser than those of a delta, but each commonly displays a fanlike shape.

12. How does a stream-eroded landscape evolve over time?

ANS: Early on, stream erosion produces steep, V-shaped valleys in an elevated landscape. With time, streams cease downcutting, producing side-to-side erosion and flattening the elevated landscape to form a broad, low-lying floodplain. Eventually, the floodplain will widen and form a very broad plane just above base level, called a *peneplain*.

13. What is stream piracy? What causes a drainage reversal?

ANS: Stream piracy occurs when two channels come to intersect, with the stream designated as the pirate stealing flow from the stream, designated as the victim. Drainage reversal is caused by the uplift of new mountain ranges that disallow a river to continue in its previous course and cause it to flow in the opposite direction.

14. How are superposed and antecedent drainage similar, and how do they differ?

ANS: Superposed and antecedent drainage are similar in that they cut across an existing mountain range; they differ in their times of formation. Antecedent drainage predates local uplift. Superposed drainage postdates the uplift and cuts down into the developing mountain range.

15. What is the difference between a seasonal flood and a flash flood?

ANS: Seasonal floods are those brought on by seasonally heavy monsoon rains or spring snowmelt. These floods are predictable and may take time to develop, so that warnings can be announced. Flash floods occur due to a sudden downpour, leading to rapidly rising waters that may take lives without warning.

16. How do people try to protect regions from flood damage?

ANS: People try to protect regions from floods by building levees, sewer systems, retention ponds, and dams, and by restoring natural wetlands along the banks of rivers.

17. What is the recurrence interval of a flood, and how is it related to the annual probability?

ANS: The recurrence interval of a flood is the average waiting time between successive floods of a given magnitude (or greater). It is equal to the multiplicative inverse of the annual probability of the flood.

18. How have humans abused and overused the resource of running water?

ANS: Humans have abused the water in streams through pollution, overzealous damming, and agricultural irrigation in dry areas.

On Further Thought

19. Records indicate that flood crests for a given amount of discharge along the Mississippi River have been getting higher since 1927, when a system of levees began to block off portions of the floodplain. Why?

ANS: The volume of floodwater hasn't changed associated with a given discharge, but the area over which the floodwater travels has decreased. Thus, the height of the associated flood (between the levees) has necessarily increased.

CHAPTER 15

Restless Realm: Oceans and Coasts

Learning Objectives

1. Students should be broadly familiar with the bathymetric profile of the world ocean and be able to picture the depths, slope, and extent of continental shelves, slopes, rises, and the abyssal plains (punctuated by the mid-ocean ridges).
2. Students should know that global deep ocean circulation is driven by temperature and salinity differences, in part. The range of temperatures in the world ocean is more extensive than the range of salinity, so modern circulation is dominated by contrasts in temperature, with cold water sinking at the poles and creeping toward the equator along the bottom. In warm, restricted seas, circulation can be induced by the evaporation of surface water to produce denser, more saline water. The freezing of water at the poles increases salinity, and rainfall in the tropics reduces it.
3. Surface currents, though generated by winds, do not flow in parallel with the wind due to the Coriolis effect. Water currents in the northern and southern oceans are dominated by clockwise and counterclockwise circular gyres, respectively. Where currents primarily flow toward the land, downwelling results; where currents flow away from the coastline, upwelling develops.
4. Tides are primarily generated by the Moon's gravitational pull on Earth. The attraction is strongest on the side of Earth facing the Moon and weakest on the side away from the Moon. Earth is stretched along the Earth-Moon axis, with a sublunar bulge tracking the Moon and a secondary bulge directly opposite to it. Along these bulges, tides are high; tides are low away from the bulges. The extent of the tidal reach (the difference in local sea level at high and low tides) is affected by the position of the Sun, with stronger (spring) tides occurring during full and new moons.

5. Waves affect the water to a depth of one-half their wavelength. When oblique waves reach the shore, the portion of the wave crest nearest the shore “feels the bottom” first and slows down. Thus, the wave is refracted (bent) and typically impacts the shore at an angle of less than 5° . Backwash is gravity driven, falling straight back away from shore. Thus, if waves are primarily impacting from a single directional angle (away from head on), the resultant of landward swash and seaward backwash is lateral (longshore) current and associated beach drift.
6. Most human attempts to combat beach drift and other forms of beach erosion have been futile. Groins increase sand deposition in the region directly upcurrent, but they increase erosion rates in the region directly downcurrent. Breakwaters put in place to quiet the waters in a harbor lead to greater deposition of sand, displacing water.

Summary from the Text

The landscape of the sea floor depends on the character of the underlying crust. Wide continental shelves form over passive-margin basins. Continental shelves may be cut locally by submarine canyons. Abyssal plains develop on old, cool oceanic lithosphere. Seamounts and guyots form above hot spots.

The salinity, temperature, and density of seawater vary with location and depth.

Water in the oceans circulates in currents. Surface currents are driven by the wind and are deflected in their path by the Coriolis effect to form gyres. The vertical upwelling and downwelling of water create deep currents. Some of this movement is thermohaline circulation.

Tides—the daily rise and fall of sea level—are caused by a tide-generating force. The largest contribution to this force comes from the gravitational pull of the Moon.

Waves are caused by friction where the wind shears across the surface of the ocean. Water particles follow a circular motion in a vertical plane as a wave passes. Waves refract (bend) when they approach the shore because of frictional drag with the sea floor.

Sand on beaches moves with the swash and backwash of waves. If there is a longshore current, the sand gradually moves along the beach and may form spits.

At rocky coasts, waves grind away at rocks, yielding such features as wave-cut benches and sea stacks. Some shores are wetlands, where marshes or mangrove swamps grow. Coral reefs grow along coasts in warm, clear water.

The differences in coasts reflect their tectonic setting, whether sea level is rising or falling, sediment supply, and climate.

To protect beach property, people build groins, jetties, breakwaters, and seawalls.

Human activities have led to the pollution of coasts. Reef bleaching has become dangerously widespread, and dead zones have formed along some coasts.

Hurricanes produce winds of between 118 and nearly 880 km per hour. The force of the winds, along with accompanying storm surge and heavy rains, can destroy coastal areas.

Video and Animation Files

LIVING WITH THE COAST

Number: Animation 15.1

Summary: This animation illustrates the problem of beach erosion and the numerous ways in which humans try to combat the problem. It shows how our penchant for damming streams has contributed to the problem of sand starvation. It also highlights how our engineered coastal structures designed to address this problem can create as many problems as they solve. Navigational jetties disrupt longshore transport of sand and push inlet sands farther offshore. Breakwaters produce a hazard to swimmers. Groins necessitate further groins by blocking the flow of sand downcurrent.

Classroom Use: This animation could be shown in-class if time permits, or as a homework activity.

Review and Discussion Questions:

1. Why has the damming of rivers worsened the problem of beach erosion? Where does the sand that normally would nourish beaches get deposited?
2. An Atlantic coast beach faces east, with longshore transport of sand primarily moving from north to south. If the owner of a hotel that owns a stretch of this beach wants to install a groin in order to keep its beach sand from eroding away, would it be wiser to place it on the northern edge of the property or the southern edge?

Answers to Review Questions

1. How much of Earth's surface is covered by oceans?

ANS: Oceans cover 70.8% of Earth's surface.

2. How does the lithosphere beneath a continent differ from that beneath an abyssal plain?

ANS: The lithosphere beneath a passive margin is much thicker than that beneath an abyssal plain, and it has crust typically composed of granite, diorite, sedimentary rocks, and sediments. The thinner lithosphere of the abyssal plain would consist of sediments atop basalt and gabbro.

3. How do the shelf and slope of an active continental margin differ from those of a *passive* margin? Why do passive margin basins exist?

ANS: At an active margin, the shelf is much thinner and the slope dips almost twice as steeply as at a passive margin. Passive margin basins form due to the breakup of continents during rifting.

4. Where does the salt in the ocean come from? How do the salinity and temperature in the ocean vary?

ANS: Salt and other ions in the ocean are carried in by rivers and groundwater, originating from the chemical weathering of terrestrial rock. Ions are also derived from

dissolved volcanic gases. The concentration of salt is greater in the ocean than it is in rivers due to evaporation. Salinity is greater in polar regions, which are subjected to freezing, and in dry climates and restricted seaways due to evaporation. Salinity is below average in tropical areas of high moisture and near the mouths of large rivers. Salinity averages 3.5% and ranges from 1% to 4.1%. Temperatures of the ocean tend to be greater at the equator, colder near the poles, and warmer at the surface, cooler with depth.

5. What factors control the direction of surface currents in the ocean? Explain thermohaline circulation.

ANS: Surface currents are primarily controlled by winds and by the Coriolis effect. Thermohaline circulation involves vertical mixing—the sinking of surface water and the rising of deep water due to contrasts in density, which are a function of temperature and salinity.

6. What causes the tides? Why does tidal reach vary with location?

ANS: Tides are generated by the gravitational attraction of the Moon, moderated by the gravitational attraction of the Sun, in combination with the rotation of Earth. At the surface facing the Moon, the sea bulges out toward the Moon because the Moon's gravitational pull is strongest at this closest point. Directly opposite this, another outward bulge arises, because at this most distant point, the Moon's force is weakest. Water responds to the centrifugal effect imposed by Earth's rotation, so it tends to bulge outward; on the side of Earth farthest from the Moon, this inertial effect is stronger than the Moon's pull. Tides are high in the regions of the bulges and low opposite them. Variation in tidal reach is related to the shape of the coastline and sea floor, as well as variable air pressure.

7. Describe the motion of water molecules in a wave. How does wave refraction cause longshore currents?

ANS: Water molecules in waves on the open ocean move in roughly circular paths. Wave refraction thus produces longshore currents directed away from headlands and toward bays. Wave refraction by itself does not cause longshore currents (see answer to question 9) but aggravates erosion rates in headlands (jutting points of land) by concentrating

wave energy there and directing longshore currents into the interior of bays.

8. Describe the components of a beach profile. How does beach sand migrate as a result of longshore drift?

ANS: Starting onshore we would see subaerial dunes that might be vegetated. Moving seaward we would find the winter berm, which is produced by strong storm waves piling up sand grains. Moving farther seaward, we would find a summer berm, a smaller pile of sand produced by gentler summer waves. (This feature may not be seen in the winter; summer berms have usually been swept seaward by strong winter storm waves.)

Waves are incident on the beach at angles that vary from the orientation of the coastline by as much as about 5° , but the gravity-driven backwash heads straight outward. Waves pull sand with them, so the net effect of this variance is longshore currents developing parallel to shore and longshore drift of sand.

9. Describe how rocky coasts evolve.

ANS: Rocky coasts generally start with irregular geometry headlands and embayments. Wave erosion breaks down the headlands and transports sediment to the embayments, straightening the shoreline.

10. What is an estuary? What is the difference between an estuary and a fjord?

ANS: An estuary is an embayment in which seawater and freshwater mix; it is formed when sea level rises to flood a river valley. Estuaries are isolated pockets of brackish (characterized by intermediate and variable salinity) water between the freshwater of rivers and the saltwater of the sea; they support a unique ecosystem, distinct from that seen in the vast ocean of normal salinity. A fjord forms when rising sea level drowns a former glacial valley.

11. Discuss the different types of coastal wetlands. What is a coral reef, and how does the reef surrounding an oceanic island change with time?

ANS: Coastal wetlands include swamps (wetlands dominated by trees), marshes (wetlands dominated by grasses), and bogs (wetlands dominated by moss). Different types of reefs include fringing reefs, barrier reefs, and atolls.

A coral reef is a massive framework of skeletal carbonate produced by a coral colony, plus the organisms that live on the coral and wave-broken debris. A reef developing around an oceanic island first forms a fringing reef just offshore of the island. With time, the island will subside, but the fringing reef will continue to grow upward, producing a barrier reef separated from the island by a lagoon. Eventually, the island will subside below sea level, leaving a circular ring-like reef called an atoll.

12. How do plate tectonics, sea-level changes, sediment supply, and climate change affect the shape of a coastline? Explain the difference between emergent and submergent coasts. What is the difference between an erosional and depositional coast?

ANS: Coastlines along active margins (plate boundaries) have relatively steep drop-offs; at passive margins, broad, flat, continental shelves offshore merge into broad, flat, coastal plains onshore.

Climate change, tectonics, and sediment supply can alter the relative position of the shoreline and thus bring change to the coast. For beaches to build up, the supply of sediment must be greater than the rate of erosion induced by waves. Stormy weather increases erosion rates, so the growth of a beach requires still greater sediment supply in order to maintain position of the shoreline.

An emergent coast is one in which local sea level has been falling; former marine environments are now exposed above sea level. A submergent coast is one in which local sea level has been rising; former terrestrial environments are now below sea level. Emergent coastlines build elevated terraces of sand that once formed a beachfront; submergence of the coastline may produce an irregular coastline shape (as when an estuary rises up and the shoreline assumes the dendritic shape of a stream-cut valley).

An erosional coast (such as a wave-cut cliff setting) is one for which the rate of rock or sediment removal is greater than the rate of sediment deposition. A depositional coast is one for which deposition of sediment takes place at a rate that is faster than erosion.

13. In what ways do people try to modify or stabilize coasts? How do the actions of people threaten coastal areas?

ANS: Humans build a number of structures locally to try to reduce the erosion of sand

and to protect the coast from strong waves. These include the construction of groins, jetties, sea walls, and breakwaters. Altering the shoreline by constructing these structures has unforeseen consequences. For example, breakwaters lead to deposition of sand behind the breakwater, which may fill up an embayment that was formerly being used. Groins and jetties reduce longshore transport of sand in the upcurrent direction, but lead to increased loss of sand in the downcurrent direction. Sea walls increase the reflective energy of impacting waves, leading to erosion of sandy sediments at the base of the sea wall and ultimately the collapse of the sea wall.

14. How can hurricanes affect coasts?

ANS: Hurricanes affect coasts through strong winds, which can uproot vegetation and destroy houses. Powerful waves can destroy boats and erode sediment from beaches. Storm surge from low atmospheric pressure and heavy rainfall can bring powerful flooding.

On Further Thought

15. In 1789, the crew of the HMS *Bounty* mutinied. Near Tonga, in the Friendly Islands (approximately 20° S and 175° W), the crew forced the ship's commanding officer, Lieutenant Bligh, along with those crewmen who remained loyal to Bligh, into a rowboat and set them adrift in the Pacific Ocean. The castaways, amazingly, survived, and 47 days later, they landed at Timor (near Sumatra), 6,700 km to the west. Why did they end up where they did

ANS: The castaways were pushed west by the current at the north end of the South Pacific gyre.

CHAPTER 16

A Hidden Reserve: Groundwater

Learning Objectives

1. Students should broadly understand the hydrologic cycle driven by evaporation, precipitation, infiltration, streamflow, and groundwater flow. Groundwater flows from regions of recharge to regions of discharge, driven by gravity and water pressure.
2. Pores occur in all geologic materials. If pores are sufficiently connected to form conduits for flow, the material will be permeable and can serve as an aquifer (impermeable rocks and sediments are termed aquitards). The water table separates an unsaturated zone (in which pores are mostly air filled) from a saturated zone (in which water permanently fills the pores) within an unconfined aquifer (one that is not bounded above by an aquitard). Locally, the water table is a subdued mimic of surface topography, rising slightly in hillsides due to increased recharge.
3. Permeability of an aquifer adjusted for the viscosity of the fluid within pores is termed hydraulic conductivity. Darcy's law states that groundwater flux per unit area (in cross-section) of an aquifer is equal to the slope of the water table multiplied by hydraulic conductivity.
4. Groundwater can both dissolve and precipitate minerals at or below the surface. Water with excessively high concentrations of dissolved ions is undrinkable. Hard water contains a relatively great concentration of dissolved calcium and magnesium.
5. Pumping water from a well produces a cone of depression in the water table around the well base. Excessive pumping may permanently lower the water table in a region. Use of groundwater at rates that make it a nonrenewable resource causes groundwater depletion.

6. A variety of human products (pesticides, sewage, fertilizer, gasoline, chemicals) have caused serious groundwater contamination problems. Wells can be contaminated by the reversal of groundwater flow in regions that have been overpumped.
7. Caves are usually etched in limestone by dilute solutions of carbonic acid at or just below the water table. Carbonic acid is introduced into groundwater by dissolved carbon dioxide in rainwater. A minority of caves are dissolved by sulfuric acid produced by bacterial interaction with hydrocarbons (such as petroleum). Water dripping through caves produces a variety of calcitic deposits termed speleothems (including the familiar stalactites and stalagmites). The collapse of caves produces sinkholes; a region dominated by sinkholes and other effects of dissolved bedrock is said to exhibit karst topography.

Summary from the Text

During the hydrologic cycle, water infiltrates the ground and fills the pores and cracks in rock and sediment. This subsurface water is called groundwater. The amount of open space in rock or sediment is its porosity, and the ease with which water can flow through is its permeability.

Aquifers are relatively permeable, and aquitards are relatively impermeable.

The water table is the surface in the ground above which pores contain mostly air and below which pores are filled with water. The shape of a water table is a subdued mimic of the shape of the overlying land surface.

Groundwater flows wherever the water table has a hydraulic gradient, and it moves slowly from recharge areas to discharge areas. The velocity of flow depends on permeability and the hydraulic gradient.

Groundwater contains dissolved ions. Hard water contains a relatively high concentration of ions; scale in pipes forms when these ions precipitate.

At a spring, groundwater exits the ground on its own. Springs form for many

reasons.

Groundwater can be extracted in wells. An ordinary well simply penetrates below the water table, so the water level in the well is the water table. In an artesian well, water rises on its own pressure.

Hot springs and geysers release hot water to Earth's surface. This water may have been heated as a result of residing very deep in the crust or by the proximity of a magma chamber.

Groundwater is a precious resource, used for municipal water supplies, industry, and agriculture. In recent years, some regions have lost their groundwater supply because of overuse or contamination. Pumping water out of a well too fast causes drawdown, yielding a cone of depression.

When limestone dissolves just below the water table, underground caves are the result. Soluble beds and joints determine the location and orientation of caves. If the water table drops, caves empty out. Limestone then precipitates out of water dripping from cave roofs, and creates speleothems (such as stalagmites and stalactites).

Regions where abundant caves have collapsed to form sinkholes are called karst landscapes. These terrains can contain sinkholes, natural bridges, and disappearing streams.

Video and Animation Files

GROUNDWATER REMOVAL

Number: Video 16.1

Length: 3 minutes, 30 seconds

Summary: The video starts by showing the major features of an unconfined aquifer: the unsaturated zone, saturated zone, and the water table separating them. The effect of pumping a well is then animated, showing the cone of depression that forms within the water table. Lastly, the adverse effects of overuse of groundwater are

shown, including emphasis on pore collapse in sediment aquifers leading to subsidence of the ground surface. Included at the end are color-coded maps of recent subsidence due to groundwater overuse.

Classroom Use: This video might be best used as an assignment, so that the student can take time to reflect on the dire consequences of groundwater removal and can go back to review photos and maps of subsidence.

Review and Discussion Questions:

1. Name a reason why parts of central California have subsided by 15 meters of within the last hundred years.
2. List four adverse consequences that may potentially arise from large-scale groundwater removal.

Answers to Review Questions

1. How do porosity and permeability differ? Give examples of substances with high porosity but low permeability.

ANS: Porosity describes the proportion of rock or sediment volume made up of pores (empty spaces), whereas permeability is a measure of the connectedness of pores and the ability of these pores (and fractures) to form conduits through the material. Muddy sediments and fine-grained rock, such as shale or mudstone, may have abundant pore space, but because the pores are tiny and poorly connected, it is difficult for a liquid to flow through these materials, which are considered aquitards (rock or sediment of very low permeability).

2. What is a water table, and what factors affect the level of the water table? What factors affect the flow direction of the water below the water table?

ANS: A water table is a boundary surface between the saturated zone of an aquifer and the unsaturated zone that lies above it. Humidity and great amounts of rainfall cause the water table to rise relatively close to the surface. Locally, the water table will lie closer to

the surface in topographic valleys than on hills. Below the water table, groundwater flows from regions of recharge (infiltration) to those of discharge (expulsion into a stream valley or lake), driven by gravity and water pressure. Restated, groundwater flows from areas where the water table is relatively high to where it is relatively low.

3. How does the rate of groundwater flow compare with that of moving ocean water or river currents? What factors control the rate of groundwater flow?

ANS: Groundwater flow is very slow compared to currents in surface water, generally moving at less than 1 1/2 meters per day. Rate of groundwater flow is affected by the hydraulic gradient (slope of the water table) and permeability of the aquifer.

4. How does the chemical composition of groundwater change with time? What is hard water?

ANS: The chemical composition of groundwater changes through the precipitation of minerals coming out of solution and the dissolution of new minerals in the rocks through which groundwater is flowing. Groundwater chemistry may also be changed by the activity of bacteria. Hard water has great amounts of dissolved calcium and magnesium.

5. How does excessive pumping affect the local water table?

ANS: Pumping will depress the water table around the pump, forming a cone of depression. Long-term pumping may permanently depress the local water table.

6. How is an artesian well different from an ordinary well?

ANS: An artesian well penetrates into a confined aquifer and produces upward flow (which may reach the surface) without any pumping.

7. Why do natural springs form? Explain why hot springs form and what makes a geyser erupt.

ANS: Natural springs occur where groundwater flows outward to the surface of the Earth. Springs form when the ground surface intersects the water table. This can happen when a cavernous aquifer flows into a sinkhole, when an aquifer meets a steeply sloped impermeable layer, or when a perched aquifer abuts the side of a hill. Hot springs may

form in environments where groundwater rises to the surface from great depths. Hot springs may also form in places where volcanoes are active or were recently active. Water under pressure within fractures in hot rock becomes superheated (above boiling temperature at surface pressure). Eventually, some water will be heated enough to form steam, which will rise up through a conduit to the surface, pushing out some water in its path. This process greatly reduces pressure below, so that an abundance of water will quickly expand into steam, explosively ejecting a great quantity of water as it rises to the surface.

8. Is groundwater a renewable or nonrenewable resource? What are the consequences of drought or overpumping

ANS: The abundance of water and rainfall on this planet, combined with the slow but persistent travel of groundwater, allows groundwater to be considered a renewable resource on long time scales of many thousands of years for the whole Earth. However, locally, on shorter time scales, overuse and pollution of groundwater have led to the consumption and destruction of usable groundwater at rates that are too fast to be balanced by natural recharge. Groundwater is being used in a nonrenewable way in these instances and places (including many municipal and arid settings).

Drought and overpumping can lead to the depletion of groundwater within aquifers, lowering the water table. Further, saline intrusion or subsidence of the land surface may result.

9. Describe some of the ways in which human activities can adversely affect the water table.

ANS: Overpumping and the diversion of surface water from areas of recharge have caused the water table to be locally depressed.

10. What are some sources of groundwater contamination? How can it be prevented?

ANS: One natural source of contamination (from a human perspective) arises from the rocks through which groundwater flows, through the introduction of unfavorable dissolved ions or gases. Human contamination includes agricultural and industrial chemicals, petroleum, sewage, radioactive waste, and acids from mine drainage. All such

wastes should be stored in carefully engineered settings, making use of impermeable materials, which prevent flow from the site.

11. Describe the process leading to the formation of caves and the speleothems within caves.

ANS: Caves form from the dissolution of limestone by carbonic acid in groundwater usually near the water table. Speleothems are produced when carbonate-rich groundwater enters a cave and evaporates, producing precipitation of new calcite.

12. Describe the various features of a karst landscape, and explain how they evolve.

ANS: Caverns form where acidic groundwater etches open spaces within soluble bedrock (usually limestone). Sinkholes are circular depressions on the landscape that form when a subterranean cavern experiences a roof collapse. Over time, the breakdown of walls separating sinkholes can leave isolated erosional remnants (tower karst).

On Further Thought

13. The population of Desert Paradise (a fictitious town in the southwestern United States) has been doubling every seven years. The town has no permanent streams or lakes nearby. In fact, the only standing water in the town occurs in the ponds of golf courses. The water in these ponds needs to be replenished almost constantly, for without added water, the water seeps into the ground quickly and the ponds dry up. Desert Paradise has been growing on a flat, sediment-filled basin between two small mountain ranges. Where does the town water supply come from? What do you predict will happen to the water table of the area in coming years, and how might the land surface change as a consequence? Is there a policy that you might suggest to the residents of Desert Paradise that could slow the process of change?

ANS: The water supply is almost certainly groundwater from aquifers that receive their recharge in the mountains and bring groundwater flow beneath the town. Given the slow

rates of recharge (arid setting) and groundwater flow (flat-lying sediments beneath the town) and the increasing demand for water in this town, groundwater depletion is most certainly taking place. The level of the water table will fall in the years to come, and the conversion of saturated zone to unsaturated zone will bring sediment compaction and subsidence of the land surface. Residents should consider at least three policy objectives to help ameliorate the situation. (1) The golf courses should be abandoned and allowed to return to a natural state (when the grandkids are in town, they can teach their grandparents how to play video golf, thus saving water, slowing subsidence, and avoiding possible heat stroke all at the same time). (2) Assuming that the abandonment of the golf courses is politically impossible, at the very least the water hazards should be replaced by sand traps. (3) Residents should be encouraged, mandated, coerced, or cajoled into forgoing their lawns in favor of decorative rock gardens and native desert plants that need little to no watering.

CHAPTER 17

Dry Regions: The Geology of Deserts

Learning Objectives

1. Students should know that deserts are defined on the basis of aridity; deserts are characterized by little annual precipitation, lengthy periods of drought, sparse vegetative cover, high rates of evaporation, and an absence of permanent streams of local origin. Deserts can be quite cold, as in the Gobi and the polar regions. Even hot deserts cool off drastically at night since the radiation of heat into space is greater in desert areas than in other environments.
2. Students should know the physiographic factors that produce deserts: descent of cool, dry air in the subtropics; development of rain shadows on the leeward side of mountain ranges; isolation from the ocean within the interior of a massive continent; and cold ocean currents. Many desert areas are arid due to a combination of these factors.
3. Chemical weathering rates are slow in arid conditions. Physical weathering and erosion take place through fracturing along joints, wind abrasion, and scouring by flash-flood waters during infrequent but torrential rains. Wind carries smaller, dust-sized particles, abrading rocks to form ventifacts and leaving behind coarser lag deposits of pebbles and boulders. Water from ephemeral streams arising from rainstorms releases its sediment when it reaches a broad plain, producing a wedge of sand and gravel termed an alluvial fan.
4. Many typical desert landforms, such as buttes, cuestas, and mesas, result from cliff retreat—episodic breakdown of the cliff face along vertical joints.
5. In many places of the world, deserts are expanding due to an influx of human populations and agricultural activities, including diversion of water for irrigation and

the expansion of grazing into semiarid regions, which cannot recover fast enough to tolerate herbivorous predation.

Summary from the Text

Deserts generally receive less than 25 cm of rain per year. Vegetation covers no more than 15% of their surface.

Subtropical deserts form between latitudes of 20° and 30°, rain-shadow deserts are found on the inland side of mountain ranges, coastal deserts are located on the land adjacent to cold ocean currents, continental-interior deserts exist in landlocked regions far from the ocean, and polar deserts form at high latitudes.

Physical weathering in deserts produces rocky debris. Chemical weathering happens slowly; it produces ions that precipitate as new minerals just below the surface.

Water causes significant erosion in deserts, mostly during heavy downpours. Flash floods carry large quantities of sediment down ephemeral streams. When the rain stops, streams dry up, leaving steep-sided dry washes.

Wind picks up dust and silt as suspended load, and it causes sand to saltate. Where wind blows away finer sediment, a lag deposit remains. Windblown sediment abrades the ground, creating a variety of features such as ventifacts.

Desert pavements are mosaics of varnished stones armoring the surface of the ground.

Talus aprons form when rock fragments accumulate at the base of a slope. Alluvial fans form at a mountain front where water in ephemeral streams deposits sediment on a plain. When temporary desert lakes dry up, they leave playas.

In some desert landscapes, erosion causes cliff retreat, eventually resulting in the formation of mesas, buttes, and inselbergs. Pediments of nearly flat or gently sloping bedrock surround some inselbergs.

Where sand is abundant, the wind builds it into dunes. Common types include

barchan, star, transverse, parabolic, and longitudinal dunes.

Changing climates and land abuse may cause desertification, the transformation of semiarid land into deserts. Windblown dust, sometimes carrying microbes and toxins, may waft from deserts across oceans.

Video and Animation Files

EVOLUTION OF DESERTS

Number: Video 17.1

Length: 2 minutes, 44 seconds

Summary: This video uses animation to show how desert landscapes evolve through jointing of exposed rock and erosion yielding cliff retreat, so that broad, elevated mesas reduce to smaller isolated buttes and eventually narrow chimneys before disappearing completely.

Classroom Use: This short video could be used immediately after discussion of cliff retreat in deserts to help students visualize the process.

Review and Discussion Questions:

1. Do buttes form from mesas, or do mesas arise from the growth of buttes? Explain your answer.
2. You come to a patch of dry terrain where outcrops of rock consist of asymmetrical, pointed ridges termed cuestas instead of flat-topped buttes and mesas. What do you know about the underlying rock in this region?

Answers to Review Questions

1. What factors determine whether a region can be classified as a desert?

ANS: Deserts are extremely arid regions marked by sparse vegetation cover (less than 15% of the ground surface), little precipitation (generally less than 25 cm per year), and high rates of evaporation. Local streams are ephemeral in deserts; only rivers fed by rain and snowfall upstream stay wet throughout the year.

2. Explain the various conditions that can lead to the formation of deserts.

ANS: Subtropical deserts form because of Hadley cell convection. Warm, moist air rises over the tropics and spreads laterally, shedding rainfall as it cools. By the time the air is above the subtropics, its moisture content is very low, and it cools enough to sink. As the cool, dry air sinks, it becomes warm, dry air. Warm air has a greater capacity to hold water vapor than does cool air, so this hot, dry air mass soaks up available moisture, causing the high evaporation rates characterizing subtropical deserts. Rain-shadow deserts form on the leeward side of mountain ranges. As moisture-laden air masses encounter mountains, they are forced to rise over the topography, cooling and shedding moisture as they journey upward on the windward side of the mountains. Most of their moisture spent, these air masses heat up as they descend down the leeward side of the mountains, and their relative humidity decreases even further. Cool-water currents absorb heat from the air above them, keeping the temperature of the air—and its capacity to carry moisture—low. Deserts form in continental interiors because moisture derived from the ocean is likely to be shed on the journey to the interior, leaving little moisture available for the land in the center of a large continent. Polar regions are arid because cold air can hold only small amounts of moisture and because air sinks at the poles, as in the subtropics.

3. Have today's deserts always been deserts? (*Hint:* Keep in mind the consequences of plate tectonics.)

ANS: The positions of deserts have shifted over time, driven by plate-tectonic movements. Collisions of continental masses produce mountains, which can form rain

shadows and lead to the assembly of large continents with dry interiors. Plate motion can pull a continent into the subtropics, and positions of the continents can influence oceanic current patterns.

4. How do weathering processes in deserts differ from those in temperate or humid climates?

ANS: In desert conditions, chemical weathering takes place at slow rates, so physical-weathering processes provide most of the loose material that may be eroded away. This process contrasts with the greater rates of chemical weathering seen in temperate and humid climates.

5. Describe how water modifies the landscape of a desert. Be sure to discuss both erosional and depositional landforms.

ANS: Water from rare but occasionally intense rainfall is an important agent of physical weathering and erosion in deserts. Without much vegetation to hold it in place, sediment can be dislodged merely by the impact of rain. The ground can quickly become saturated with water, and a sheet wash may course across the land surface, carrying loose sediment with it. The water heads for arroyos, and a flash flood of water and entrained sand, mud, and gravel travels downstream at high velocity. The sediment load scours the channel as it travels, and grains abrade one another to produce finer particle sizes, which can be carried farther by the ephemeral stream. Because of the great sediment load of desert floodwaters, erosion is extremely powerful. When the stream channel terminates in a planar region, it breaks into a braided network of distributary channels and deposits sand and gravel in a wedge-shaped deposit termed an alluvial fan. Alluvial fans from adjacent canyons may merge over time to form a continuous, apron-like wedge of sediment termed a bajada.

6. Explain the ways in which desert winds transport sediment.

ANS: Wind can support fine dust as a suspended load, which may be blown outside the desert itself to form a loess deposit. Sand is transported as a bed load through the rolling and saltation of grains.

7. What phenomena may lead to the formation of desert varnish, desert pavement, and ventifacts?

ANS: Desert varnish forms when water dissolves iron and manganese from the interior of a rock and pulls them to the surface, where the water then evaporates, leaving behind a rind of iron and manganese oxides.

Desert pavements form from the coarse pebbles, cobbles, and boulders in lag deposits that remain after sand and finer material have been blown away from an area or deposited beneath the stones. After fracturing, these coarse grains pack together to form a mosaic, or pavement, at the surface.

Ventifacts are rocks with smooth surfaces, produced through wind abrasion, that meet along sharp edges. The multiple facets form because either the rock has shifted its orientation with respect to prevailing winds or the direction of the prevailing winds has changed direction relative to the rock.

8. Describe the process of formation of alluvial fans, bajadas, and playas.

ANS: Alluvial fans are wedge-shaped bodies of relatively coarse sediment that arise at the mouths of channels that scour into mountains. On reaching flat land, the channel breaks into distributaries, which, after being fed by upstream flooding, deposit lenses of sand and gravel. Bajadas are aprons of sandy and gravelly sediment that form through the merger of adjacent alluvial fans. Playas are flat-lying deposits of clay and evaporite minerals that form when a temporary lake evaporates.

9. Describe the process of cliff (scarp) retreat and the landforms that result from it.

ANS: Cliff retreat involves the loss of material along a cliff face due to weathering along vertical joints. The retreat of cliff faces produces isolated uplands, including broad mesas, tall but narrow chimneys, and buttes of intermediate lateral extent; these three landforms are flat-topped because they are formed from flat-lying strata.

10. What are the various types of sand dunes, and what factors determine which type of dune develops at a particular location?

ANS: Various shapes of dunes have been given the names barchan, star dune, transverse dune, and longitudinal dune. Sand-dune geometry is controlled by wind speed,

consistency of wind direction, and sediment supply.

11. What is the process of desertification, and what causes it? How can desertification in Africa affect the Caribbean?

ANS: Desertification is the expansion of deserts into land that was previously nondesert. This process is hastened by agricultural grazing and plowing of the land, which remove vegetation, as well as through natural droughts and the diversion of water to provide agricultural irrigation (or to meet the needs of a rapid influx of population). Winds can blow fine dust from the Sahara and deposit it in the Caribbean.

On Further Thought

12. You are working for an international nongovernmental organization (NGO) and have been charged with the task of providing recommendations to an African nation that wishes to slow or halt the process of desertification within its borders. What are your recommendations?

ANS: The best recommendation would be to eliminate farming and grazing in subarid steppe environments surrounding the desert. As much as possible, large-scale human habitation (with their great demands for freshwater) should be kept outside of the steppe and desert environments.

13. The Namib Desert and the Kalahari Desert both formed in southern Africa. Look at *Google Earth*[™] to find these deserts and examine some of the features in them. Did both of these deserts form for the same reason? Explain your answer.

ANS: The Namib is a coastal desert, similar to the Atacama of South America, where aridity is largely due to a cold ocean current bringing cool air to a warmer environment. As this air warms, it is able to hold a greater amount of moisture as water vapor (decreasing its relative humidity and the likelihood of precipitation). The Kalahari is too far inland to be much affected by the cold current; its aridity comes primarily from its

subtropical latitude, with warm, dry air sinking in the troposphere above the desert through much of the year.

CHAPTER 18

Amazing Ice: Glaciers and Ice Ages

Learning Objectives

1. Glaciers are terrestrial bodies of recrystallized ice that persist year-round and flow in response to gravity. Mountain glaciers travel down slopes; continental glaciers flow because of pressure applied by the weight of ice at their source areas.
2. Mountain and continental glaciers produce a variety of distinctive erosional and depositional features. Students should be familiar with appearance and mode of formation for some of these, including cirques, arêtes, horns, glacial valleys, ground moraines, end moraines, drumlins, eskers, and kettle holes.
3. Glacial drift consists of a variety of sediments representing distinct environments. Till is poorly sorted sediment dropped by glaciers when they melt. Meltwater streams produce stratified deposits termed outwash. Meltwater lakes deposit fine sediment in rhythmic couples termed varves. Strong winds blow fine silt and clay over long distances; these sediments settle out as the wind dies down to form loess.
4. Glaciers have advanced over the continents in the past during broad spans of Earth history, including the early Proterozoic, late Proterozoic, late Paleozoic, and late Cenozoic. The last of these episodes is the familiar Pleistocene Ice Age.
5. During ice ages, glaciers advance over the continents due to Milankovitch orbital parameters (changes in orbital eccentricity, axial tilt, and precession), augmented by an increase in global albedo that results from widespread ice, interruption of global ocean currents.
6. The most recent series of glacial advances (the Pleistocene Ice Age) began about 2.6 million years ago. Four major episodes of glacial advance and retreat were first recognized in North America from sedimentary evidence, but many more events are

recorded by marine sediments (the continental record is much more incomplete due to erosion). Short intervals (thousands of years) of minimal glacial extent between the times of maximum ice advance are termed interglacials. Ratios of oxygen isotopes in marine fossils are important indicators of ancient temperatures.

Summary from the Text

Glaciers are streams or sheets of recrystallized ice that survive for the entire year and flow in response to gravity. Mountain glaciers exist in high regions and fill cirques and valleys. Continental glaciers (ice sheets) spread over substantial areas of the continents.

Glaciers form when snow accumulates over a long period. With progressive burial, the snow first turns to firn and then to ice.

Temperate glaciers are melting during at least part of the year. Polar glaciers do not. Glaciers move by basal sliding over water or wet sediment, and/or by plastic deformation of ice grains. In general, glaciers move tens of meters per year.

Gravitational pull causes glaciers to flow in the direction of their overall surface slope.

Whether the toe of a glacier stays fixed in position, advances, or retreats depends on the balance between the rate at which snow builds up in the zone of accumulation and the rate at which glaciers melt, calve, or sublimate in the zone of ablation.

Icebergs break off glaciers that flow into the sea. Continental glaciers that flow out into the sea along a coast make ice shelves. Sea ice forms where the ocean's surface freezes.

As glacial ice flows over sediment, it incorporates clasts. The clasts embedded in glacial ice abrade the substrate and can polish bedrock and cut striations into it.

Mountain glaciers carve numerous landforms, including cirques, arêtes, horns, U-shaped valleys, hanging valleys, and truncated spurs. Fjords are glacially carved valleys that filled with water when sea level rose after an ice age.

Glaciers can transport sediment of all sizes. Till consists of unsorted sediment dropped by melting ice. Glacial marine collects underwater, by melting of icebergs. Streams sort till and deposit it as glacial outwash. Some of the finer sediments accumulate as lake-bed mud, or as wind-blown loess.

Glacial depositional landforms include moraines, knob-and-kettle topography, drumlins, eskers, meltwater lakes, and outwash plains. Lateral moraines accumulate along the sides of valley glaciers, medial moraines down the middle, and end moraines at a glacier's toe.

Continental crust subsides as a result of ice loading. When the glacier melts away, the crust rebounds.

When water is stored in continental glaciers, sea level drops. When the glacier melts away, the underlying lithosphere rebounds. When continental glaciers store substantial amounts of water, global sea level drops. When these glaciers melt, sea level rises.

During past ice ages, the climate in regions south of the continental glaciers was wetter and pluvial lakes formed. Permafrost exists in periglacial environments.

During the Pleistocene Ice Age, large continental glaciers covered much of North America, Europe, and Asia.

The stratigraphy of Pleistocene glacial deposits indicates that glaciers advanced and retreated many times during the ice age. The record of glaciations is more complete in oceanic sediment.

Over the long-term, plate tectonics and changes in the concentration of atmospheric CO₂ may set the stage for ice ages. Short-term advances and retreats may be caused by Milankovitch cycles.

Video and Animation Files

GLACIAL DYNAMICS

Number: Animation 18.1

Length: Length will vary based on student interaction.

Summary: This animation shows how glacial advance and retreat are related to the snow and ice budget, and how the rate of flow within a glacier is affected by terrain and temperature. Retreat or advance at the toe of the glacier is shown to depend not only on local temperatures, but also on glacial flow (in turn related to available precipitation, temperatures, and terrain at the zone of accumulation). Students can pull virtual levers to show the effects of variables influencing ice-flow rate and toe advance, both singly and in combination.

Classroom Use: This animation is strongly recommended viewing either during lecture or outside of class. The ability for students to experiment with the effects of multiple variables influencing glacial flow rate and advance or retreat of the toe, as well as the resolution of the conceptual paradox presented by forward ice flow and a retreating toe, makes this animation definitely worth viewing.

Review and Discussion Questions:

1. When a glacier retreats at its toe, is it a result of ice flowing back uphill or back toward high latitudes?
2. Describe three factors that influence the rate at which ice flows within a glacier.

Answers to Review Questions

1. What evidence did Louis Agassiz offer to support the idea that an ice age happened?

ANS: He noticed that many European deposits contained boulders, which water could not carry, and they were unsorted (water produces sorted deposits because carrying

capacity is a function of velocity).

2. How do mountain glaciers and continental glaciers differ?

ANS: Continental glaciers are thicker, much more expansive sheets. Mountain glaciers flow downhill as a result of gravity acting on the mass of ice. Continental glaciers move in response to pressure from the weight of material in their thick midsections.

3. Describe the transformation from snow to glacial ice.

ANS: Fluffy snow, when sufficiently buried, packs together and melts in places due to pressure from above. The liquid refreezes to produce more tightly packed firn (one-quarter air by volume), and ultimately, a solid mass of interlocking ice (interrupted by bubbles).

4. Explain how arêtes, cirques, and horns form, and how they differ in shape.

ANS: Arêtes are residual, elongate ridges between cirques, formed by glacial erosion and mass wasting. Cirques are bowl-shaped depressions scoured by mountain glaciers and the sediments they carry. Horns are residual, pointed peaks at the intersection of three or more arêtes. They are the highest erosion remnants of a mountain that has been glaciated.

5. Describe the mechanisms that enable glaciers to move, and explain why glaciers move.

ANS: If the bottom surface along which a glacier is traveling is wet, it may slide along the surface. Generally, movement is accomplished through the plastic deformation of internal ice crystals. At the surface, expansion and travel is accommodated by fracture. Glacial movement is ultimately driven by gravity.

6. How fast do glaciers normally move? How fast can they move during a surge?

ANS: Glaciers normally move from 10 to 300 m per year. During a surge, they can move as fast as 110 m per day.

7. Explain how the balance between ablation and accumulation controls advances and retreats.

ANS: If accumulation of new snow to feed a glacier exceeds ablation (loss of ice due to melting or sublimation), the glacier will grow and advance; if the reverse is true, the

glacier will retreat (disappear).

8. How can a glacier continue to flow toward its toe even though its toe is retreating?

ANS: Downhill flow of ice toward the toe is driven by gravity and is not interrupted by melting that occurs elsewhere. Ice in the toe is not truly retreating uphill but is merely melting or sublimating.

9. How does a glacier transform a V-shaped river valley into a U-shaped valley? Discuss how hanging valleys form.

ANS: Glaciers and their abrasive sedimentary load not only carve into the floor of a valley but also hollow out the sides. Valley glaciers carving through a tributary to a major stream will not cut as deeply as the floor that is cut by the glacier in the main stream valley. Tributary glaciers contain smaller volumes of ice than do the main glaciers into which they feed. This smaller ice volume limits the depth to which tributary glacial valleys are eroded. The floor of the tributary glacial valley is thus elevated above the valley floor of the main glacier. After the glacial ice has melted away, the tributary valley can be seen as a hanging valley suspended above the main glacial valley.

10. Describe the various kinds of glacial deposits. Be sure to note the materials from which the deposits are made and the landforms that result from deposition.

ANS: Glacial materials include erratic boulders and unsorted tills dropped directly from the glacier, in addition to outwash sands and gravels from meltwater streams, glacial lake sediment, and windborne loess. Landforms include end moraines, dropped ridges of till at the frontal margin of a glacier that form when a glacier ceases to advance and melts away; lodgment till, the smeared remains of an end moraine steamrolled by an advancing glacier; and ground moraine, a plain of till released over the broad area of glacial recession. Drumlins are asymmetric hills of till shaped by glacial ice (with a steeper slope in the upstream direction). Kettle holes are depressions formed when till buries ice, which later melts and flows outward. Meltwater streams deposit outwash consisting of stratified sediments, and varved sediments may accumulate at the bottom of meltwater-fed lakes. Eskers are sorted sediments that reflect the course of a stream that existed on the bottom surface of a glacier.

11. How does the lithosphere respond to the weight of glacial ice? How does sea level change during an ice age?

ANS: Thick glacial ice may cause local subsidence of the lithosphere, which presses down into the softer asthenosphere below. When the glacier melts, the lithosphere rebounds to its prior elevation, and asthenosphere flows in underneath the rising lithosphere. Sea level falls as glaciers expand, because water is locked out of the ocean and into the ice of the glaciers. Consequently, as glaciers melt, sea level rises with the additional available water from ice melt.

12. How was the on-land chronology of glaciations developed? Why is it so incomplete? How was it modified with the study of marine sediment?

ANS: The on-land chronology was developed by the study of distinct layers of till of differing ages (glacial advance), separated by soils with fossil remains suggesting returns to warmer climates (interglacials). The record of advances and retreats, like so much of the terrestrial sedimentary record, is vastly incomplete due to erosion of many glacial deposits. Marine sediments offer a more complete, continuous record and can be tested for oxygen isotope ratios that serve as gauges of past ocean temperatures; these sediments also contain distinctive fossil assemblages associated with warm-water or cool-water settings.

13. Were there ice ages before the Pleistocene? If so, when?

ANS: Yes. There were ice ages during the early Proterozoic, late Proterozoic, and late Paleozoic.

14. What are some of the long-term causes that lead to ice ages? What are the short-term causes that trigger glaciations and interglacials?

ANS: The proportion of carbon dioxide (a greenhouse gas) and plate-tectonic activity are the major factors affecting long-term climate. Active mid-ocean-ridge volcanism can increase the greenhouse effect by adding carbon dioxide to the atmosphere. Similarly, rapid ridge volcanism increases the volume of the ridges and can push sea level over the continents. The configuration of continents is also important; large continental masses near the poles favor the possibility of terrestrial glaciers.

Short-term advance and retreat are related to Milankovitch orbital variation. Variation in the eccentricity of Earth's orbit affects the evenness of global insolation through the year. Additionally, Earth travels more slowly when it is more distant from the Sun, spending proportionately more time near aphelion in a more eccentric (elliptical) orbit. Variation in tilt affects seasonality. A small tilt means the poles will not receive a warm summer and favors glacial advance. Precession affects the timing of equinoxes and solstices. Summer will be cooler in the northern hemisphere if it occurs in conjunction with aphelion. Milankovitch variation is reinforced by positive feedback. A glaciated Earth has a high albedo, reflecting much sunlight back to space.

On Further Thought

15. If you fly over the barren cornfields of central Illinois during the early spring, you will see slight differences in soil color due to variations in moisture content—wetter soil is darker. These variations outline the shapes of polygons that are tens of meters across. What do these patterns represent, and how might they have formed?

ANS: These features are termed patterned ground; they are formed today in regions of permafrost, where soil moisture undergoes freeze-thaw cycles in summer, widening fractures in the soil that eventually form the boundaries of the polygons. Their presence suggests that local climate during glacial episodes was very cold. (These features form in areas where the average yearly temperature is below freezing.)

16. An unusual late Precambrian rock unit crops out in the Flinders Range, a small mountain belt in South Australia. This unit consists of clasts of granite and gneiss, in a wide range of sizes, suspended through a matrix of slate. The rock unit lies unconformably above a basement of granite and gneiss, and if you dig out the unconformity surface, you will find that it is polished and striated. What is this unusual rock?

ANS: The unusual rock is a metamorphosed tillite (or “metatillite”); metamorphism has altered the original muddy matrix to form slate (with its characteristic cleavage) and has deformed the once more-spherical clasts into ellipsoids. Glaciers that deposited this material as till abraded the surface of underlying rocks, yielding the polish and striations.

CHAPTER 19

Global Change in the Earth System

Learning Objectives

1. Students should have an appreciation of the complexity and degree of interconnectedness of physical and biological systems on Earth. Earth has been changing since its beginnings, and students should be able to contrast the first crust and first atmosphere with those of the modern world.
2. Some changes during Earth's history have been unidirectional (changes in the solid Earth, oceans, and atmosphere, and biological evolution), whereas many other systems fluctuate or cycle from one state to another (global climate, sea level, and configuration of the continents).
3. The rock cycle is an important theme in geology. Any of the three major rock types may be recycled to form rocks belonging to the other two major types (as well as a new lithology of the same type, such as phyllite being metamorphosed into schist).
4. The carbon cycle is an important example of a biogeochemical cycle. Carbon passes back and forth among the biosphere, atmosphere, hydrosphere, and lithosphere. Carbon dioxide is an important greenhouse gas, helping to keep Earth warm through absorption of infrared radiation. Had liquid water not formed at the surface, most carbon on Earth would have persisted as carbon dioxide in the atmosphere (where it originally built up due to volcanic outgassing), which would have made conditions too hot for life as we know it.
5. Human industrial activity has led to the pollution and destruction of terrestrial ecosystems, the development of atmospheric smog over cities, and a hole in the ozone layer.
6. Atmospheric carbon dioxide has increased markedly in the past two centuries,

particularly within the last 50 years. The rapidity of change in atmospheric carbon dioxide concentration is too rapid to be explained by natural geologic processes and is due rather to increasing human input through the burning of fossil fuels. Carbon dioxide is a greenhouse gas that warms Earth by trapping infrared radiation that would otherwise be emitted to outer space. Over the same time span, Earth's climate has been getting progressively warmer. The overwhelming majority of scientists with relevant expertise are convinced by the evidence that human activities are responsible for this global warming trend and that further warming is in store for the future. Effects of global warming that have already been documented include sea-level rise, the breakup of polar ice shelves, the melting of glaciers, a reduction in sea-ice formation, shifts in patterns of precipitation and climate belts, changes in the range distributions of plants and animals (shifting northward in the northern hemisphere), and the imperilment of polar wildlife. Warming and rapid climate change may also be at least partly responsible for the increasingly massive floods, powerful hurricanes, and severe droughts that have been experienced in recent years.

Summary from the Text

We refer to the global interconnecting web of physical and biological phenomena on Earth as the Earth System. Global change involves the transformations or modifications of physical and biological components of the Earth System through time. Unidirectional change results in transformations that never repeat, whereas cyclic change involves repetition of the same steps over and over.

Examples of unidirectional change include the gradual evolution of the solid Earth from a homogenous collection of planetesimals to a layered planet, the formation of the oceans, the gradual change in the composition of the atmosphere, and the evolution of life.

Examples of physical cycles that take place on Earth include the supercontinent

cycle, the sea-level cycle, and the rock cycle.

A biogeochemical cycle involves the passage of a chemical among nonliving and living reservoirs. Examples include the hydrologic cycle and the carbon cycle. Global change occurs when factors change the relative proportions of the chemical in different reservoirs.

Tools for documenting global climate change include the stratigraphic record, paleontology, oxygen–isotope ratios, bubbles in ice, growth rings in trees, and human history.

Studies of long-term climate change show that, at certain times in the past, the Earth experienced greenhouse (warmer) periods; at other times, there were icehouse (cooler) periods. Factors leading to long-term climate change include the positions of continents, volcanic activity, the uplift of land, and the addition or removal of CO₂, an important greenhouse gas.

Short-term climate change can be seen in the near-term record of the last million years, and it can be studied by examining micropaleontology, oxygen-isotope ratios, bubbles in ice, and growth rings in trees.

During only the past 15,000 years, we see that the climate has warmed and cooled a few times. Causes of short-term climate change include the Milankovitch cycle, fluctuation in solar and cosmic rays, changes in reflectivity, and changes in ocean currents.

Mass extinction, a catastrophic change in biodiversity, may be caused by the impact of a comet or an asteroid, or by intense volcanic activity.

During the last two centuries, humans have changed landscapes; modified ecosystems; and added pollutants to the land, air, and water at rates faster than the Earth System can process.

The addition of CO₂ and CH₄ to the atmosphere appears to be causing global warming, which could shift climate belts and lead to a rise in sea level. Sources for added CO₂ include fossil fuel burning, cement production, and deforestation.

In the future, in addition to climate change, Earth will witness a continued rearrangement of continents resulting from plate tectonics and will likely suffer the impact of asteroids and comets. The end of Earth may come in about 5 billion years,

when the Sun runs out of fuel and becomes a red giant.

Video and Animation Files

GLOBAL SEA LEVEL CHANGE

Number: Animation 19.1

Length: 3 minutes, 23 seconds

Summary: This animation shows how global sea level is influenced by melting glaciers, thermal expansion of water, mid-ocean ridge volcanism, and oceanic plateau volcanism.

Classroom Use: This animation could be used as a study guide to help students recall the processes that affect sea level.

Review and Discussion Questions:

1. Name four factors that can cause sea level to rise.
2. Which two of these are primarily responsible for currently rising sea level?

Answers to Review Questions

1. What do we use the term “Earth System” to describe the components of processes operating on this planet?

ANS: Earth processes feature complex interactions among living and nonliving components of the Earth.

2. How have Earth’s crust and atmosphere changed since they first formed?

ANS: Early in its history, Earth was hot enough to be completely molten, even at its

surface. The first crust was a thin skin, which was subjected to subduction and remelting. As Earth cooled, subducted material from the surface no longer completely melted, and partial melting produced magmas that were more silicic than the ultramafic chemistry of the initial mantle and crust. Basaltic magmas formed oceanic crust, and intermediate and silicic magmas crystallized to form buoyant continental crust.

Earth's primordial atmosphere of hydrogen and helium was likely lost to space; a secondary atmosphere dominated by volcanic gases: water vapor, carbon dioxide, sulfur dioxide, and nitrogen. The first three of these were lost to the oceans, which formed as Earth cooled. Oxygen was added by biotic photosynthesis to the remnant nitrogen, and these two gases dominate the modern atmosphere.

3. What processes control the rise and fall of sea level on Earth?

ANS: Global sea level is primarily controlled by the volume of glacial ice on continents, which is inversely related to sea level, and the volume of mid-ocean-ridge volcanoes, which has a positive effect. At times of rapidly moving plates (abundant mid-ocean-ridge volcanism), excess carbon dioxide leads to a stronger greenhouse effect, warming the ocean and melting glaciers (if any are present), which raises sea level by adding ocean water. Rapid volcanism also produces thick mid-ocean-ridge volcanic chains, which displace water onto the continents. Conversely, when sea-floor-spreading rates are low, ridge volume is small, and the atmospheric level of carbon dioxide is also low. The resultant reduction in the greenhouse effect favors the formation of continental glaciers, freezing out water that is now unavailable to the ocean.

4. How does carbon cycle through the various Earth systems?

ANS: Carbon is found in the atmosphere, oceans, biosphere, soils, sediments, and rocks. Carbon dioxide in the atmosphere dissolves in the ocean to form carbonate (and bicarbonate) ions. These ions are removed by a variety of organisms to produce calcium carbonate skeletons, which collect as fragments and grains at the bottom after the organisms die, perhaps later lithifying to form limestone. Carbon dioxide can also be removed, either directly from the atmosphere or from solution in the ocean, through biogenic photosynthesis, to produce organic carbon. Organic carbon may become incorporated into the rock record in shale, oil, and coal, but some may be released to the

environment through animal respiration and flatulence. Weathering of silicate rocks removes atmospheric carbon dioxide, producing bicarbonate ions. Burning fossil fuels releases atmospheric carbon dioxide, as do volcanic eruptions.

5. Contrast icehouse and greenhouse conditions.

ANS: A greenhouse climate is warmer than that of today (especially at the poles), and it is characterized by a high atmospheric concentration of carbon dioxide and a relatively high sea level, with no continental glaciers at the poles. In contrast, icehouse conditions are colder, with permanent ice present at the poles and relatively low levels of atmospheric carbon dioxide and low sea level.

6. What are the possible causes of long-term climatic change?

ANS: (a) The sizes and positions of the continents are important; in order for large continental glaciers to grow, it is favorable to have large continents in regions near the poles; small continents bathed in tropical oceans favor greenhouse conditions. (b) Volcanoes emit carbon dioxide, which adds to the greenhouse effect. (c) Uplifted areas are sites of intense weathering, and chemical weathering draws down atmospheric carbon dioxide. (d) Limestone, coal, organic-rich shale, and oil contain carbon, so when produced in vast quantities and buried, they keep carbon from reaching the atmosphere as carbon dioxide. Carbon burial is a check on the greenhouse effect.

7. How do paleoclimatologists study ancient near-term climate change?

ANS: The record of sediments and sedimentary rocks can be used to decipher ancient climate change because certain rocks are characteristic products of specific environments; further, fossils provide environmental clues because many organisms have narrow environmental tolerances. Oxygen isotope ratios in ice and carbonate sediments provide a proxy for average temperatures. Ancient air bubbles may reveal atmospheric carbon dioxide levels (and thus the effectiveness of Earth's greenhouse). Variations in growth rings and recorded human history can be used to infer climate change in the very recent past.

8. What factors explain short-term climatic change?

ANS: (a) The abundance of sunspots (cool spots on the surface of the Sun, which may represent magnetic storms) varies over the course of a decade or so, and may affect total incident solar radiation. (b) Earth's orbital shape, magnitude of tilt, and direction of tilt vary over Milanković cycles with periods in the tens of thousands of years. These parameters influence whether glaciers are likely to descend over the continents or melt. (c) Earth's albedo can be increased by an increase in aerosols (such as volcanic ash), cloud cover, and surface ice, or the spread of deserts and grasslands over land that was once forested. (d) Ocean currents may change course, altering the hydrologic system that brings warmth to some areas and cold, dry conditions to others.

9. Give some examples of events that cause catastrophic change.

ANS: Comet or asteroid impact, explosive or hyperactive volcanism, and sudden episodes of global warming or cooling can cause catastrophic change.

10. What is the ozone hole, and how does it affect us?

ANS: The ozone hole is a region in the stratospheric ozone layer over Antarctica (a smaller hole sits atop the Arctic) where the volume of ozone has been dramatically reduced: it resulted from the reaction of ozone with anthropogenic chlorofluorocarbons. Stratospheric ozone protects life on the Earth from dangerous ultraviolet radiation. Growth of the ozone hole could lead to increased rates of skin cancer and other forms of cancer.

11. Describe how contemporary global warming takes place and how society may play a role in causing it.

ANS: Carbon dioxide is an important greenhouse gas, allowing solar radiation to reach Earth, but trapping infrared radiation emitted by the Earth. Levels of carbon dioxide in the atmosphere have increased rapidly since the early 20th century. Human activities are primarily responsible for this increase in atmospheric carbon dioxide (and resultant greenhouse warming) because the burning of fossil fuels, the production of cements, and the destruction of forest habitats all emit carbon dioxide into the atmosphere.

12. What effects might global warming have on the Earth System?

ANS: Effects of global warming on the Earth System include sea-level rise, the breakup of polar ice shelves, the melting of glaciers, a reduction in sea-ice formation, shifts in patterns of precipitation and climate belts, changes in the range distributions of animals, imperilment of polar wildlife, stronger storms (including hurricanes), and disruption of oceanic currents (which may bring further climatic change, including cooling of high latitudes).

13. Give some examples of how humans have changed the Earth.

ANS: Extraction of rock and groundwater; overhunting and overfishing; destruction of forests and grasslands; and pollution of the air, streams, and oceans have led to increased mass wasting, famine, high rates of biotic extinction, acid rain, smog, a hole in the ozone layer, climate change, etc.

14. What are some likely scenarios for the long-term future of Earth?

ANS: Unless destroyed by impact (which is very unlikely), Earth will most likely be consumed by the red-giant stage of our Sun's evolution, approximately 5 billion years from now.

On Further Thought

15. If global warming continues, how will the distribution of grain crops change? Might this affect national economies? Why?

ANS: In the modern continental configuration, major belts of grain crops and spruce forests are essentially limited to the northern hemisphere. Substantial warming would cause the climatic belts optimal for grain crops and spruce forests to shift northward. National economies will be affected by these shifts; some more southerly nations in the grain belt will see a substantial loss of agriculturally productive land. Further, because of

the spherical shape of Earth, there is less total land area available at high latitudes than at midlatitudes, so the world's grain supply would likely be reduced. These problems can be mitigated by developing strains of heat-resistant grain or converting to other crops that are suited to the new climatic conditions. Compounding the problem is a less predictable shift in precipitation patterns.

16. Currently, tropical rainforests are being cut down at a rate of 1.8% per year. At this rate, how many more years will the forests survive? In the eastern United States, the proportion of land that has forest cover today has increased over the past century. In fact, most of the farmland that existed in New York State in 1850 is forestland today. Why?

ANS: Assuming a linear rate of deforestation, the forests would survive for 55.55 years. In the mid-19th century, farms were of much smaller scale than they are today, with a variety of crops being grown to feed the family of the farmer and the surrounding community. Small-scale farmers today have difficulty competing with larger-scale farms, and New York has hilly topography that makes large-scale farming less viable than it is in the midwestern "grain belt" of flatter land stretching from Ohio to North Dakota and Kansas. New York also has a short growing season, so vegetable farms are not as successful there as they are in warmer, sunnier states, such as California and Florida.

17. Using the library or the Web, examine the change in the nature of world fisheries that has taken place in the last 50 years. Is the world's fish biomass sustainable if these patterns continue? What has happened to whale populations over the past 50 years?

ANS: Fisheries' stocks, for the most part, are not sustainable into the indefinite future given current rates of consumption. Many whale species are endangered, and populations have continued to decline for some species even though most nations no longer participate in commercial hunting. Whales are still threatened by hunters from Norway, Japan, and the North American Inuit, as well as by pollution, global warming, and ship strikes. Particularly vulnerable are the northern and southern right whales and the bowhead, blue, sei, fin, and humpback whales. Less endangered are the smaller minke whale and the sperm whale, which spends most of its life hundreds of meters below the surface. Recently, there has been some good news with the recovery of populations of the Pacific gray whale.