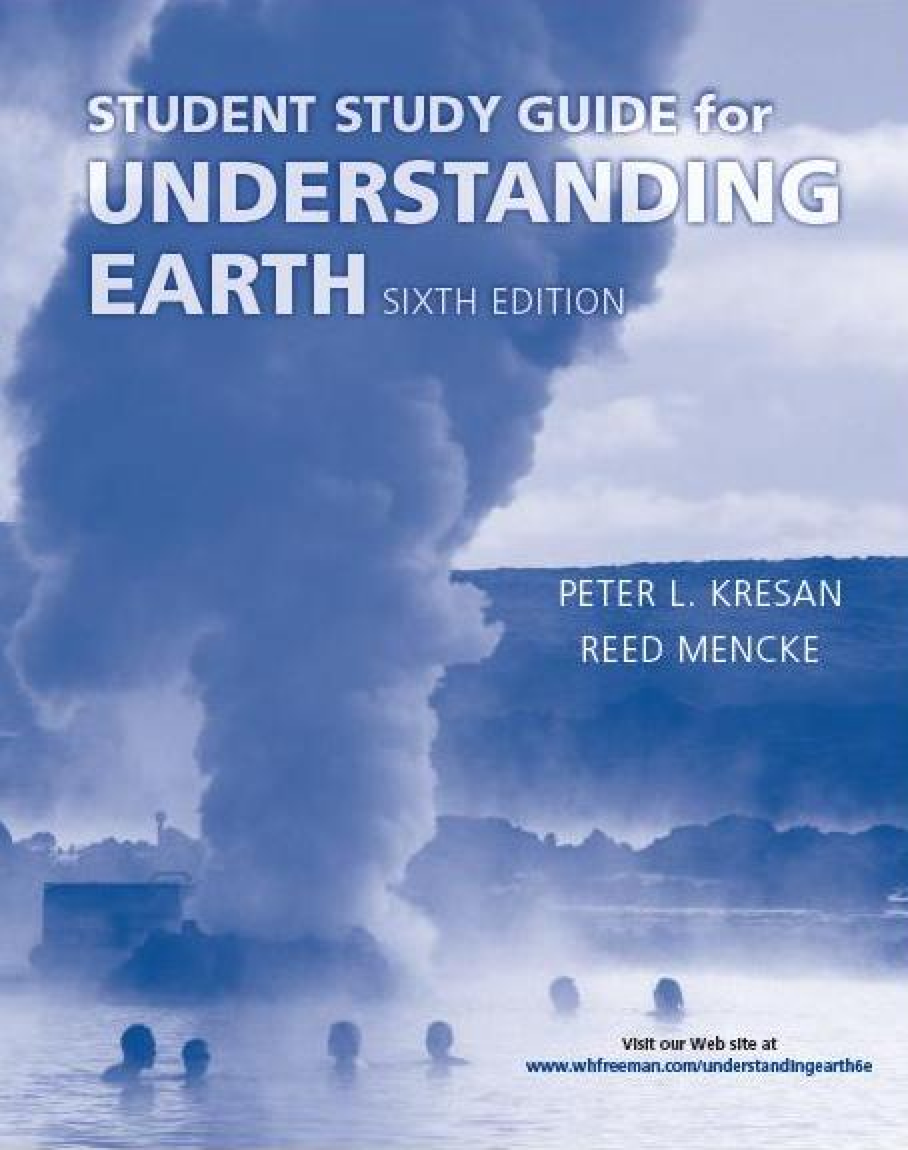

STUDENT STUDY GUIDE for UNDERSTANDING EARTH

SIXTH EDITION

PETER L. KRESAN

REED MENCKE

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Student Study Guide

for

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UNDERSTANDING EARTH
Sixth Edition

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CHAPTER 1

Brief Preview of the Study Guide for *Understanding Earth*

We know from personal experience that studying geology can be very rewarding. Geology allows you to look at the Earth around you and understand how it came to look the way it does. Geology offers scientifically sound explanations for geologic disasters such as earthquakes and volcanoes. We also know that mastering the ideas of geology can be challenging. The main goal of this Study Guide is to help you meet that challenge. We think you will find the organization of this guide both practical and helpful. Success in geology revolves around lecture, as do the study aids in this guide. Specific geology study strategies are woven throughout the guide, including how to take great notes and how to prepare for exams. Study aids are laid out step by step (see the flow chart on page 3) so you know what to do before lecture, during lecture, after lecture, and during exam preparation. A final appendix, **How to Study Geology,** brings all these aids together into a short course on effective study strategies. Here's how to use these materials.

Before Lecture: Preview

The key to taking good notes is to arrive in class with an overview of what will be covered already in mind. That way you will already know what geological processes will be explained and what key questions the lecture will answer. In lecture you can *actively* listen for answers to those questions. Listening actively with specific questions in mind is guaranteed to result in understanding more of what is said and including more of the key points in your notes.

The method you use to gain an overview is called **Chapter Preview.** To make previewing easier for you, we begin each chapter of the Study Guide with the three or four key questions the chapter (and its corresponding lecture) will cover. Brief answers designed to help you start thinking about the material are supplied as well. Working with these questions and answers ahead of time will bring you to lecture ready to listen and take good notes.

During Lecture: Take an Excellent Set of Notes

With the basic questions in mind, you have a head start on taking good notes. But note taking is a skill, and as is true with just about everything else in life, you get better with practice. We provide a **Note-Taking Checklist:** specific actions you can take to get more of the content into your notes in a usable form. For many chapters we provide additional note-taking tips that are specific to the chapter, for example, suggestions about what to listen for or figures you need to review carefully before a particular lecture.

After Lecture

After each lecture we suggest that you schedule two separate sessions: a brief note review and improvement session and an **Intensive Study Session** (lasting at least an hour) during which you achieve mastery of the lecture's content.

Have you checked your notes? Note taking is not confined just to lecture. Notes can almost always be improved after lecture. Good students know this and take the time after lecture to revise their notes. These students also pull additional points on every midterm as their "paycheck." Specific suggestions in every chapter of the Study Guide will help you improve your lecture notes. Often these suggestions focus on adding visual material from the text or summarizing what was covered in a form that will be easy to remember.

Intensive Study Session. The purpose of the intensive study session is to master the material taught in lecture. Learning and cognitive psychology teaches us that reading passively is an inefficient way to learn. You learn best if you spend your study time answering questions. With this method you read portions of the text as you need them to find answers to questions. It's a lot like the way we learn a new software package on the computer. We may not read the software manual first. Instead we load a program and start using it. Then we go to the manual (or online help) when we need to find out if we can do something with the program, or to see how to do it. Applying this to the textbook, you will learn geology most efficiently by working backward from questions, and for each chapter we suggest questions you can use this way. And often we suggest other guiding questions from *Understanding Earth* or the Web site. Simply stated: Do answer questions, don't "just read." You will learn and remember more science much faster.

Exam Prep

Doing well on college exams is mostly about organization. Effective study requires a systematic, orderly review. Most of your review time (about 70 percent) should be spent answering review questions. For each chapter of the text the Study Guide includes a **Chapter Summary, Practice Exercises, Review Questions,** and **Web activities.** Using these features is the fastest way to learn and the best way to remember the information you have learned. Study tips for preparing for midterm and final exams, helpful hints that will improve your test-taking skills on multiple-choice tests, and information on how to use your personal learning style to your advantage during exams may also be found in this section.

How to Study Geology

BEFORE LECTURE

Prepare for lecture: Arrive with an overview in mind.

- Chapter preview
- Vital information from other chapters

DURING LECTURE

Take an excellent set of notes.

- Note-Taking Checklist

RIGHT AFTER LECTURE

- Review notes.
- Fill in what you missed.
- Add visual material.
- Use the "Have You Checked Your Notes?" section of this guide.

AFTER LECTURE

Intensive study session
Master the key concepts.

- Web site activities and tools
- Practice Exercises and Review Questions

EXAM PREP

Begin review one week before the exam.

- Chapter Summaries
- Practice Exercises and Review Questions
- Tips for Preparing for Geology Exams (Appendix B)
- Eight-Day Study Plan (Appendix A)

CHAPTER 2

Meet the Authors of *Understanding Earth*: How to Use Your Geology Textbook

As you begin your study of geology, first take a minute or two to get acquainted with your text. First of all, why do you think it was written? Here is what your text authors have to say about why they wrote the book:

> *Geology fascinates and excites us. We wrote* Understanding Earth *to help you discover for yourselves how interesting geology is in its own right and how important an understanding of geology has become for making decisions of public policy. What can we do to protect people and property from natural disasters such as volcanoes, earthquakes, and landslides? How can we use the resources of Earth—coal and oil, minerals, water, and air—in ways that minimize damage to the environment? In the end, understanding Earth helps us understand how to preserve life on Earth.*

They add that people tend to enjoy what they do well. They designed their text to help you do well in your geology course. Many aids to learning are built into the text. Let's spend a minute or two talking about these aids and how you can use them.

Clues and Tools: "What's Important?"

One of the toughest things about taking an introductory course is that you typically have very little knowledge of the subject matter. Not only do you have a lot to learn, but you have a lot to learn about *how* to learn it. Where should you focus your attention? What skills and concepts should receive the bulk of your study energy? Aids to help you see what material is important are built into every page of *Understanding Earth*. But you have to know where to look for these aids and how to use them. Here is a short list of learning aids in your text and a few preliminary thoughts about how to maximize their usefulness.

✓ **Chapter Outline** The authors begin each chapter with an outline of what will be covered. To use this tool you need to look actively for clues. Look at the outline for Chapter 1. Each item in the outline is a clue to what will be covered in the chapter. Try turning each item in the outline into a question. **Example:** Ask yourself, "What is the scientific method?" as you read that section. Pay particular attention to material in the outline you find intriguing, surprising, or puzzling in any way. Use your surprise or puzzlement to motivate yourself when you read that section. **Example:** Consider the item "Earth as a System of Interacting Components." Here there are two possibilities. You may be puzzled about what components the authors are referring to. In that case, activate your curiosity. Frame your surprise in a question such as "What in the world are the authors talking about?" or "What are Earth's interacting components?" Read with the question in mind.

✓ **Chapter Summary** At the end of each chapter a brief summary emphasizes the most important ideas of the chapter. This is a very useful resource when you are studying for an exam.

Time Saver Tip

Before reading a chapter of the text, read the Chapter Summary first, referring as you do so to the Chapter Outline. The outline and summary will provide an overview, or organizer, that will greatly accelerate your reading and understanding of material. **Hint:** Also use the **Chapter Preview** questions in this Study Guide. These questions are specially devised to help you focus on the most important material.

✓ **Key Terms** within the text are printed in bold. You can speed up your reading time by being vigilant for key terms. When you see a **boldfaced term** you know it is the most important concept in that paragraph. Focus on understanding the concept.

✓ **Photographs** Geology is a very visual science. Pictures in the text are essential. Use them as a "virtual field trip" to help you learn what particular rocks and formations look like. Perhaps you have heard of or even visited some of the photo sites. **Example:** See Figure 1.4 in Chapter 1. Pay particular attention to the photographs that are paired with schematic figures or diagrams and refer to them as you read.

Study Tip

Having a tough time getting yourself started in a study session? Use the art to motivate you. Start a chapter study session by scanning the images and captions to find material that interests you. Begin your reading with this material. This approach works like starting a fire. You generate a small spark of interest and then fan it by bringing in new material.

✓ **Figures (Flowcharts)** Figures are even more important than photographs. Flowcharts such as the rock cycle in Figure 3.26 present key concepts. Pay careful attention to the arrows in flow models and ask yourself what drives the process and what products are formed. If you are a visual learner, you may even want to study the figures and sketches before you start to read. Then read text on an as-needed basis, to clarify the figure.

✓ **Color** is used in the figures to provide you with clues about how each process works and what is involved. Look at Figure 1.15 in Chapter 1. What color is used to describe processes that utilize heat? What color depicts water? Cooling? Such cues can support learning at a subliminal level of awareness, particularly if you are a visual learner—so be sure to pay close attention to the colors in the figures!

✓ **Clues to rock texture** are also cleverly built into the text. Look at Figure 3.25. The igneous rock is shown in shades of black with lots of dots and specks of varying size. This makes sense given that igneous rock is classified on the basis of the size of its crystals.

Why are sediments and sedimentary rock depicted as horizontal stripes? Because sediments are formed of earthy materials like sand and mud, and they are originally laid down in horizontal sheets and layers. Why is metamorphic rock depicted with a series of distorted and folded bars? Because metamorphic rock is created when other kinds of rock are subjected to high pressures and temperatures that may distort the rock into folds and its crystals into wavy, foliated bands. Thus the figure speaks to us about what the rock looks like as well as the processes that produce it. Pay close attention to these and other visual learning clues.

Questions and Exercises to Help You Learn

✓ **Exercises** (end of chapter)
✓ **Thought Questions** (end of chapter)

Psychologists have firmly established the importance of actively learning by asking ourselves questions about the new information we are attempting to learn and then seeking the answers to these questions. When we formulate inquiries before we start reading new material, we tend to read in a more active manner since we are reading in search of specific answers. This is far more efficient than trying to read about the information you are attempting to learn in a passive manner (passive reading is okay for magazines such as *Sports Illustrated* but not for a college science textbook). Think of the end-of-chapter summaries and review questions as your own personal tutor. What does a good tutor do? She or he asks you questions to get you thinking about the material. Like a good tutor, the questions at the end of each chapter clue you in to what is important and encourage you to really master the material.

You can use both the Exercises and Thought Questions at the end of each chapter of *Understanding Earth* in three different ways. First, use them to preview the chapter. Skim quickly to get an overview of what you will be expected to know after you have read the chapter. Second, seek out answers. Active learning works better than passively reading the text. So organize your study time around finding an answer to one or more exercises or questions using your text as you would a reference book. Third, use the questions to review for exams. Quiz yourself by trying to answer the questions without using the text as your reference. Go back to your annotated text to check the accuracy of your answers. The best way to learn from a text is to use it as a reference to answer questions.

Text-Marking Strategy for *Understanding Earth*

You can make the 30 percent of your study time you spend reading the text even more efficient by skillful text marking. Marking your text as you read is a vital part of learning the material and may be particularly important if you are a kinesthetic learner. The action of marking will aid your kinesthetic memory. If you are a visual learner, you will tend to remember marked sections during exams. Good marking involves both thinking and planning. First, you think about what is important. Then you plan for exam review, deciding which of the marking techniques in the following table will best help you when you return to the chapter during exam review. Only then should you mark. The authors have already marked **key terms** in **bold** letters. You will want to add underlines, numbers, and annotations in the margin. If you use the eBook, you can use the highlighting, Top Note and Stick Note features. Here are some brief suggestions for how and when to use each kind of mark.

Useful markings for geology	Text-marking tips
Underlining Underline important points. Underline to highlight the **key ideas**. Do pay attention to the **key terms** that are in boldfaced type in the text.	1. Read before you mark. To avoid overusing underlining, set your pencil down on the table as you begin to read a paragraph. Don't let yourself pick up the pencil until you have read the entire paragraph. Stop and think. Then underline what you consider to be the key point(s). 2. Be selective. Underline brief but meaningful phrases or key words that will trigger your memory. Mark just enough so that you can review without rereading the paragraph. 3. Use different color markings if it helps you remember.
Summarizing Write a brief summary statement of **key geology processes** in your own words in the text margin. Use these annotations to facilitate exam review.	1. Use your own words. Putting ideas into your own words is a powerful learning strategy. 2. Be neat. This takes time. But it will pay off later when you review because your annotation will be legible and easily read. 3. Organize your annotations into categories. Grouping ideas into categories or bulleted lists makes them easier to remember. 4. Use annotations during exam review. Avoid rereading the text word for word. This will save you a lot of time.
Annotating	**Circled numbers** in the margin indicate sequences, such as the processes of the rock cycle. **Question mark?** Put a question mark in the margin to remind yourself to ask your instructor about a point you do not understand. **Asterisks ***** Use asterisks to mark ideas of special importance. Use asterisks sparingly. Save them for the two or three most vital ideas in the entire chapter. **TQ (test question)** Use TQ to mark material in the chapter that you know will be covered on the exam. This will remind you to pay particular attention to these items.

Marking the text will aid kinesthetic learning. Good text marking will aid visual memory—so use caution when marking up your text. *Mark carefully and selectively*. If you mess up the text with excessive and illegible markings, you may interfere with some of the good memory aids that are built into the careful design of the text. Remember, a well-marked text will make exam review far more efficient because the marks will focus your attention on the key material you need to find and review. If you are worried about the impact of marking on your textbook's resale value, be sure to ask your bookstore. Many bookstores have policies that encourage effective text marking.

STOP

TRY THIS NOW!

1. Try underlining. Choose a section you consider to be important, key material. Read the passage several times until you are sure you understand it. Then mark the passage following the directions in the table.

2. Summarize a geological process. Choose a section that contains a geological process that you think is important enough to be covered on the next exam. Annotate the process in the margin in a manner that will help you remember it. Use the directions in the table as a guideline.

3. Try some annotating. Where would circled numbers be helpful in this chapter? Put them in. What material do you need to discuss with your instructor? Mark with a question mark.

4. Figure out what is the most important idea in the entire chapter. Put three asterisks (***) and a TQ beside that section to insure you master it before the exam.

CHAPTER 3

How to Be Successful in Geology (and Just About Any Other Challenging Course)

Academic success is largely a matter of strategy. If you manage your time well and study strategically (rather than haphazardly), you will be successful. In this chapter we discuss successful studying strategies for your geology course. The best way to use this chapter is to read each strategy and then try it out. We recommend reading one section of this chapter each day at the beginning of a new semester. Try the strategy in that section before reading further. Following are the success strategies that will be covered in this introduction:

- Learning style
- Chapter preview
- Note taking
- Note review
- Exam preparation

Many other learning strategies and hints about learning specific material are provided throughout this Study Guide. Look for them and try out as many of the strategies as possible. Learning strategically initially takes an investment of time, but you will find that it is an investment that pays off. Studying strategies make you more efficient so that you can learn more in less time. More important, you get more enjoyment out of your learning because you know exactly what you are doing.

Customize Each Strategy to Your Learning Style

Each of us learns differently. Successful people in any activity tend to be those who find a way to express their own unique talents in the activity. Most of us worry too much about competing. We would do better to seek a way of using our best skills and talents. It is our individuality that makes us stand out from the pack and become a leader. It is our individuality that leads us to be successful academically. We recommend that you spend some time thinking about your individual style, your strengths as a learner, and how you prefer to learn. Here's a simple beginning. Which mode of learning do you prefer to use and use best?

- ☐ **Visual Learning** Visual learners learn by seeing. They often have a good memory for pictures and even words of text.
- ☐ **Auditory Learning** Auditory learners learn by listening. They are good listeners and remember best by just listening.
- ☐ **Kinesthetic Learning** Kinesthetic learners learn by moving. They learn and remember best when they get to practice an activity.

STOP

TRY THIS NOW!

Put a 1 in the box next to the mode of learning you prefer most strongly, a 2 for your next strongest mode, and a 3 beside the mode you think you use least well and least prefer to use. **Hint:** Usually, the mode we prefer is the one we use best. If you are not sure which mode you prefer, try taking the Learning Style Inventory online at the University of Arizona Learning Center Web site: www.ulc.arizona.edu (click on Self-Assessment).

Throughout the Study Guide we will make suggestions about how particular strategies might work best for those who prefer one of the aforementioned learning styles.

Make Geology Lecture a High-Priority Activity

This is step 1 in any strategic approach to course success. Your geology course centers on lecture. Geology is a very content-intensive subject. There's so much to learn that instructors have to make some difficult decisions about what to cover. Sometimes the faculty in a geology department try to address this problem by mapping out required content, perhaps even creating a core syllabus for instructors to follow. Even then instructors can and do manage to create very different courses. In our conversations with other instructors we have been quite impressed with the degree to which teaching approaches differ. Two geology instructors may use the same text and perhaps even the same basic lecture outline yet still teach two very different courses *with very different exam questions.* Therefore, attending lecture is fundamental to success. Most students who fail geology do so because they fail to attend lecture. Just attending will put you far ahead of those who fail.

However, just attending is not enough to ensure that you get an A in geology. Research shows that few of us have the attention span to listen actively and take good notes for an entire hour. The average note taker gets most of the main points during the first 10 minutes of the lecture. Then attention wanders, confusion sets in, and less and less of what is said gets into the notes. Indeed, most students absorb less than 15 percent of the points that are covered in the final 10 minutes of the lecture. This is doubly unfortunate since, inevitably, the lecture gets to the heart of the topic and the material you will certainly be tested on toward the end.

What you actually do in lecture is fundamental to success in geology. You need to be a strategist. You need to target your approach to your geology course on getting the most possible out of lecture. That is our best advice and we have adhered to it rigorously in constructing this guide. The entire Study Guide is organized around lecture. Every chapter begins with what you do *before lecture* for that particular chapter topic. Next comes a section with tips on what to do *during lecture;* after that, a checklist to help you improve your notes *after lecture;* and finally, lots of exercises and review questions to help you with *exam prep* before your midterm.

In this chapter we present general strategies you can use every day of your course to ensure success—all organized around lecture.

Before Lecture

Strategy: Preview the chapter before going to the lecture

To preview a chapter, use the **Chapter Preview** questions. These questions are provided at the beginning of each chapter of the Study Guide. Read each question, then skim the chapter to find the relevant material. Feel free to annotate the brief answers provided for each question. The idea is to go to lecture with a general idea of the answers to the questions in mind.

Why preview? Introductory courses can be difficult. There are lots of new terms, new ideas, and new skills during a first-semester geology course. But which ideas are "important"? How do you focus your effort in this new and seemingly strange terrain?

> *Picture a house under construction. Imagine that the contractor was very careless and neglected to construct whole sections of the frame. Finishing the areas lacking a frame would be impossible. You can't tack siding onto thin air! This metaphor describes your geology lecture. You are the contractor. You need to arrive at class with an overview of the lecture already in mind. You have already identified what geological processes will be explained and what key questions the lecture will answer. Going to class without a frame of key questions is like building a house with no supporting structure. You will have nothing on which to hang the lecturer's main points (information). Without the main points, the details are meaningless. As the lecture progresses you are likely to feel increasingly confused and bored. By the time the lecturer gets to the most important material, you may be completely lost.*

Where do you get the overview? The answer is surprisingly simple. Just spend a few minutes before lecture previewing the chapter that will be covered. Previewing is the method by which you generate and master a framework for listening. Here's how to do it.

Step 1. Read the preview questions. You will find **Chapter Preview** questions at the beginning of each chapter of the Study Guide.

Step 2. Skim the text chapter for answers. Quickly find and read only the material in *Understanding Earth* you need to understand and answer the questions. Don't bog down in details. Don't try for complete understanding. Don't read the whole chapter. Your goal is to a gain just a general understanding of each question. Do use the **brief answers** provided in the Study Guide to cue your reading.

Step 3. Memorize the questions and brief answers. You may find that you need to add a few notes to the brief answer. Annotate the answers just enough to ensure that the answers make sense to you. Annotate in a way that will ensure that you memorize the questions.

Before you go to lecture, be sure to spend some time previewing. You will find that as little as 10 to 15 minutes of time spent previewing can make a big difference in how much you understand of the lecture. With the key points already in mind, you can focus in lecture on understanding the details. This, in turn, will help ensure you get an excellent set of notes.

TRY THIS NOW!

Move immediately to the chapter that will be covered in your next lecture. Preview the chapter. Then return here to read the next strategy.

During Lecture

Strategy: Note-Taking Checklist

Your basic goal during lecture is to take good notes. The notes should answer the **Chapter Preview** questions in depth. To avoid getting lost in details, keep the big picture in mind. Have a copy of the **Chapter Preview** questions in front of you. Better yet, develop preliminary answers to the questions and commit them to memory before the lecture.

Another way to keep the big picture in mind is to bring a copy of the key figure or flowchart to lecture to refer to. In many chapters we suggest which figure you should have handy.

During some classes the lecturer may show rock formations and may pass around specimen rocks. You will get more out of these demonstrations if you sit close to the front of the room where you can see the sample rocks as the lecturer discusses them. Remember to focus on clues the lecturer provides for recognizing a particular sample in the field. Focus in particular on the texture of samples and learn to recognize differences, for example, the fine texture of a volcanic rock and the coarse texture of a plutonic rock.

As you listen to lecture, identify questions you need to ask to understand the material. Try to formulate at least one good question you can ask during every lecture.

The most important task during lecture is, of course, taking a good set of notes. Note taking is not easy. It is a skill that improves with practice. Here are a few tips that will help you.

Note-Taking Checklist

- ☐ Organize your notes in a three-ring binder so that you can easily reorganize them.
- ☐ Leave space in your notes for important visual material (flowcharts, simple sketches, comparison charts). To make this easy, employ a double-column or double-page note-taking format. Take notes on the right-hand page or column. Save the facing left page as a "sketch page."
- ☐ Sit near the front of the room—not to be a teacher's pet but simply so that you can hear and see better!
- ☐ Date each day's notes so that you can find material later.

- ☐ Take notes in a format that makes the main topics and concepts easy to identify. Some students accomplish this by taking notes in outline format. But many other approaches are possible. Visual learners may find it helpful to highlight main points (after class) in color. Another good approach would be to use the questions we provide in the **Chapter Preview** as heads. You can add them during class or during your after-class review session.
- ☐ Keep the preview questions in front of you during lecture. Be sure to leave class with a good answer to each of the preview questions.
- ☐ Mark areas where you need to do follow-up work with your text, instructor, or tutor with a question mark in the margin.
- ☐ Indicate possible test questions by writing TQ (test question) in the left margin where you can easily see it.
- ☐ Write assignments in the left column where you can easily find them. After class enter the due date in your personal planner or calendar.

STOP

TRY THIS NOW!

Take the note-taking checklist with you to your next lecture. Try to follow all the suggestions. After lecture review your notes and check off each point that you actually followed. Then return here to read the next strategy.

Hint: Photocopy the checklist and use it for every lecture until all the strategies become habits. Used this way, the checklist becomes a visual record of your progress as a skillful note taker.

After Lecture

Review Your Notes Immediately

Good note taking continues after the lecture is over. Right after lecture, while the material is fresh in your mind, is the perfect time to review your notes. Review to be sure you understood the key points and wrote them down in a form that will be easy to review later.

Don't postpone this activity. The best time is right after lecture before you go to your next class or activity. Learning experts tell us that most of us will forget 80 percent of what we heard in a lecture by the following day. On the other hand, if you review right after the lecture, there will have been no interruptions. Much of what was said will still be in your short-term memory. If you missed something, you can probably remember it and put it into your notes. The basic idea of reviewing your notes is to fill in what you missed and to add helpful visual material from the text. Use the following checklist as a guide.

Check Your Notes: Have you…

- ☐ written legible notes? (Rewrite them if you need to!)
- ☐ identified the important points clearly? (You should have headings in your notes for each of the questions in the **Chapter Preview.**)
- ☐ filled in the holes (missing material) while the lecture was still fresh in your short-term memory?
- ☐ marked areas where you don't remember what was said for a follow-up session with your instructor, tutor or study partner?
- ☐ indicated possible test questions (TQ) in the margin?
- ☐ added additional visual material?
- ☐ reworked notes into a form that is efficient for your learning style?
- ☐ created a brief big picture overview of this lecture (using a sketch or written outline)?

TRY THIS NOW!

After the next lecture, review your notes and improve them using the points in the checklist as a guide. Check off each point as you complete it. Then return here to read the next strategy. **Hint:** Consider photocopying the checklist so that you can use it repeatedly.

Intensive Study Session

Ask yourself questions as you study. Then answer them.

You should schedule at least one hour after each lecture for intensive study. This can occur anytime before the next lecture. (Short-term memory is no longer a problem since you have completed a note review and have good notes.)

Why do you need an intensive study session? Think about the house/construction example that we mentioned earlier. You need frames before you can add the siding, so you construct a frame of questions before each lecture. During lecture, you add the siding—the answers to the questions. After lecture, master the ideas and details during an intensive study session.

Now you have constructed the first story. But this geology course is a skyscraper with 23 floors (one for each chapter). Each chapter supports those above it. If you don't completely master a chapter, the next will be more difficult.

Mastery is not gained by just reading the text. Mastery occurs as the result of asking yourself questions and answering them. To help you we provide **Practice Exercises** and **Review Questions** for every chapter of the text. This interactive learning material is specifically designed to help you master the key concepts of each chapter. The greater the number of these exercises and questions you can work into your intensive study sessions early in the course, the easier subsequent chapters will be. Plan to spend the majority of your study time (70 percent) on these exercises and questions.

Use your text as a reference. Read it as needed to answer questions and master material. When you read, read efficiently. Read with purpose and read to find answers to questions. **Hint:** To use your text effectively you must know it like the back of your hand. Carefully read Part I, Chapter 2, How to Use *Understanding Earth* in this guide.

STOP

TRY THIS NOW!

Each chapter of the Study Guide contains a section titled **Intensive Study Session.** Turn now to the chapter you are currently working on and try out its **Intensive Study Session** material. Do enough to get a feeling for how **Intensive Study Session** works. Then return here and read the next section.

Exam Prep

Materials in this section are most useful during your preparation for midterm and final examinations. For optimal performance, midterm preparation should begin about eight days before the exam (see the **Eight-Day Study Plan** in Appendix A). The basic idea is a systematic review of material divided into short study sessions.

Tips for Preparing for Geology Exams

- Use the clues your instructor has provided in lecture about what is important. Even when a department agrees on a common core of material (a very rare occurrence), each instructor carves out a course that is unique, has a particular character or flavor, and has distinct areas of emphasis. Your instructor is the ultimate guide on what is important.
- Be sure you know the format of the exam. Multiple choice? True–false? Essay? Thought problems?
- Review your notes marked TQ (test question).
- Ask your instructor if exams are available from the previous semester. Review them to check the format of questions, see what areas of content are stressed, and find out what types of problem solving are included. Don't make the mistake of assuming that the same questions will be asked this semester.
- Be sure to attend review sessions if they are offered.
- If you have tutors, preceptors, supplemental instruction leaders, or other peer helpers who have taken the class, ask for their suggestions about preparing for the exam.
- Once you are clear about the nature of the exam, begin your review. Conduct review in an orderly, systematic manner that focuses on all the important material. The **Eight-Day Study Plan** (Appendix A) is a good model for an orderly review.

Test Taking

In every college exam, a number of students know the material yet fail the test because they get anxious, panic, and freeze up. We have found over the years that the best way to overcome or avoid test anxiety is by coming to the test well prepared and confident and by working strategically on the test. Exam prep will not be a problem if you use the materials provided for this purpose in this Study Guide. In this section, we will suggest strategies to try out during your exam. You may want to return to this section a day or so before your exam.

Test-Taking Tips for Different Learning Styles

Visual Learners

- Use written directions.
- When you get stuck on an item, close your eyes and picture flowcharts, pictures, field experiences, or text.

Auditory Learners

- Pay attention to verbal directions.
- Repeat written directions quietly to yourself (moving your lips should be enough).
- If you get stuck, remember the lecturer's voice covering this section.

Kinesthetic Learners

- When you get stuck, move in your chair or tap your foot to trigger your memory.
- Feel yourself doing a lab procedure.
- Sketch a flowchart to unlock the memory of a process.

Many exams are in multiple-choice format. Here are some tips to maximize your performance on multiple-choice questions.

Test-Taking Tips for Multiple-Choice Exams

10. **Answer the questions you know first.** Flag items where you get stuck and come back to them later. Often you will find the answer you are looking for embedded in another, easier question.

9. **Try to answer the item without looking at the options.** Then check to see if your answer matches any of the options.

8. **Eliminate the options.** Treat each alternative answer as a true–false item. If "false," eliminate it.

7. **Use common sense.** Reasoning is more reliable than memory.

6. **Underline key words in the stem.** This is a good strategy when you are stuck. It may help you focus on what question is really being asked.

5. **If two alternatives look similar,** it is likely that one of them is correct.

4. **Answer all questions.** Unless points are being subtracted for wrong answers (rare), it pays to guess when you're not sure. Research indicates that the item with the most words in the middle of the list is often the correct item. But be cautious. Your professor may have read the research, too!

3. **Do not change answers.** Particularly when you are guessing, your first guess is often correct. Change answers only when you have a clear reason for doing so.

2. **If the first item is correct, check the last.** If it says "all (or none) of the above," you obviously need to read the other alternatives carefully. Missing an "all of the above" item is one of the most common errors on a multiple-choice exam. It is easy to read carelessly when you are anxious.

1. **READ THE DIRECTIONS BEFORE YOU BEGIN!**

Final Exam Week

At the end of each semester, in one or two weeks, you take an exam in each and every course. Most of the exams are comprehensive finals that cover the entire semester. Dealing with finals week successfully is a major challenge. Here are some tips that will ensure that you do your best work during final week.

Tips for Surviving Finals Week

Be organized and systematic. Use the Final Exam Prep Worksheet (Appendix B) to help you get organized for finals. Use the Eight-Day Study Plan (Appendix A) for every course where the final exam will be an important factor in determining your grade.

Stick to priorities. Say **no** to distractions.

Build in moments of relaxation. Take regular short breaks, exercise, and get enough sleep.

Be confident. By now you have built up a good set of study habits. You are a competent learner.

Organizing for final exams can be quite a challenge. As with any big project, spending organizing time up front will pay big dividends. Modify the suggestions in the **Final Exam Prep Worksheet** to fit your personal situation and needs.

We wish you success!

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CHAPTER 1

The Earth System

***Civilization exists by geological consent…
subject to change without notice.***

—WILL DURANT

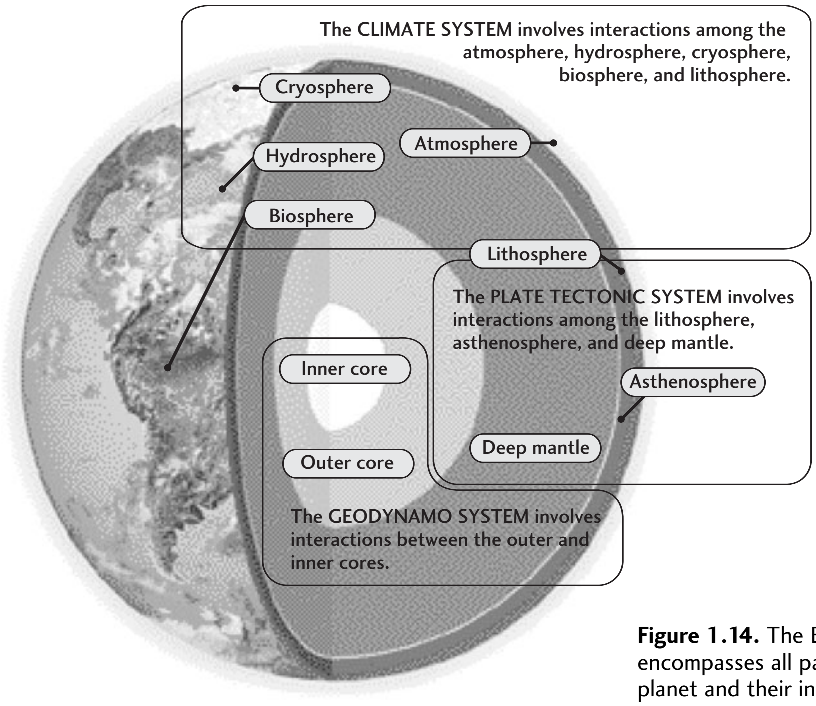


Figure 1.14. The Earth system encompasses all parts of our planet and their interactions.

Before Lecture

Chapter Preview

- **How do geologists study Earth?**
  Brief answer: Using the scientific method. Figure 1.1 is an excellent preview to the process.

- **How was Earth's size first measured and what is Earth's topographic relief?**
  Brief answer: Eratosthenes measured the circumference of the Earth sometime around 250 B.C. Figure 1.8 shows Earth's topography with respect to sea level. The sense of scale provided by Figure 1.8 is very important.
- **What is Earth's internal structure and composition?**
  Brief answer: The crust, mantle, and core are the major concentric layers within the Earth. These layers and their subdivisions are thought to represent changes in composition and in physical state (solid versus liquid). Preview Figures 1.9, 1.11, 1.12 and 1.15.
- **What are the major components of the Earth System?**
  Brief answer: Figure 1.14 illustrates Earth as a system of interacting components, including the atmosphere, hydrosphere, biosphere, and interior.
- **What were some key events in the history of the Earth?**
  Brief answer: Figure 1.17 presents the highlights. Focus on the connections between geologic and life history.

During Lecture

This will be your very first lecture for this course. Get off to a good start. Arrive 10 minutes early. Find the best seat in the house: close to the front of the room, where you can hear the lecture and see the slides. This section is referred to by some as the "A section." Quite apt, since there really is a correlation between where you sit in a lecture hall and the grade you are likely to receive. Test this out. Try sitting in different locations the first week. Notice where it is easiest to concentrate and where it is most difficult. In many lecture halls the back row is the worst place to be. It is the location chosen by students who arrive late and leave early. It may even be noisy. Always feel free to change locations if your view is impeded by projection equipment or if you can't hear because of the whispered conversations of other students. Talk to your instructor if you need to.

Okay, you have good seat. What can you do while you wait for lecture to begin?

- **Motivate yourself to want to listen to this lecture.** Open your text to Chapter 1. Thumb through the chapter. Take a good look at the photos and figures. Look for topics that interest you. Chapter 1 is loaded with visual material that should make it easy to find subjects of interest. Ask yourself what you would like to know about this chapter. What would you ask your teacher if this were a one-on-one tutorial? Finally, try to think of some experience you have had that relates to this chapter. Maybe you visited a planetarium or read a catchy version of the formation of the universe like *Cosmic Comics* by Italo Calvino. Or maybe you saw a volcano on your last vacation. Actively look for experiences to hook your interest and to connect you personally with course information. Notice that the more you look at the chapter and the more you let yourself think about the pictures, the more your interest builds. Five minutes should be enough to get your "motivational engine" turned on and humming.
- **Prepare your mind for learning.** Master football players warm up by running, stretching, and passing the football. Master learners warm up by focusing their attention on what will be covered during lecture. Spend a minute or two looking over the **Chapter Preview** questions. Try to anticipate how these questions will be answered in lecture. If you have time, read the **Chapter Summary** for Chapter 1. When you preview, the goal is not to learn the material but merely to formulate questions that you expect to be answered during the lecture. With questions in mind you are ready to take notes.

Learning Tip

Do a learning warm-up before every lecture. Arrive 10 minutes early. Anticipate questions that will be answered in lecture.

The man who is afraid of asking is ashamed of learning.

—Danish proverb

After Lecture

Review Notes

The perfect time to review your notes is right after the lecture while the material is still fresh in your mind. Review to be sure you observed all the key points and wrote them down in a form that will be readable later. As you review, you can polish your notes by adding useful visual material and a summary.

Check Your Notes: Have you....

- ☐ added a simple sketch or two to clarify the key points? **Hint:** Try sketching your personal version of how convection drives plate tectonics based on Figure 1.15. Make it simple—something you will easily picture and remember.
- ☐ written a brief (one-paragraph) summary of the most important concept you learned from this lecture? Feel free to use your notes and figures in your text as needed. Reviewing preview questions may help.

You will spend some of your study time reading *Understanding Earth,* particularly sections of the text that are emphasized in lecture. The text is loaded with tools and clues to help you learn. You will find our suggestions about how to take advantage of these learning aids in Part I, Chapter 2, Meet Your Authors, in this Study Guide.

Web Site Study Resources

http://www.whfreeman.com/understandingearth6e
Check out the Web site to get an idea of the study aids that are available there. You will find **Graded Quizzing** and **Flashcards** (to help you learn new terms).

Exam Prep

Materials in this section are most useful during preparation for exams. The **Chapter Summary** and the **Practice Exercises** and **Review Questions** should simplify your chapter review. Read the **Chapter Summary** to begin your session. It provides a helpful overview that should refresh your memory.

Next, work on the **Practice Exercises** and **Review Questions.** Complete the exercises and questions just as you would an exam, to see how well you have mastered this chapter. After you answer the questions, score them. Finally, and most important, review each question you missed. Identify and correct the misconception(s) that resulted in your answering the question incorrectly.

Chapter Summary

How do geologists study Earth?

- Field and lab observations, experiments, and the human creative process help geoscientists formulate hypotheses (models) for how the Earth works and its history. A "hypothesis" is a tentative explanation that can help focus attention on plausible features and relationships of a working model. If a hypothesis is eventually confirmed by a large body of data, it may be elevated to a "theory."

Theories are abandoned when subsequent investigations show them to be false. Confidence grows in theories that withstand repeated tests and are able to predict the results of new experiments and computer models.

How was Earth's size first measured and what is Earth's topographic relief?

- The Practicing Geology box on page 8 illustrates how Eratosthenes measured Earth's size.
- Earth's topography is measured with respect to sea level. The lowest point in the Pacific Ocean is actually deeper than Mount Everest rises above sea level; see Figure 1.8.

What is Earth's internal structure and composition?

- Earth's interior consists of concentric layers distinguished by differences in composition and physical state (solid versus liquid) and associated changes in density.
- Earth's crust (continental and ocean) is composed of low-density silicate rocks, which are rich in aluminum and potassium. Refer to Figure 1.11. The crust essentially floats on the mantle, like an iceberg floats in water.
- The mantle is composed of silicate rocks of higher density than the crust and contains more magnesium and iron. The Moho is the boundary between the crust and mantle.
- The core is thought to be metallic, composed mostly of iron and nickel.
- Seismic waves allow geoscientists to detect the presences of a liquid outer core and an inner solid core. Changes (jumps) in density between Earth's major layers are caused by changes in their chemical composition and can be studied using seismic waves.

What are the major components of the Earth system?

- The major components of the Earth system are climate, plate tectonics, and the geodynamo.
- The climate system is driven by heat from our Sun and is influenced by the hydrosphere, the cryosphere, the biosphere, and the lithosphere.
- The plate tectonic system is primarily driven by Earth's internal heat, which escapes through the convection of material in Earth's solid mantle. Tectonic plates consist of the lithosphere, which includes the continental and oceanic crust, and the rigid, uppermost mantle.
- The geodynamo system involves interactions in the outer core that produce Earth's magnetic field.
- Earth's magnetic field reverses in polarity (the north and south poles flip) at irregular intervals.

What were some key events in the history of the Earth?

- Earth formed 4.5 billion years ago.
- Earliest life forms are found in rocks about 3.5 million years old.

- By 2.7 billion years ago, photosynthesis by early plant life produced increasing levels of oxygen in Earth's atmosphere.
- Only one-half billion years ago animals appeared, diversifying rapidly in an explosion of evolution.
- Life history is marked by periodic mass extinctions. About 65 million years ago, dinosaurs were killed off in an extinction event that was caused by a large bolide impact.
- Our species *(Homo sapiens)* arrived 200,000 years ago—a tiny fraction of the 4.5-billion-year history of the Earth.

Practice Exercise

Earth's topography

A. Where is the highest point on Earth relative to sea level?
B. Where is the lowest topographic point on Earth?
C. Relative to sea level, how much lower is the lowest point compared to the highest point?
D. What is the total topographic relief on the Earth?

Hint: Refer to Figure 1.8.

Review Questions

1. What purpose does a scientific hypothesis serve?
   A. It represents a widely accepted explanation.
   B. It provides an opportunity for feedback and testing.
   C. It serves little purpose as part of the scientific method.
   D. It typically results in unanimous agreement between scientists.
2. Of the following statements about the scientific method, which one is true?
   A. A hypothesis that has withstood many scientific tests is called a theory.
   B. The outcome of scientific experiments cannot be predicted by a hypothesis.
   C. For a hypothesis to be accepted, it must be agreed on by more than one scientist.
   D. After a theory is proven to be true, it may not be discarded.

   Hint: Figure 1.1 is an excellent overview of the scientific method.
3. How did Eratosthenes measure the circumference of Earth?
   A. He measured the time it takes for a sailing ship to appear fully on the horizon.
   B. He measured the difference in the angle of sunlight hitting the Earth at the summer solstice at two different places in Egypt.
   C. He used data logged by Columbus.
   D. He measured the change in the position of stars at night at two different places in Egypt.

4. The principle of uniformitarianism can be summarized by which statement?
   A. The Earth's surface and life change very slowly over time.
   B. Human activity has a small but significant effect on the Earth.
   C. The present is the key to the past.
   D. The Earth system is all parts of our planet and their interactions.

5. Which of the following internal layers of the Earth is the most massive?
   A. crust
   B. inner core
   C. mantle
   D. outer core

   Hint: Refer to Figure 1.9.

6. The crust is
   A. thickest in the continents.
   B. thickest in the oceans.
   C. about the same thickness in both the continents and oceans.
   D. of a completely unknown thickness.

   Hint: Refer to Figure 1.11.

7. Which of the following elements is more abundant in the Earth's crust compared to the Earth as a whole?
   A. iron
   B. magnesium
   C. nickel
   D. silicon

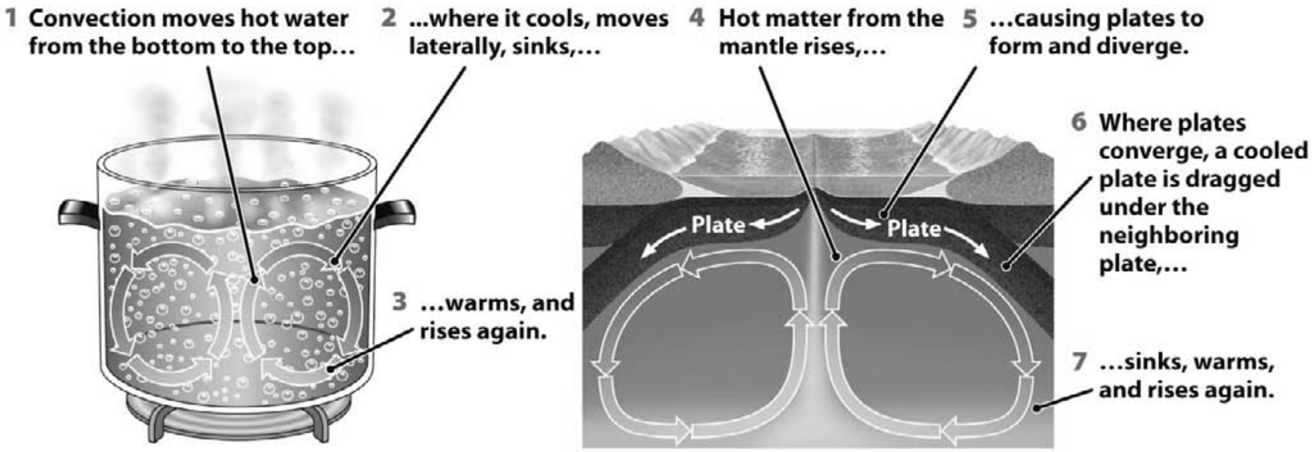
   Hint: Refer to Figure 1.12.

8. Why do geoscientists think tectonic plates move across the Earth's surface?
   A. Centrifugal force of Earth's rotation spins plates across the Earth's surface.
   B. Volcanic eruptions on the seafloor push tectonic plates apart.
   C. Tidal forces drive plate motion.
   D. Movement of the plates is a result of convection in the mantle.

9. The Earth's magnetic field is caused by
   A. the permanent magnetism of the Earth's solid inner core.
   B. the flow of molten iron in the inner core.
   C. the geogdynamo, created by convection in the outer liquid core, and electrical currents.
   D. solar radiation bombarding the Earth.

10. Earth's magnetic poles
    A. reverse at irregular intervals.
    B. consist of four poles.
    C. are generated by a permanently magnetized inner core.
    D. are very stable and do not change.

11. Convection transfers heat (see Figure 1.15) by the physical circulation of hot and cold matter. How does it work?
    A. Heated matter rises under the force of buoyancy because it is less dense.
    B. Hot matter within the mantle sinks because it is denser.
    C. Cold matter rises under the force of buoyancy because it is less dense.
    D. Meteor bombardment acts to stir up the mantle and drive convection.
12. When did biology's Big Bang (evolutionary explosion) occur?
    A. about 65 million years ago
    B. about 540 million years ago
    C. about 2200 million years ago
    D. about 3500 million years ago



CHAPTER 2

Plate Tectonics: The Unifying Theory

From time to time in the history of science, a fundamental concept appears that unifies a field of study by pulling together diverse theories and explaining a large body of observations. Such a concept in physics is the theory of relativity; in chemistry, the nature of the chemical bond; in biology, DNA; in astronomy, the Big Bang; and in geology, plate tectonics.

—*Understanding Earth,* Frank Press and Raymond Siever

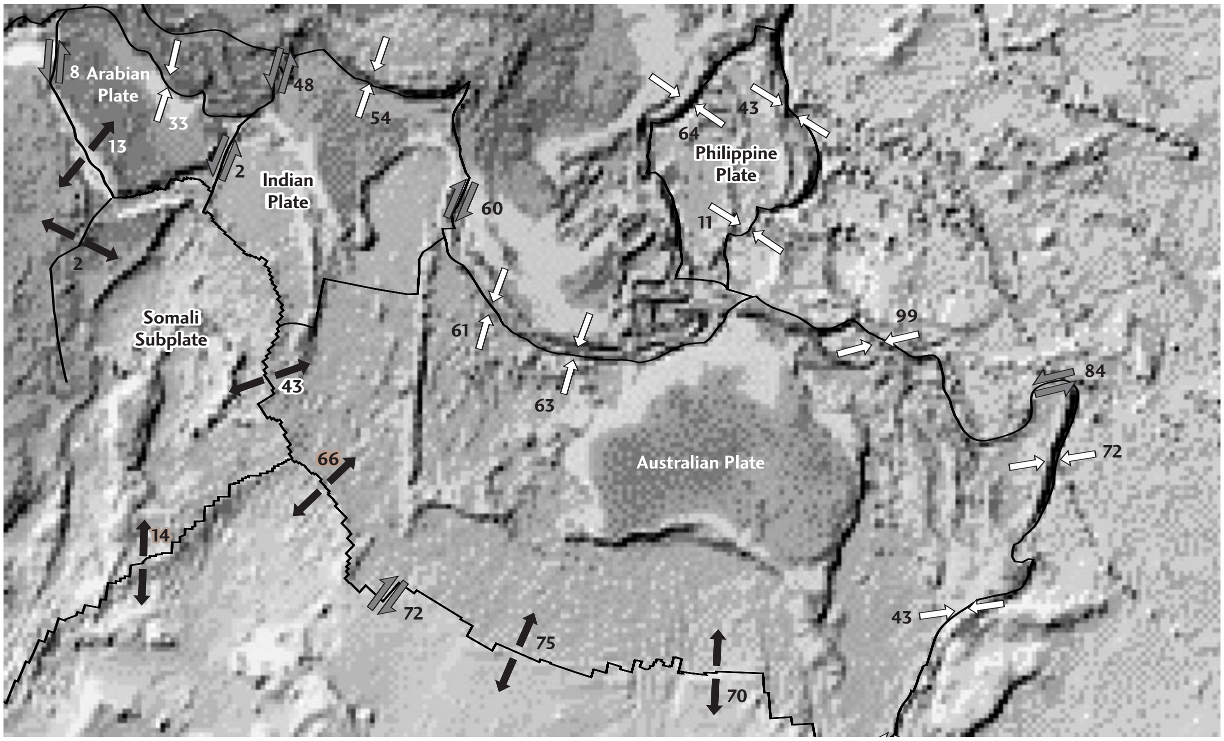


Figure 2.7. Earth's lithosphere is made of moving plates.

Before Lecture

This is a particularly important chapter. Plate tectonics is *the* major concept that guides modern geology. Before you attend lecture be sure to spend some time previewing the chapter. Previewing will greatly increase your understanding of the lecture (see the **Chapter Preview** in Part I, Chapter 3, How to Be Successful in Geology). For an efficient preview use the following questions.

Chapter Preview

This chapter contains extraordinarily helpful figures and photos. The goal is to learn how the continents and ocean plates can float about the Earth. Focus your Chapter 2 study time on examining the fascinating figures and photos of some of Earth's most amazing features.

- **What is the theory of plate tectonics?**
  Brief answer: The theory of plate tectonics describes the movement of lithospheric plates and the forces acting between them. It also explains the distribution of many large-scale features that result from movements at plate boundaries: mountain chains, earthquakes, volcanoes, topography of the seafloor, and distribution of rock assemblages and fossils. Refer to Figure 2.7, Earth's lithosphere is made of moving plates, on page 28.
- **What are some of the geologic characteristics of plate boundaries?**
  Brief answer: Volcanoes and earthquake activity are concentrated along plate boundaries. Where divergent plate boundaries are exposed on land, subsiding basins and volcanism are typical. Mountain chains form along convergent and transform plate boundaries. It is important to visualize each major type of plate boundary and their locations on Earth. Use the following figures in the text to do so: Figures 2.7, 2.8, 2.9, and 2.10 for divergent plate boundaries; Figures 2.7 and 2.8 for convergent plate boundaries; and Figures 2.7, 2.8, and 2.11 for a transform boundary. If you have seen or lived near the San Andreas, a volcano, or a rift valley, like the Rio Grande in New Mexico, start with the actual feature.
- **How can the age of the seafloor be determined?**
  Brief answer: A pivotal discovery in the history of plate tectonics was the determination of the age of the seafloor using magnetic anomalies. Figure 2.12 shows how the age was determined.
- **How is the history of plate movement reconstructed?**
  Brief answer: Transform boundaries indicate the directions of relative plate movement, and seafloor isochrons reveal the positions of divergent boundaries in earlier times. Refer to Figures 2.14 and 2.15.
- **What drives plate tectonics?**
  Brief answer: Earth's internal heat creates convective currents (flow of rock material from hotter to cooler areas) in the mantle. Convection, the force of gravity, and the existence of an asthenosphere are all important factors in any explanation of plate movement. Review Figure 1.15 to see how convection works.

Vital Information from Other Chapters

Review Figure 1.15 in Chapter 1 to remind yourself how convection drives plate tectonics.

Web Site Study Resources

http://www.whfreeman.com/understandingearth6e

During Lecture

One goal for the lecture should be to leave the class with good answers to the preview questions.

- To avoid getting lost in details, keep the big picture in mind. Chapter 2 tells the story of plate tectonics: Earth's moving plates, how the plates move, and the geological features associated with converging and diverging plate boundaries. Plate tectonics underlies and explains much about modern geology. In that sense, this chapter provides a preview of your entire geology course.
- Focus on understanding Figure 2.8. It will be helpful to have this figure handy during lecture. Annotate the text figures with comments made by your instructor.
- If you haven't already done so, read the discussion of note taking in Part I, Chapter 3, How to Be Successful in Geology. **Hint:** You can use the **Note-Taking Checklist** before you go to lecture as a one-minute reminder of what to do to improve your note-taking skills. After lecture, use it as a quality check.

After Lecture

Review Notes

The perfect time to review your notes is right after lecture. The following checklist contains both general review tips and specific suggestions for this chapter.

Check Your Notes: Have you…

- ☐ marked areas where you don't remember what was said? Do you need a follow-up session with your instructor, tutor, or study partner to get what you missed?
- ☐ added visual material? Example: For the lecture on Chapter 2, it is very important to distinguish the difference between diverging and converging plates (Figure 2.8). You could insert a visual cue about this distinction into your notes. For example, the simplest possible representation of Figure 2.8 would be two arrows pointed away from each other. You also want to remember that divergence can cause both ridges and valleys. You could draw a ridge (zigzag lines) and a valley (dropping plates) between your arrows

Study Tip: Learn by drawing

Sketching simplified versions of figures in your notes is a helpful way to learn and remember. Visual learners will remember material best after they look at and study a figure. Visual learners learn more if they enrich their notes with visual cues. For kinesthetic learners memory is activated by the act of drawing, so you learn as you look and draw. As you take notes, be sure to leave room so that you can insert material later. The ultimate goal is notes you can study from.

There are two important caveats here. First, you need to budget your time. Focus on very important material, such as the figures we suggested in the preview questions. You don't have time to redo all the artwork in *Understanding Earth.* Second, the art in the text is especially well done. It includes many details you cannot easily execute in your notes. Also the captions in the text are very helpful, so when you are working on sketches be sure to refer to the text figure and caption.

Get off to a good start. Try this idea for Chapter 2 and observe how it works for you. Modify it to fit your learning style.

Intensive Study Session

Set priorities for studying this chapter. There is a lot to do, probably more than you will have time for in one intensive study session. Set priorities and always do the important things first.

- **Instructor.** Pay particular attention to any exercises recommended by your instructor during lecture and always answer them first. Your instructor is also your best resource if you are wondering which material is most important.
- **Practice Exercises and Review Questions.** Use the Study Guide Practice Exercises and Review Questions. Be sure to do Exercise 1 because it involves the key information you need to learn in this chapter.
- **Text.** Work on your responses to Exercises 2, 4, and 5 and Thought Questions 1 and 3 at the end of Chapter 2 in the textbook.
- **Web Site Study Resources**
  http://www.whfreeman.com/understandingearth6e
  Complete the **Online Quiz.**

Exam Prep

Materials in this section are most useful during your preparation for exams. The **Chapter Summary** and the **Practice Exercises** and **Review Questions** should simplify your chapter review. Read the **Chapter Summary** to begin your session. It provides a helpful overview that should refresh your memory.

Next, work on the **Practice Exercises** and **Review Questions.** Complete the exercises and questions just as you would an exam, to see how well you have mastered this chapter. After you answer the questions, score them. Finally, and most important, review each question you missed. Identify and correct the misconception(s) that resulted in your answering the question incorrectly.

Chapter Summary

What is the theory of plate tectonics?

- For over the last century some geologists have argued for the concept of continental drift because of the jigsaw-puzzle fit of the coasts on both sides of the Atlantic, the geological similarities in rock ages and trends in geologic structures on opposite sides of the Atlantic, fossil evidence suggesting that continents were joined at one time, and the distribution of glacial deposits as well as other paleoclimatic evidence.

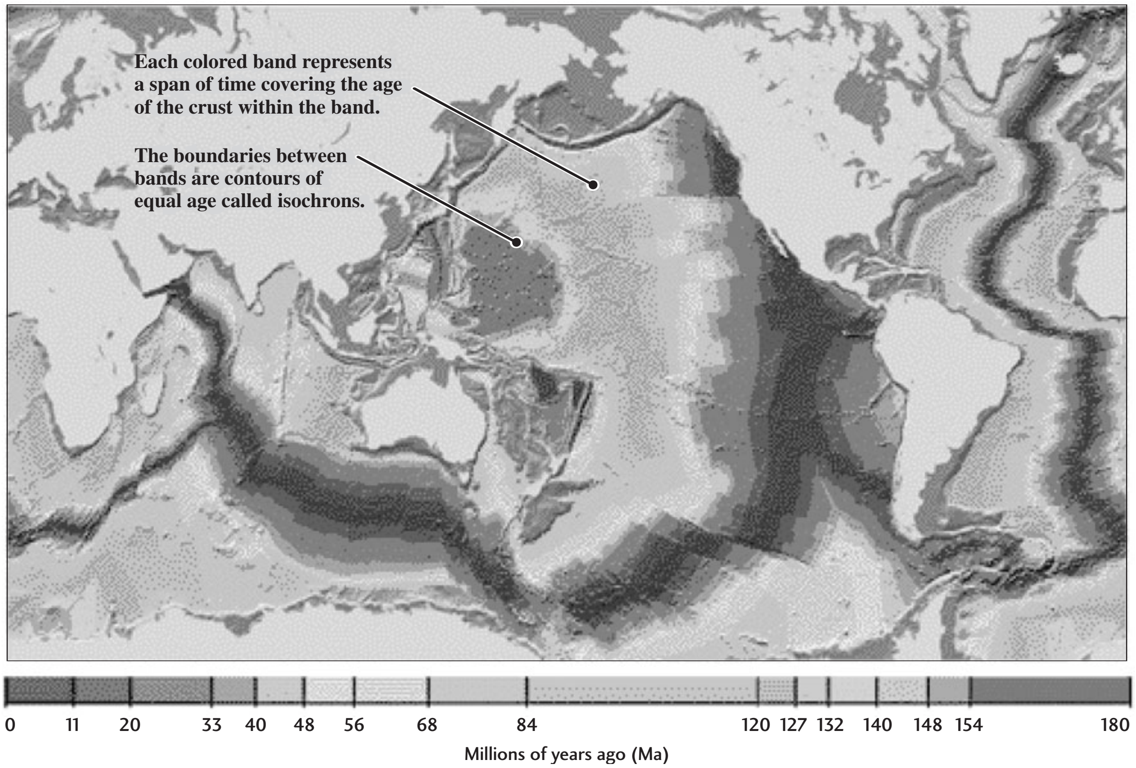


Figure 2.15. This global isochron map shows the ages of rocks on the seafloor. The time scale at the bottom gives the age of the seafloor in millions of years since its creation at mid-ocean ridges. Light gray indicates land; dark gray indicates shallow water over continental shelves. Mid-ocean ridges, along which new seafloor is extruded, coincide with the youngest rocks (red). [*Journal of Geophysical Research* 102 (1997): 3211–3214. Courtesy of R. Dietmar Müller.]

- In the last half of the twentieth century the major elements of the plate tectonic theory were formulated. Starting in the 1940s, ocean floor mapping began to reveal major geologic features on the ocean floor. Then the match between magnetic anomaly patterns on the seafloor with the paleomagnetic time scale revealed that the ocean floor had a young geologic age and was systematically older away from the oceanic ridge systems. The concepts of seafloor spreading, subduction, and transform faulting evolved from these and other observations.
- According to the theory of plate tectonics, the Earth's lithosphere is broken into over a dozen moving plates. The plates slide over a hot and weak asthenosphere, and the continents, embedded in some of the moving plates, are carried along. The assembly breakup of Pangaea (see Figure 2.15) provides a dramatic example of how the movement of plates creates geography and geological features such as the Himalaya Mountains and even changes climate as land masses travel about. (Note Antarctica's location during the late Proterozoic. Would Antarctica have been covered with ice at that time? What would its climate have been like?)

What are some of the geologic characteristics of plate boundaries?

- There are three major types of boundaries between lithospheric plates: divergent boundaries, where plates move apart; convergent boundaries, where plates move together and one plate often subducts beneath the other; and transform boundaries, where plates slide past each other. Volcanoes, earthquakes and mountains are concentrated along the active plate boundaries. Mountains typically form along convergent and transform plate boundaries. Where divergent plate boundaries are exposed on land, subsiding basins and volcanism are typical.

How can the age of the seafloor be determined?

- The age and relative plate velocity are inferred from changes in the paleomagnetic properties of the ocean floor.
- Various other methods are now used to measure the rate and direction of plate movements. Relative plate speeds in millimeters per year are shown in Figure 2.7.

How is the history of plate movement reconstructed?

- Seafloor isochrons provide the basis for reconstructing plate motions for about the last 200 million years.
- Distinct assemblages of rocks characterize each type of plate boundary. Using diagnostic rock assemblages embedded in continents and paleoenvironmental data recorded by fossils and sedimentary rocks, geologists have been able to reconstruct ancient plate tectonic events and plate configurations.

What is the engine that drives plate tectonics?

- Driven by Earth's internal heat, convection within the mantle, coupled with the force of gravity and the existence of a soft zone, called the asthenosphere, are important factors in models for how plate tectonics works.

Practice Exercises

Exercise 1: Characteristics of active tectonic plate boundaries

Complete the table by filling in the blank spaces and boxes.

Characteristics	**Divergent** See Figures 2.7, 2.8, 2.9, and 2.10.	**Convergent** See Figures 2.7 and 2.11. **Ocean/ Ocean**	**Ocean/ Continental**	**Collision**	**Transform** See Figures 2.7, 2.8, and 2.11.
Examples		Japanese islands Marinas Trench Aleutian Trench		Himalayas and Tibetan Plateau	
Topography	*oceanic ridge, rift valley, ocean basins, ocean floor features offset by transforms, seamounts*	*trench, island arc*			*offset of creek beds and other topographic features that cross the fault*
Volcanism		*present*			*not characteristic*

Exercise 2: Construct a conceptual flowchart or diagram illustrating how plate tectonics works

Construct a conceptual flowchart or diagram that illustrates modern ideas on how plate tectonics works. Include thorough captions or a written description of how it works. Be sure the roles played by the following important factors are addressed.

- Earth's internal heat
- convection
- asthenosphere
- divergent and convergent boundaries
- density differences
- lithosphere
- the push and pull of gravity

Hints: This is a complex task. Break it down into pieces. First, make a sketch for each factor on separate pieces of paper. Then ask yourself where (in which Earth layer) each process operates and arrange your sketches accordingly. Finally, try to combine all this material into a single chart.

Review Questions

1. The most important process in building the ocean floor is
   A. volcanism.
   B. subduction.
   C. earthquake activity.
   D. magnetic reversal.
2. The youngest ocean crust is located
   A. along the oceanic ridges.
   B. in the oceanic trenches.
   C. around hot spots.
   D. on the abyssal seafloor.
3. Rates of seafloor spreading today are in
   A. millimeters per year.
   B. centimeters per year.
   C. meters per year.
   D. kilometers per year.
   Hint: Refer to Figure 2.7.
4. Along a transform plate boundary, the two plates
   A. move apart to create a widening rift valley.
   B. are being consumed by subduction.
   C. are being forced together to produce a mountain system.
   D. move horizontally past each other.
5. The _________________ is an example of a divergent plate margin.
   A. East African Rift
   B. Japan Trench
   C. Himalayas
   D. San Andreas fault
6. All the following features mark plate boundaries except
   A. the Red Sea.
   B. the San Andreas fault.
   C. the Hawaiian Islands.
   D. Iceland.
   Hint: Refer to Figure 2.7.
7. Which of the following features is not associated with a type of active plate boundary?
   A. Atlantic coast of North America
   B. northwestern North America
   C. Gulf of California
   D. Himalayas
8. The name given to the supercontinent that broke up in the Early Jurassic (195 Ma) was
   A. India.
   B. Atlantis.
   C. Laurasia.
   D. Pangaea.
   Hint: Refer to Figure 2.16.

9. Mid-ocean ridges, according to the plate tectonic theory, are
   A. places where oceanic crust is consumed.
   B. pull-apart zones where new oceanic crust is produced.
   C. locations of plate convergence.
   D. transform faults.

10. The ____________________________ are an example of a collision zone between two pieces of continental crust riding on converging lithospheric plates.
    A. Himalaya Mountains
    B. islands of Japan
    C. Aleutian Islands in Alaska
    D. Andes Mountains in South America

11. At which type of plate boundaries are volcanoes least likely to form?
    A. divergent boundaries
    B. convergent boundaries
    C. transform boundaries
    D. hot spots

12. During the early Triassic (237 Ma),
    A. India collided with Asia to form the Himalayan Mountains.
    B. the supercontinent Rodinia formed.
    C. the supercontinent Pangaea was mostly assembled.
    D. the Atlantic Ocean had already begun to open.

    Hint: Refer to Figure 2.16.

13. South America lay closest to the South Pole during the
    A. late Proterozoic (650 Ma).
    B. last 65 million years.
    C. late Jurassic (152 Ma).
    D. early Devonian (390 Ma).

    Hint: Refer to Figure 2.16.

14. The significance of the magnetic anomaly patterns discovered in association with the seafloor was that the anomaly patterns
    A. could be matched with the magnetic reversal chronology to establish an estimated age for the seafloor.
    B. provided evidence for mantle convection, a driving mechanism for plate tectonics.
    C. allowed geomagnetists to reconstruct the supercontinent Rodinia.
    D. represented absolute proof that the seafloor was spreading apart.

    Hint: Refer to Figure 2.12.

15. The oldest rocks on the seafloor are about
    A. 20 million years old.
    B. 200 million years old.
    C. 500 million years old.
    D. 1 billion years old.

    Hint: Refer to Figure 2.15.

16. The oceanic crust
    A. becomes progressively younger away from the oceanic ridges.
    B. becomes progressively older away from the oceanic ridges.
    C. is the same age virtually everywhere.
    D. ranges in age from Jurassic to Precambrian.

17. Volcanic island arcs like the Japanese islands are associated with
    A. convergent boundaries.
    B. divergent boundaries.
    C. transform boundaries.
    D. a chain of hot spots.

    Hint: Refer to Figure 2.8.

18. Rift valleys are associated with
    A. convergent boundaries.
    B. divergent boundaries.
    C. transform boundaries.
    D. active continental margins.

    Hint: Refer to Figure 2.8.

19. With what tectonic activity is a rift valley usually associated?
    A. subduction
    B. movement on a transform fault
    C. continental rupture
    D. continental collision
20. Magnetic anomalies in the seafloor are caused by
    A. magnetic reversals recorded by lavas erupted at oceanic spreading centers.
    B. changes in the atomic structure of minerals in response to changing ocean depth.
    C. the metamorphism of deep-sea sediments.
    D. the heating up of subducting oceanic lithosphere as it plunges deeper into the mantle.

    Hint: Review Figure 2.12.
21. Where do the plate-driving forces originate?
    A. Tectonic plates are passively dragged by convection currents.
    B. Gravity pulls and/or pushes old, cold, heavy lithosphere.
    C. Injection of magma from the mantle pushes the lithosphere apart.
    D. Earthquakes cause the plates to move.
22. Earth's lithosphere can be characterized as
    A. having an average thickness of about 100 km.
    B. including the crust and upper mantle.
    C. being solid and above the asthenosphere.
    D. all of the above.

CHAPTER 3

Earth Materials: Minerals and Rocks

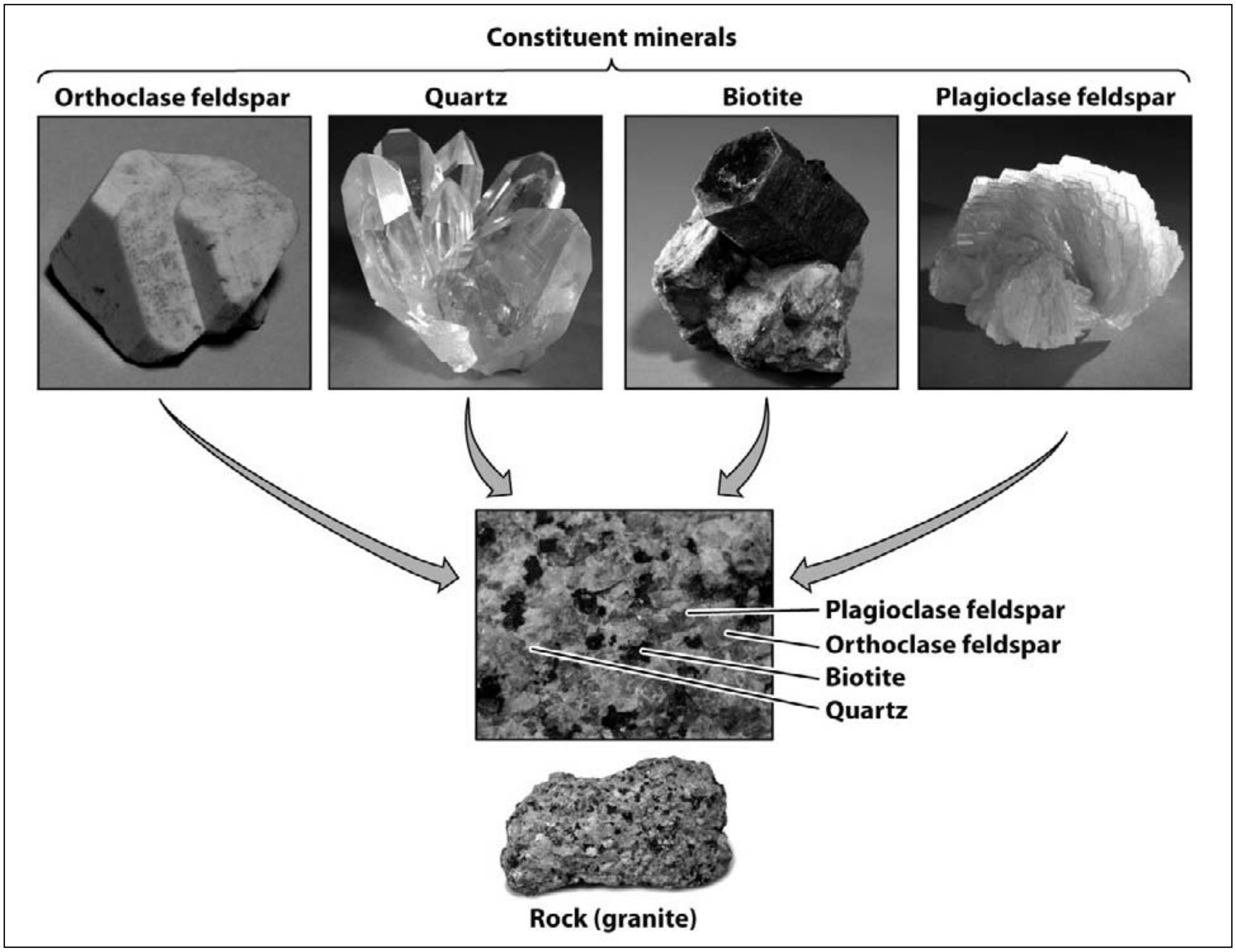


Figure 3.23. Rocks are naturally occurring aggregates of minerals. [John Grotzinger/Roman Rivera-Moret/ Harvard Mineralogical Museum.]

Before Lecture

Chapter Preview

- **What is a mineral?**
  Brief answer: A naturally occurring inorganic, crystalline solid.
- **How are rocks related to minerals?**
  Brief answer: Minerals are the building blocks of rocks. Study Figure 3.23 (p. 71).
- **How do atoms combine to form the crystal structure of minerals?**
  Brief answer: How atoms combine (chemically bond) depends on the electronic charge on their ion, the size of the ion, and the degree to which the bond is ionic or covalent.
- **What is the atomic structure of minerals?**
  Hint: See Figures 3.3 (halite), 3.10 (graphite and diamond), 3.11 (silicates), 3.12 (calcite), and 3.17 (mica).
- **What are the major rock-forming minerals and their physical properties?**
  Brief answer: The major minerals are silicates, carbonates, oxides, sulfides, and sulfates. Diagnostic properties include hardness, cleavage, luster, color, density, and the shape of the crystal.
- **What determines the properties of rocks?**
  Brief answer: Mineral content and texture.
- **What are the three types of rocks and how are they formed?**
  Brief answer: Igneous, sedimentary, and metamorphic rocks.
- **How do the three types of rocks interact with each other via plate tectonics, the climate system, and the rock cycle?**
  Brief answer: Refer to Figures 3.24, 3.25, 3.27, and 3.28.
- **What is an ore mineral?**
  Brief answer: Mineral deposits become ore deposits when they are rich and valuable enough to mine economically.
- **How do ore deposits of metal-bearing minerals form?**
  Brief answer: Many metal ore deposits are formed by magmatic and hydrothermal processes that are closely linked to modern and ancient plate tectonic boundaries. Refer to Figure 3.30.

Previewing Tips

Tip 1

To preview a chapter quickly, focus on the figures. It is often possible to get a good overview just by examining the figures and captions. Note that preview questions often refer you to specific figures. As little as 5 or 10 minutes previewing the figures before lecture will improve the quality of your note taking.

Tip 2

The more material a chapter contains the more important it becomes to *chunk* material into a schema that is meaningful to you and is simple enough to remember. Example: Think of Chapter 3 as answering three simple questions: (1) What is a mineral? (2) How is a mineral related to a rock? (3) How do the three kinds of rocks interact with each other in the system called the rock cycle? If you can remember those three questions and use them to tie the details of the chapter together, you are likely to find that the chapter suddenly seems much simpler and that the material seems much easier to remember.

Minerals are the alphabet and rocks are the words.

—Tom Dilley

Vital Information from Other Chapters

- Review Figure 1.12 (the relative abundance of elements in the whole Earth compared to that of elements in Earth's crust) on page 12 of the textbook.
- Plate tectonic processes drive the formation of igneous and metamorphic rocks plus the burial sediments. It will be particularly useful to review Chapter 2, especially the text and figures regarding converging and diverging plate boundaries.

During Lecture

Do a learning warm-up. Arrive early. Look for pictures in the text that catch your interest. Look over the preview questions and keep them handy for easy reference.

Your basic goal during lecture is to take good notes. The notes should contain in-depth answers to the preview questions. To avoid getting lost in details, keep the "big picture" in mind. Chapter 3 explains how rocks are built out of minerals and how minerals are built out of atoms.

Keep in mind the typical geologic conditions needed for the formation of the three major rock types. This is nicely summarized in Figure 3.24. Open your book to this figure and put a bookmark there. You won't have time during lecture.

The lecturer may show slides of mineral crystals and may pass around specimens of particular minerals and rocks. You will get more out of the samples if you sit close to the front of the room where you can see the samples as they are discussed. Remember to focus on clues the lecturer provides for recognizing a particular sample in the field. As you listen, try to formulate at least one good question you can ask during the lecture.

The important thing is not to stop questioning.

—Albert Einstein

Lecture Tip: Rock texture

The lecturer may show or pass around samples of the three types of rocks to help you learn how they differ. Pay particular attention to the crystal or grain size (texture) and to the presence or absence of layering, fossils, and patterns produced by the alignment of minerals. You will have a better chance of seeing the samples if you sit at the front of the room.

After Lecture

Review Notes

Right after lecture while the material is fresh in your mind is the perfect time to review your notes. Review to be sure you understand all the key points and wrote them down in a form that will be readable later. One good check is that your notes should provide detailed answers to all the **Chapter Preview** questions. The following checklist contains both general review tips and specific suggestions for this chapter.

Check Your Notes: Have you…

- ☐ added a comparison chart to help you sort out the key differences between the three rock types? (See the example.)
- ☐ added simplified sketches of key text figures? Trying to simplify a figure is often the best way of studying it, since you get involved in the important details. Example: Draw a simplified version of Figure 3.24 that will help you remember the difference in texture (crystal size) between intrusive and extrusive igneous rocks.

Differences Between the Three Rock Types

	Igneous	Sedimentary	Metamorphic
Source of materials	Melting of rocks in crust and mantle	Weathering and erosion of rocks exposed at the surface	High temperatures and pressures in deep crust and upper mantle, breaks from faulting or impact
Rock-forming process	Crystallization (solidification of melt)	Sedimentation, burial, and lithification (compaction and cementation)	Shearing and recrystallizing in the solid state

Refer to Figure 3.24 for the three different types of rock.

Intensive Study Session

Study Tip: Intensive study session

The process of learning geology is similar to the procedure for building a house. Before each lecture, construct a frame of questions. During lecture, attach details and ideas to the frame. After lecture, master the ideas during an intensive study session. By learning about plate tectonics you have laid a good foundation, but geology is a skyscraper with 23 floors (one for each chapter). Each floor (chapter) supports the one above it. If you don't completely master this chapter, the next one will be more difficult.

Schedule about an hour after each lecture for intensive study. Devote this time to mastering key concepts. Mastery is not gained by just reading the text. Mastery occurs as the result of asking yourself questions and answering them. The **Practice Exercises** and **Review Questions** are designed to help you reach mastery quickly. The more of these exercises and questions you can work into your study schedule early in the course, the easier subsequent chapters will be.

Everything you do in life is worth infinite care and infinite effort.

— J.D. McDonald

Here are a few suggestions for how you might do an intensive study session for this chapter.

- **Review Questions.** Start your study session by determining how much you already know. Try answering the Study Guide **Review Questions**. Notice that you can check the answers to these questions at the end of the Study Guide. Often we provide some additional information with an answer. The **Review Questions** are a great way to start studying because trying to answer them will help you focus on what you need to work on. Afterward you can go back and read the text concerning any points you missed.

- **Practice Exercises.** Immediately before the **Review Questions** you will find **Practice Exercises**. These exercises always focus on some key material that you will learn best by an interactive approach that requires you to think. For Chapter 3 the exercises deal with understanding how the structure of a mineral determines its physical properties.

- **Text.** Work on Exercises 5 and 12 at the end of the chapter. Also work on Thought Questions 5, 9, 12 (see Figure 3.28), and 14.

- **Web Site Study Resources**
  http://www.whfreeman.com/understandingearth6e
  A lot of the fun of geology has to do with figuring out the hows and whys of interesting and beautiful natural phenomena. Go online and explore how the wondrous blue color of the Hope Diamond is related to its atomic structure and composition by doing the **Geology in Practice** exercises. The *Rock Cycle Review Online Review Exercise* provides an excellent tour through the rock cycle and how it works in the context of plate tectonics. Other useful study aids on the Web site:
  - **Flashcards** to help you learn new terms
  - Additional **Chapter Review** questions in the **Online Quiz**

Obviously you don't have time to do all these things for every chapter. The idea is to try out some of the tools and then decide which will be most helpful given your personal learning style.

"Crystal" comes from the Greek word *krustallos,* which means ice. Is ice—water ice—a mineral? **Hint:** Ask yourself if ice has the three properties of a mineral. (1) Is ice naturally occurring? (2) Does it have a solid crystalline structure? (3) Does it have a definite chemical composition?

Exam Prep

Materials in this section are most useful during your preparation for midterm and final examinations. The **Chapter Summary** and the **Practice Exercises** and **Review Questions** should simplify your chapter review. Read the **Chapter Summary** to begin your session. It provides a helpful overview that should refresh your memory.

Next, work on the **Practice Exercises** and **Review Questions**. To determine how well you have mastered this chapter, complete the exercises and questions just as you would a midterm. After you answer the questions, score them. Finally, review each question you missed. Identify and correct the misconception(s) that resulted in your answering the question incorrectly.

Chapter Summary

What are minerals?

- Minerals are naturally occurring inorganic solids with a specific crystal structure and chemical composition.

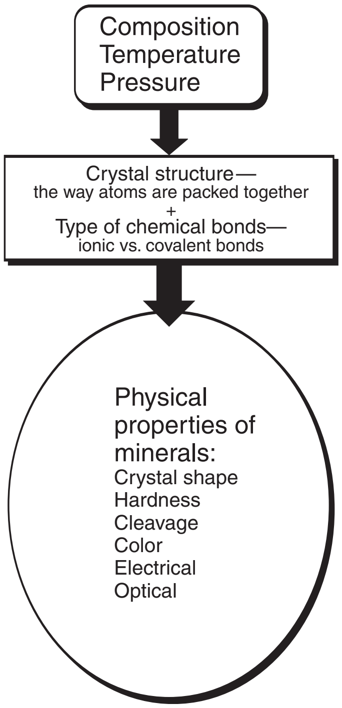
How do atoms combine to form the crystal structure of minerals?

- Minerals form when atoms or ions chemically bond in an orderly, three-dimensional geometric array—a crystal structure. The character of the chemical bond can be ionic, covalent, or metallic. Ionic bonds are the dominant type of chemical bonds in mineral structures.

What is the atomic structure of minerals?

- The atomic structure is determined by how the atoms or ions pack together to form a crystalline solid. The packing of atoms depends on their size and the characteristics of chemical bonds between the atoms.

Conceptual flowchart illustrating the factors that influence the physical properties of minerals



What are the major rock-forming minerals and what are their physical properties?

- The strength of the chemical bonds and the crystalline structure determines many of the physical properties of minerals, such as hardness and cleavage.
- Silicate minerals are the most abundant class of minerals in the Earth's crust and mantle.
  Isolated and chain silicates—olivine, pyroxene, and hornblende
  Sheet silicates—micas and clay minerals
  Framework silicates—feldspar and quartz
- Other common mineral classes include carbonates, oxides, sulfates, sulfides, halides, and native metals.

Why study minerals?

- The composition of rocks can be deduced from the composition of its minerals.
- The environment in which the rock formed can be inferred because most minerals are stable under only certain conditions of temperature and pressure.

- For fun and profit. Gemstones are treasured for their beauty, color, and rarity. Many minerals are used in industrial processes and manufacturing.

What determines the properties of rocks?

- The properties and names of rocks are determined by mineral content (the kinds and proportions of minerals that make up rocks) and texture (the size, shapes, and spatial arrangement of a rock's crystals or grains).

What are the three types of rocks, and how are they formed?

- There are three major rock types. Igneous rocks solidify from molten liquid (magma). Crystal size within igneous rocks is largely determined by the cooling rate of the magma body. Sedimentary rocks are made of sediments formed from the weathering and erosion of any preexisting rock. Deposition, burial, and lithification (compaction and cementation) transform loose sediments into sedimentary rocks. Metamorphic rocks are produced by alteration in the solid state of any preexisting rock by high pressures and temperatures, which result in a change in texture, mineral composition, or chemical composition.

What is the association of different rock types with plate tectonics, the climate system, and the rock cycle?

- The rock cycle is the result of interactions between plate tectonic and climate systems.

  The schematic of the rock cycle presented in Figure 3.28 shows how the three major rock types are strongly associated with plate tectonic and climatic settings.

What is an ore mineral?

- Mineral deposits are considered ore deposits when they are rich and valuable enough to be mined economically.
- Hydrothermal, metamorphic, chemical, and mechanical weathering and sedimentary processes can enrich metal-bearing minerals to form economical deposits.

How do ore deposits of metal-bearing minerals form?

- Many metal ore deposits are formed by magmatic and hydrothermal processes, which are closely linked to both modern and ancient plate boundaries. Knowledge of how mineral deposits form and the association of mineral deposits and plate boundaries has greatly facilitated the discovery of new deposits.

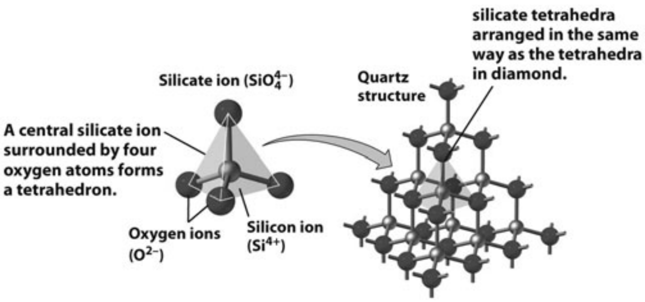


Figure 3.11. (c) A model showing the structure of the silicon-oxygen molecule. In the center of this model is one silicon ion carrying a positive charge of 4. It is surrounded by four oxygen ions, each carrying a minus charge of 2. After bonding, the resulting silicate ion carries a negative charge of 4 (4 minus 8 equals −4).

Practice Exercises

Exercise 1: Crystal structures of some common silicate minerals

Three crystal structures of silicate minerals are illustrated here. The illustration provides a bird's-eye view of a plane of atoms within the crystal structure of the mineral. The triangles, representing silica tetrahedra, are equivalent to the blue pyramids in Figure 3.9.

- Write the name for each major silicate structure (single chain, double chain, sheet, framework, or isolated tetrahedra).
- Give an example of a mineral with that crystal structure.
- Using the symbols given in the Cleavage Symbol Key below, characterize the cleavage properties for minerals with this crystal structure.

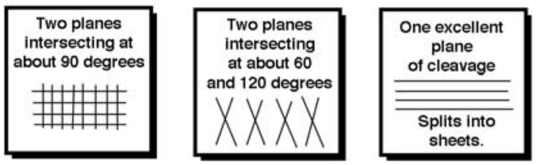
Hint: Refer to Figure 3.11.

Key for Practice Exercise 1

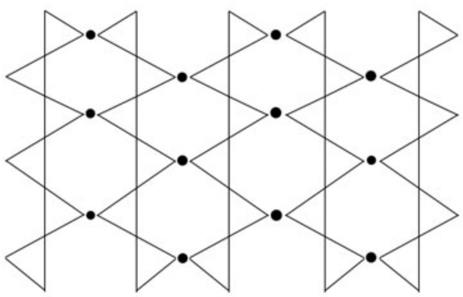
● Iron (Fe) or magnesium (Mg) ions

▷ Silica tetrahedra

Cleavage symbols



Silicate structure A



Basic crystal structure

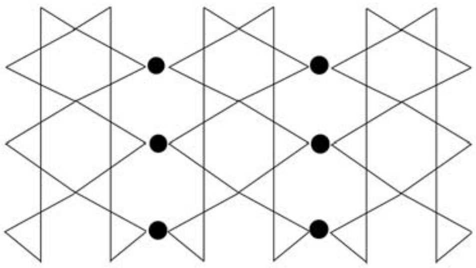
____

Example mineral

____

Cleavage (Fill in the box with one of the cleavage symbols given in the key.)

Silicate structure B



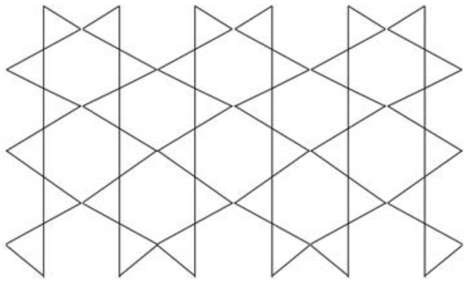
Basic crystal structure ______________________

Example mineral ______________________

Cleavage (Fill in the box with one of the cleavage symbols given in the key.)

☐

Silicate structure C



Basic crystal structure ______________________

Example mineral ______________________

Cleavage (Fill in the box with one of the cleavage symbols given in the key.)

☐

Exercise 2: Major mineral classes

Fill in the blank with the name of the mineral class to which each mineral belongs. The common classes of minerals include silicates, carbonates, sulfates, sulfides, oxides, native elements, and halides. **Hint:** Refer to Figure 3.11 and page 62 in the textbook.

1. hornblende *silicate*
   Hint: an amphibole
2. spinel ______________
3. clay minerals ______________
4. calcite ______________
5. gypsum ______________
6. quartz ______________
7. diamond ______________
8. dolomite ______________
9. plagioclase ______________
   Hint: a feldspar
10. ruby ______________
11. halite ______________
12. hematite ______________
13. graphite ______________
14. pyrite ______________
15. muscovite ______________
    Hint: a mica
16. anhydrite ______________
17. enstatite ______________
    Hint: a pyroxene
18. pyrite ______________
19. sapphire ______________
20. orthoclase ______________
    Hint: typically a tan-to-pink feldspar
21. silver ______________
22. albite ______________
    Hint: typically a white feldspar
23. olivine ______________
24. biotite ______________
    Hint: a black mica

Geology Puns

Why did the geologist skip the mineralogy luncheon?
She didn't have any apatite.

The geology teacher asks a student if he can name the felsic mineral with crystal faces, conchoidal fracture, and a hardness of 7 on the Mohs' scale.
"Of quartz I can," says the student.

The geologist is at the eye doctor, being fitted for a new pair of glasses. "Do you ever see double?" asks the doctor.
"Only when I look through calcite samples in lab," says the geologist.

Exercise 3: Identifying minerals by their physical properties

Give the name for each of the mineral samples described.

Hint: Refer to figures and text in Chapter 3 and Appendix 3.

Mineral Sample A

This mineral is colorless and has a silvery shine. It separates into thin sheets or flakes that can bend without breaking. It is within a rock that contains large crystals of quartz and feldspar. **Hint:** This mineral is named after Moscow where it was commonly used as a substitute for window glass.

Mineral name: __________

Mineral Sample B

This mineral sample is pale yellow and occurs as a vein within a rock fracture. Many small cubic crystals of this mineral were exposed in the vein when the rock broke apart along the fracture. The powdered form (streak) of the mineral is black and has a sulfurlike smell. It is a common metal sulfide ore mineral.

Hint: A common name for this mineral is "fool's gold."

Mineral name: __________

Mineral Sample C

This mineral is on display at a mineral exhibition both as a mineral specimen and cut and polished in pieces of jewelry. It consists of beautiful concentric bands of various shades of green. A knife blade can easily powder its surface but my fingernail cannot scratch it. Acid reacts with the mineral, especially if powdered. The specimen was labeled as coming from a copper mine in Bisbee, Arizona.

Hint: The mineral is a copper carbonate.

Mineral name: __________

Mineral Sample D

This tan-to-pink sample occurs as many 5- to 7-centimeter crystals surrounded by flakes of mica and grains of white-to-clear quartz. The tan-to-pink crystals are prismatic—rectangular or box shaped. It has a hardness between that of a knife blade and that of a steel file.

Hint: It is one of the most common minerals in the Earth's continental crust. A semiprecious variety, called moonstone, is used in jewelry. Refer to Figure 3.23.

Mineral name: __________

Mineral Sample E

Exhibiting excellent cleavage in three directions, this mineral breaks into beautiful rhombohedral-shaped pieces. Samples vary in color from clear to white to tan. A fingernail does not scratch the surface, but a knife blade easily powders the surface. Weak acid readily reacts with the surface of the mineral.

Hint: Marine organisms typically produce this mineral from seawater to generate their skeletons—seashells. Refer to Figure 3.18.

Mineral name: __________

Mineral Sample F

This sample was found as a series of thin layers with other layers of mud and silt. My fingernail can easily scratch its surface and form a white powder. Water dissolves the powder, but the sample does not react with acid. Samples commonly exhibit a splintery aspect but do not separate into individual fibers, such as asbestos does. The sample easily breaks (cleaves) along one plane but does not form the thin sheets typical of mica.

Hint: This mineral is a major constituent of plaster of Paris and wallboard used in buildings and houses. Refer to Table 3.2.

Mineral name: __________

Exercise 4: Rock cycle review

Information and figures in Chapters 2 and 4 will be helpful references for this exercise.
Also refer to Figure 3.28.

A. What are the three plate tectonic settings for the generation of magma?

hotspots, like Hawaii

____

____

B. Given the two types of igneous rocks, intrusive and extrusive, fill in the table with their characteristic cooling rates (*fast vs. slow*) and textures (*fine grained vs. coarse grained*).

Types of igneous rocks	Cooling rates	Textures
Extrusive		
Intrusive		

C. Rock and mineral particles are transported and laid down as sediments by what natural agents of transport?

Hint: Three different agents of transport are shown in Figure 3.26.

____

____

____

D. What are the two ways loose sediments are converted into solid sedimentary rock?

____

____

E. What are the two main types of sediments, and what are they made of?

Type of sediment	What is it made of?

F. What are the four major conditions that result in metamorphic rocks?

____

____

____

____

Hint: Refer to Figure 3.27

G. Are metamorphic rocks formed by melting? Answer yes or no.

____

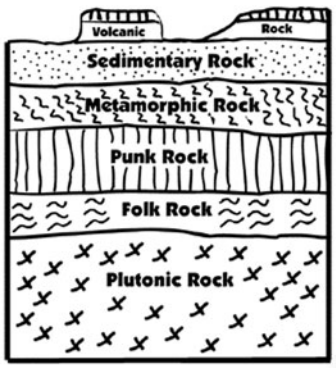
Review Questions

1. The bonds between Na and Cl in halite are strongly ionic. In ion form, Cl has seven electrons in its outer shell and Na has one. After these two elements bond, Cl has ______ electrons in its outer shell and Na has ______ electrons in its outer shell.
   A. six, two
   B. four, four
   C. one, seven
   D. eight, eight

   Hint: Refer to Figure 3.4.
2. ______ and ______ are examples of minerals with identical chemical compositions but different crystal structures.
   A. Calcite, dolomite
   B. Hematite, magnetite
   C. Pyrite, gypsum
   D. Graphite, diamond
3. The term geologists use for a naturally occurring aggregate of minerals is
   A. element.
   B. rock.
   C. compound.
   D. crystal.
4. When a substance is made of atoms that are arranged in a fixed, orderly, and repeating pattern, it is said to be
   A. amorphous.
   B. glassy.
   C. crystalline.
   D. liquid.
5. Which of the following statements is NOT true of minerals?
   A. They are crystalline.
   B. They possess a definite chemical composition.
   C. They are naturally occurring.
   D. They are organic.

6. Which of the following objects is NOT a mineral?
   A. native copper
   B. glass
   C. diamond
   D. water ice
7. The most common mineral group on Earth is
   A. carbonates.
   B. silicates.
   C. oxides.
   D. halides.

   Hint: Refer to Figure 1.12 and page 12.
8. The structure of feldspars, such as orthoclase and plagioclase, consists of
   A. double chains of silica tetrahedra.
   B. a three-dimensional framework of silica tetrahedra.
   C. single chains of silica tetrahedra.
   D. isolated silica tetrahedra.
9. Micas are known for their tendency to split into thin sheets; their silicate crystal structure is
   A. isolated silica tetrahedra.
   B. chains of silica tetrahedra.
   C. sheets of silica tetrahedra.
   D. a framework arrangement of silica tetrahedra.
10. Which of the following does NOT belong to the carbonate class of minerals?
    A. calcite
    B. anhydrite
    C. dolomite
    D. aragonite
11. Which of the following minerals has a sheet silicate structure?
    A. clay minerals
    B. feldspar
    C. amphibole
    D. graphite
12. Amphiboles and pyroxenes are mineral groups that belong to the class of minerals called
    A. chain silicates.
    B. framework silicates.
    C. sulfide minerals.
    D. sheet silicates.
13. Which of the following statements is NOT true of quartz and calcite?
    A. Calcite has excellent cleavage; quartz has poor to no cleavage.
    B. Quartz is a carbonate mineral.
    C. Both are often colorless.
    D. Quartz has a hardness of about 7 and calcite a hardness of about 3.
14. The characteristic of certain minerals to break along planes of weakness is called
    A. crystal symmetry.
    B. cleavage.
    C. hardness.
    D. luster.
15. Graphite and diamond are two very different minerals. Why are the physical properties of graphite and diamond so different even though they are both made from pure carbon?
    A. The chemical bonds between the carbon atoms and their crystal structures are significantly different.
    B. Graphite has strikingly different physical properties from diamond because of impurities within its crystal structure, whereas diamond is pure carbon.
    C. Actually, graphite and diamond are not minerals because they are made from carbon and all matter made from carbon is organic. Their physical properties are different because they were produced by very different living organisms.
    D. None of the above.



16. Chemical bonding along cleavage planes within the crystal structure of a mineral typically
    A. is more covalent.
    B. is more ionic.
    C. is more magnetic.
    D. involves electron sharing between atoms.

    Hint: Refer to the section in the textbook titled *Cleavage*.

17. Iron and magnesium ions are similar in size and both have a +2 charge. Therefore we would expect iron and magnesium to
    A. bond easily.
    B. share electrons.
    C. form minerals with different crystal structures.
    D. substitute for each other within the crystal structure of minerals.

    Hint: Refer to Figures 3.3 and 3.4 and the section in the textbook titled *How Do Minerals Form?*

18. The chemical bonds between carbon atoms within diamond are predominantly
    A. covalent.
    B. ionic.
    C. metallic.
    D. nuclear.

19. Which of the following rocks forms from molten material cooling and solidifying within the Earth's crust?
    A. volcanic
    B. plutonic
    C. sedimentary
    D. metamorphic

20. Molten rock within the Earth's crust is called
    A. silica.
    B. lava.
    C. magma.
    D. mica.

21. Coarse-grained igneous rocks, such as granite, are exposed today at the Earth's surface due to
    A. uplift and erosion.
    B. quickly cooled lavas erupting from ancient volcanoes.
    C. silicate minerals precipitated from rainwater.
    D. all of the above.

22. Lithification is the process that converts sediments into solid rock by
    A. cooling and crystallization.
    B. pressure cooking.
    C. subduction.
    D. cementation and compaction.

23. Bedding (layering) is a major identifying characteristic of
    A. sedimentary rocks.
    B. metamorphic rocks.
    C. intrusive rocks.
    D. none of the above.

24. Contact metamorphism
    A. occurs in areas of very high temperature and pressure, like subduction zones.
    B. extends over very large areas.
    C. is characteristic of continental collision zones.
    D. occurs in areas where magma intrudes and metamorphoses neighboring rock.

    Hint: Refer to Figure 3.27.

25. In the rock cycle, weathering
    A. creates sediments.
    B. results in burial and lithification.
    C. creates mountains.
    D. can cause metamorphism.

26. In the rock cycle, mountains typically form as a result of
    A. weathering and erosion.
    B. metamorphism.
    C. sedimentation piling up rock.
    D. subduction and continents colliding.

    Hint: Refer to Figure 3.28.

Study Tip: Construct a Simplified Rock Cycle

Figure 3.28 packs much information into one page and provides an overview of how rock types are linked to Earth's plate tectonic and climate systems. As a review for an exam, construct your own rock cycle flowchart. Keep it relatively simple and focus on presenting the following information:

- Major rock types
- One or two important diagnostic characteristics of each rock type
- Process(es) that transform a rock into another rock type

Use sketches, words, phrases, or bulleted lists to describe each component (each major rock type) and connecting pathways (processes that transform rocks into another type).

If you are a visual learner, concentrate on drawing simple illustrations that characterize how each rock type forms and how it is linked to other rock types. If you learn better from reading or listening, then use arrows and describe the major elements of the rock cycle in words and read it out loud.

CHAPTER 4

Igneous Rocks: Solids from Melts

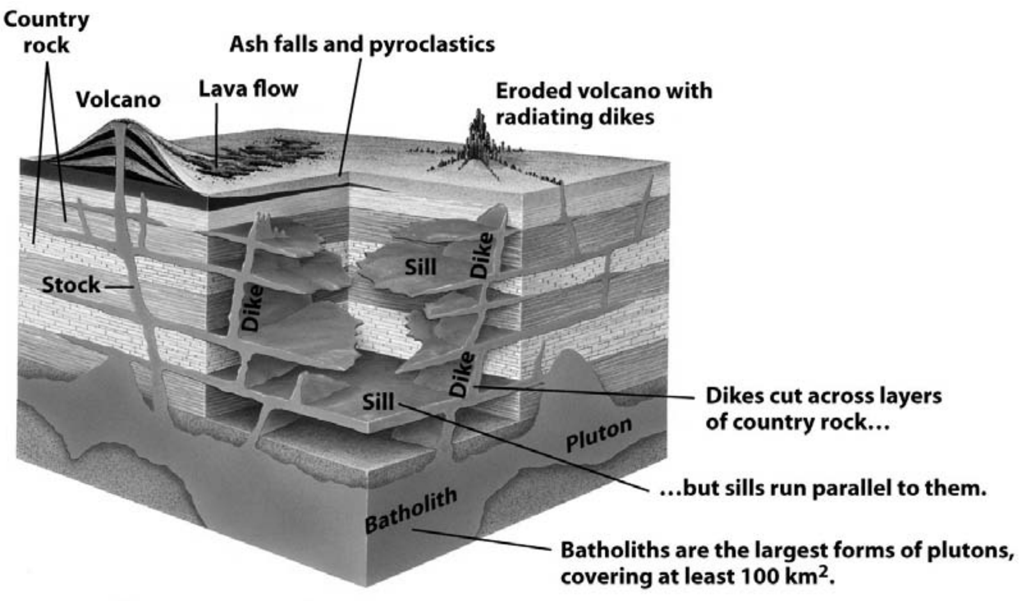


Figure 4.9. Basic forms of extrusive and intrusive igneous structures.

Before Lecture

Before you go to lecture, spend some time previewing Chapter 4. We have made it easier by identifying the five key questions on igneous rocks for you (see **Chapter Preview**). These questions constitute the framework for understanding this chapter. Working with the **Chapter Preview** questions before lecture and committing them to memory should help you understand the lecture better and take excellent notes.

Chapter Preview

- **How are igneous rocks classified?**
  Brief answer: Composition and texture (cooling history). Preview Figures 4.1, 4.3, and 4.4 and Table 4.1
- **How and where do magmas form?**
  Hint: Table 4.2 and Figure 4.13 in the textbook provide an overview.
- **How does magmatic differentiation account for the great variety of igneous rocks?**
  Hint: Figures 4.6 and 4.7 tell the classic differentiation story. Figure 4.8 adds important details.
- **What are the forms of intrusive and extrusive igneous rocks?**
  Hint: Figures 4.9 and 4.12 show the basic intrusive and extrusive igneous rock bodies.
- **How do igneous rocks relate to plate tectonics?**
  Brief answer: Magmas tend to form at divergent and convergent plate boundaries and hot spots. **Hint:** Refer to Figures 4.13, 4.15, and 4.16, Rock Composition, and Types of Magmas section of Chapter 4 for more details.

Preview of magma types in relation to plate tectonic settings

Plate tectonic setting (examples)	Magma type (example rock type)
Spreading centers	
• oceanic ridge (Mid-Atlantic Ridge)	• mafic (basalt)
• continental rift (East African Rift)	• mafic to felsic (silicic)—more variable because some continental crust may melt.
Subduction zones	
• oceanic island arc (Japan)	• mafic to intermediate
• continental volcanic arc (Cascade Range, Mt. St. Helens, Mount Rainier, and Andes in South America)	• mafic to felsic (silicic)—more variable because continental crust may melt.
Note: Not much volcanism occurs in association with collision plate boundaries.	
Intraplate mantle plumes ("hot spots")	
• oceanic hot spots (Hawaii)	• mafic (basalt)
• continental hot spots (Yellowstone)	• mafic to felsic (silicic)—more variable because continental crust is melted.

Vital Information from Other Chapters

Review Figures 3.24 and 3.25.

Web Site Study Resources

http://www.whfreeman.com/understandingearth6e

During Lecture

A lot of important visual material will be covered in this lecture. Be sure you preview the chapter before lecture. Because the material is somewhat technical, you will want to take notes in as organized a manner as possible. Following are some ideas you may find helpful.

- **Big picture for Chapter 4.** To avoid getting lost in details, keep the big picture in mind throughout the lecture.

  Chapter 5 explains how plate tectonics drives the formation of magma and how igneous rocks of varying composition and texture are produced at particular plate locations. For example, fine, textured volcanic rock of basaltic composition is produced at a diverging ocean plate (see Figure 4.15).
- **Key figures for lecture.** This chapter introduces many new words and concepts to learn. It may be helpful to bookmark one or two of the most important textbook figures you previewed before coming to lecture. Figure 4.3 will help you with igneous rock classification. Figures 3.28, 4.13, 4.15, and 4.16 summarize where and how magmas are formed.
- You will also be developing a new skill: identifying igneous rocks. Often lecturers use slides or rock samples to help you learn this skill. The following tip and chart tool will help you master this skill efficiently.

Note-Taking Tip: How to take notes on rock samples

During lecture the instructor may show slides of igneous rock formations and may pass around specimens of igneous rocks. The specimens will be easier to see if you sit close to the front of the room. For the instructor, each sample tells a story. You can become proficient at reading rock stories, too. It just takes practice and a little organization. For igneous rocks, a chart like the following example will help you organize what you see and hear. The chart focuses on the two things you need to pay the most attention to: *texture* (whether or not you can see crystals) and *composition* (the likely mineral content of this rock). If the instructor tells an interesting story about the rock, make a note or two; stories help us remember details we might otherwise forget.

What to do. Before the lecture on igneous rocks, make a chart like the one that follows on a full sheet of notebook paper. Leave plenty of room for notes about each sample. Try to put something in every column for every rock sample. If you miss a column or were unable to see some of the minerals in the rock, be sure to talk to the instructor right after lecture (while your memory is fresh and the rock sample is handy) and fill in what you need to complete the chart. **Hint:** This idea is also going to be useful in subsequent chapters on sedimentary and metamorphic rocks.

Example: Rock sample-note taking chart

(Set up on one full page of your notebook.)

Rock name	Texture clues (coarse, fine, etc.)	Composition clues (mineral clues, color, dark/light, etc.)	Story about the rock to help you remember it	Other notes
(Example) ***Granite***	Coarse	I could make out crystals of black hornblende, white and pink feldspars, and thin, shiny sheets of mica in a light gray matrix (quartz).	"Came from [you name it] Mountain near our campus. I slipped and fell just before I found this sample." Stories will help you remember information.	Crystals were clearly visible in the slide. Crystals were mostly feldspar and muscovite mica! What I thought was hornblende turned out to be biotite. I tried to scratch the rock with a penny; no luck, must be kind of hard (above 3 on the Mohs' scale). Minerals in granite average greater than 5 on the Mohs' scale. Too bad I didn't bring my bowie knife to class.
Sample 1 . . . . ***Sample 2 and so on***				

After Lecture

Review Notes

Chapter 4 is a bit technical, so it will be particularly important to rework and improve your notes after lecture.

Check Your Notes: Have you…

☐ used the five preview questions as section headings for your notes? You should have sections dealing with (1) classification, (2) magma formation, (3) magma differentiation, (4) igneous structures, and (5) plate tectonics and igneous rock formation.

- ☐ added exercise material from this guide to your notes? A great place to begin is to complete Exercise 1 (see **Practice Exercises**). Exercise 1 will help you understand what is perhaps the single most fundamental idea about igneous rock, namely rock texture. If you do the exercise sketches on notebook paper, you can clip them somewhere near the beginning of your notes on igneous rocks for future review.
- ☐ added visual material to your notes? Key figures to consider adding are Figure 4.4, classification model of igneous rocks; Figures 4.6 and 4.7, fractional crystallization which explains the composition of a basaltic intrusion; Figure 4.9, basic extrusive and intrusive igneous structures; and Figure 4.13, plate tectonics and magma formation. Remember, the idea is to draw simplified versions that emphasize the features discussed in lecture.
- ☐ included a brief summary of this chapter? Writing a brief summary of the essence of a chapter is a good way to help focus on what is important and avoid getting bogged down in less essential details.

Intensive Study Session

You learn geology much as you would build a house. Before each lecture, construct a frame of questions. During lecture, attach details and ideas to the frame. After lecture master the ideas during an intensive study session. Now you have constructed the first few stories. But geology is a skyscraper with 23 floors (one for each chapter). Each chapter supports the one above it. If you don't completely master this chapter, the next will be more difficult.

- **Test your understanding of rock texture and other important concepts identified in the Chapter Preview.** There are some great features built into this chapter that you can use to learn. One good example is Figure 4.2. Read the section Texture at the beginning of the chapter. You will learn how James Hutton deduced the nature of igneous rock by assessing three lines of evidence (clues 1–3). Then look at Figure 4.2. You can have an experience of discovery not unlike Hutton's. Study Figures 4.1, 4.2, and 4.3 until you think you understand texture. Then do Exercise 1 and really master interpreting rock textures. Move on through the chapter, paying particular attention to Figures 4.3, 4.4, 4.6, 4.7, 4.8, and 4.13.
- **Practice Exercises and Review Questions** Next use the Study Guide Practice Exercises and Review Questions in the Study Guide. Be sure to do Exercise 1. It involves the key information you need to learn in this chapter.
- **Web Site Study Resources**
  http://www.whfreeman.com/understandingearth6e
  Flashcards will help you learn new terms. Try your hand at being a field geologist by doing the exercises in **Geology in Practice,** an excellent review of basic information on igneous rocks.

Exam Prep

Materials in this section are most useful during your preparation for exams. The following **Chapter Summary** and the **Practice Exercises** and **Review Questions** should simplify your chapter review. Read the **Chapter Summary** first. It provides a helpful overview that should refresh your memory.

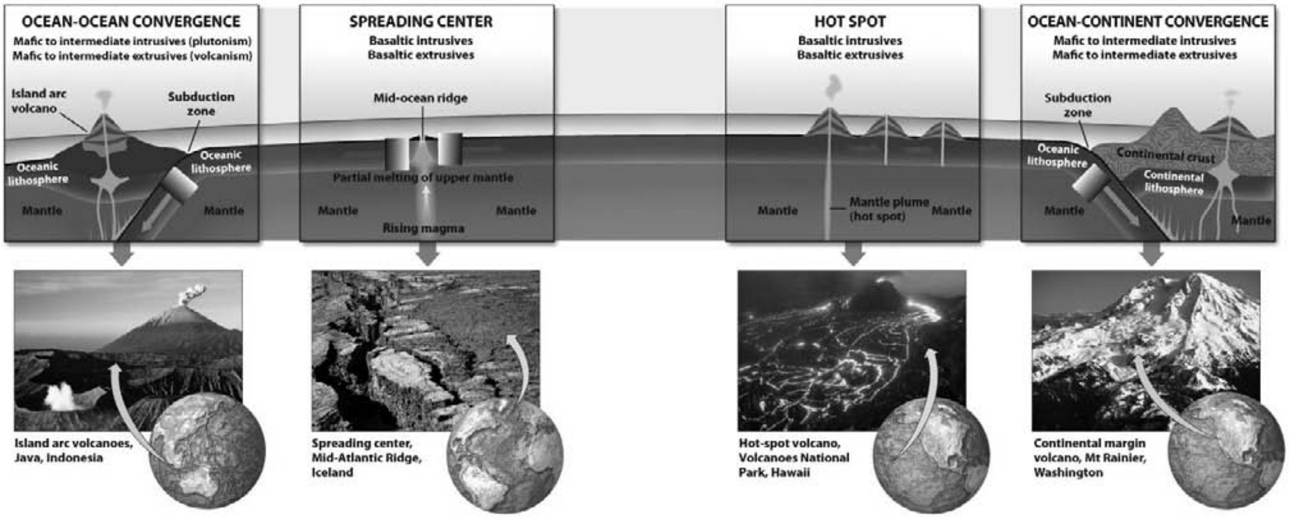


Figure 4.13. Magmatic activity is related to plate tectonic settings.

Next, work on the **Practice Exercises** and **Review Questions.** Complete the exercises and questions just as you would an exam, to see how well you have mastered this chapter. After you answer the questions, score them. Finally, and most important, review each question you missed. Identify and correct the misconception(s) that resulted in your incorrect answer.

Chapter Summary

How are igneous rocks classified?

- Igneous rocks can be divided into two broad textural classes: (1) coarsely crystalline rocks, which are intrusive (plutonic) and therefore cooled slowly, and (2) finely crystalline rocks, which are extrusive (volcanic) and cooled rapidly. Within each of these broad textual classes, the rocks are subdivided according to their composition. General compositional classes of igneous rocks are felsic, intermediate, mafic, and ultramafic, with decreasing silica and increasing iron and magnesium content.

How and where do magmas form?

- The lower crust and the upper mantle are typical places where physical conditions induce rock to melt. High temperatures, a reduction in pressure, and the presence of water all cause melting. Composition is also a factor in the melting temperature of rocks.

How to melt a rock—the generation of magma

- Increase the temperature.

  Not all minerals melt at the same temperature (refer to Figures 4.6 and 4.7). The mineral composition of the rock affects the melting temperature. Felsic rocks with higher silica content melt at lower temperatures than do mafic rocks, which contain less silica and more iron and magnesium.

- Lower the confining pressure.

  A reduction in pressure can induce a hot rock to melt. A reduction in confining pressure on the hot upper mantle is thought to generate the basaltic magmas that intrude into the oceanic ridge system to form ocean crust (refer to Figure 4.15).

- Add water.

  The presence of water in a rock can lower its melting temperature by up to a few hundred degrees. Water released from rocks subducting into the mantle along convergent plate boundaries may be an important factor in magma generation, especially at the convergent plate boundaries (refer to Figure 4.16).

How does magmatic differentiation account for the great variety of igneous rocks?

- There is an amazing variety of igneous rocks on Earth. Two processes help to explain how the composition of igneous rocks can be so variable. They are partial melting and fractional crystallization (refer to Figures 4.6, 4.7, and 4.8).
- The Bowen's reaction series in Figure 4.6 is a flowchart describing how the very general bulk composition of a magma can change as the magma solidifies or as a rock melts.

What are the forms of intrusive and extrusive igneous rocks?

- Names are given to igneous rock bodies based on their size and shape. Figure 4.9 summarizes the common igneous rock bodies, such as batholith, pluton, dike, and sill.

How do igneous rocks relate to plate tectonics?

- Mid-ocean ridges and subduction zones are the major sites of magmatic activity (refer to Figures 4.13, 4.15, and 4.16).

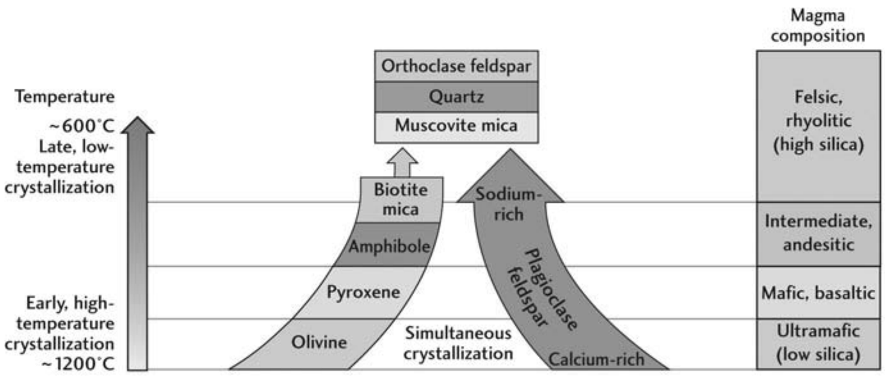


Figure 4.6. Bowen's reaction series provides a model of fractional crystallization.

Practice Exercises

Exercise 1: Igneous rock textures

In each of the four boxes, sketch the igneous rock texture that is consistent with the origin of the rock as described above each box. Fill in the blank with the appropriate texture term from the list. Figures 3.25 and 4.3 will be helpful.

Texture terms

Fine grained (aphanitic)

Intermediate grain sizes—visual grains but not very coarse grained

Coarse grained (phaneritic)

Mixture of coarse and fine grains (porphyritic)

A. Draw the texture of an igneous rock from a pluton solidified at depth within the crust.

phaneritic
Name of texture

B. Draw the texture of an igneous rock from a shallow magma body, like a dike or sill.

____
Name of texture

C. Draw the texture of a lava erupted from a magma chamber after some minerals had begun to crystallize.

____
Name of texture

D. Draw the texture of a lava flow that erupted before the magma chamber underwent any crystallization.

____
Name of texture

Exercise 2: Distribution of igneous rocks within the Earth

Complete the table with terms from the lists that follow the table. Refer to Figure 4.4 in your textbook. Some answers are provided. Note that the Earth's core is not included in this table because it is thought to be composed mostly of iron and nickel, not silicate minerals.

Major layer in the Earth	Example igneous rock	General compositional group	General chemical composition
Continental crust (For continental crust, there are two appropriate answers.)	*Granite*		
		Intermediate	
Ocean crust			
Mantle			*Less Si, Na, K* *More Fe, Mg, Ca*

Example igneous rocks
granite/rhyolite
basalt/gabbro
andesite/diorite
peridotite
granodiorite/dacit

General compositional group
ultramafic
felsic
intermediate
mafic

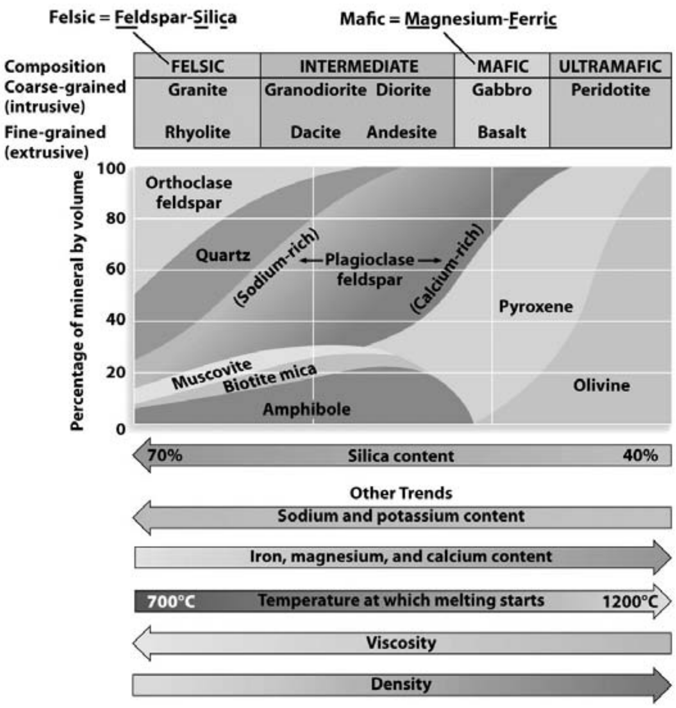
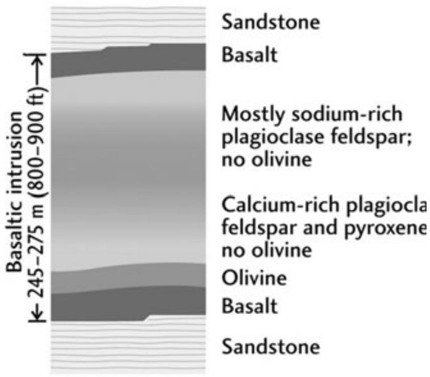


Figure 4.4. Classification model of igneous rocks. The vertical axis measures the mineral composition of a given rock as a percentage of its volume. The horizontal axis shows the silica content by weight. Thus, if you know by chemical analysis that a coarsely textured rock sample is about 70 percent silica, you could determine that its composition is about 6 percent amphibole, 3 percent biotite, 5 percent muscovite, 14 percent plagioclase feldspar, 22 percent quartz, and 50 percent orthoclase feldspar. Your rock would be a granite. Although rhyolite has the same mineral composition, its fine texture would eliminate it.

Exercise 3: Predicting the change in composition in crystallizing magma



A basaltic magma intruded between sandstone layers to form the sill. As the magma cooled in place, fractions of the crystals that formed settled into layers—it underwent fractional crystallization. Using Figures 4.4, 4.6, and 4.7, predict how the silica and iron content of the Palisades sill changes. Indicate whether the silica and iron content increase, decrease, or stay the same in each layer of the sill. Explain the reason(s) for your answers.

Predict how the silica and iron content of the mafic Palisades sill changes as the magma cools. Circle the correct answer.

A. Olivine → Pyroxene → Calcium-rich plagioclase feldspar and pyroxene with no olivine

1. Silica content: increased / decreased / stay the same
2. Iron content: increased / decreased / stay the same

Explanation:

B. Calcium-rich plagioclase → sodium-rich plagioclase feldspar and no olivine

1. Silica content: increased / decreased / stay the same
2. Iron content: increased / decreased / stay the same

Explanation:

Exercise 4: Sequence of mineral crystallization in a solidifying magma

Circle the answers that correctly complete the following statements.

A. The atomic (crystal) structure of the earliest formed silicate minerals in a magma tend to be MORE / LESS complex than the crystalline structures of minerals formed during later stages in the solidification of the magma.

B. During the solidification of a magma, the minerals with the highest silica content will crystallize FIRST / LAST.

C. In the last stages of solidification of a magma, the remaining silicate melt will contain MORE / LESS silica than the original melt.

Hint: You do not need to know the bulk composition (mafic, intermediate, felsic) of the magma to answer these questions. Refer to Figures 4.4, 4.6, and 4.7.

Exercise 5: Partial melting and magma composition

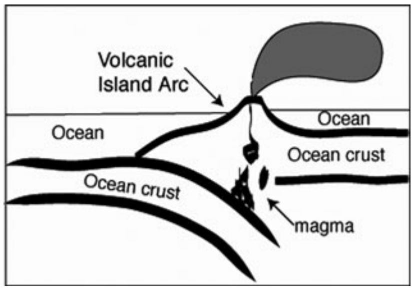
Circle the answers that correctly complete the following statements.

Compared to the bulk composition of the rock, the minerals with the lower melting temperature are

A. HIGHER / LOWER in the Bowen's reaction series.
B. DEPLETED / ENRICHED in Mg, Fe, and Ca.
C. DEPLETED / ENRICHED in Si, Na, K.
Hint: Refer to Figures 4.5, 4.6, and 4.7.

Exercise 6: Predicting the composition of magma generated in subduction zones

Circle the answer for each statement that correctly completes the following sentence: Compared to the basaltic ocean crust, the magma generated by partial melting of the subducting slab of ocean crust will



A. have MORE / LESS silica.
B. have MORE / LESS iron and magnesium.
C. have MORE / LESS sodium and potassium.
D. be MORE / LESS mafic.

Review Questions

1. Igneous rock names are based on
   A. texture and composition.
   B. fine grain and coarse grain.
   C. intrusive and extrusive.
   D. where the magma chamber erupts.
2. What rock has the same mineralogy as granite but a fine-grained texture?
   A. andesite
   B. basalt
   C. obsidian
   D. rhyolite
3. Which of the following rocks contains the most silica?
   A. basalt
   B. rhyolit
   C. fissure eruptions
   D. dacite

4. Which of the following pairs of intrusive and extrusive rocks are made from the same minerals—i.e., have the same chemical composition?
   A. gabbro and basalt
   B. diorite and basalt
   C. fissure eruptions
   D. gabbro and rhyolite

5. In the field or in hand-sized specimens, intrusive and extrusive igneous rocks are distinguished by which characteristic?
   A. composition
   B. color
   C. porphyritic versus nonporphyritic texture
   D. grain size

6. Which of the following iron-rich minerals is most common in basalt?
   A. pyroxene
   B. quartz
   C. muscovite
   D. Na-plagioclase

7. Granite is made up mainly of
   A. quartz, orthoclase (K-feldspar), and Na-plagioclase.
   B. quartz, Ca-plagioclase, Na-plagioclase, and amphibole.
   C. quartz, pyroxene, and muscovite.
   D. quartz, orthoclase (K-feldspar), Ca-plagioclase, and olivine.

   Hint: Refer to Table 4.1 and Figure 4.4.

8. An igneous rock made of a mixture of both coarse- and fine-grained minerals is called porphyritic and is formed by
   A. rapid cooling followed by a period of slow cooling.
   B. slow cooling followed by a period of rapid cooling.
   C. very slow cooling of a water-rich magma.
   D. very rapid cooling in the presence of water.

9. Only iron and magnesium-rich minerals are found in which of the following lists of minerals?
   A. pyroxene, hornblende, K-feldspar, biotite
   B. plagioclase, biotite, pyroxene, clay
   C. quartz, muscovite, biotite, plagioclase
   D. biotite, pyroxene, olivine, hornblende

10. Following Bowen's reaction series, the later, lower-temperature fractions of liquid magma become progressively
    A. depleted in silica.
    B. enriched in silica.
    C. enriched in magnesium.
    D. depleted in potassium.

    Hint: Refer to Figures 4.6 and 4.7.

11. Which of the following minerals are the earliest highest-temperature minerals to crystallize in Bowen's Reaction Series?
    A. quartz and feldspar
    B. plagioclase and amphibole
    C. plagioclase and olivine
    D. chert and mica

12. The formation of granitic batholiths occurs
    A. within the ocean crust.
    B. within the continental crust.
    C. along spreading centers in the ocean.
    D. under hot spots.

13. Considering the following minerals, which pairs would you predict would NOT be found together in the same igneous rock?
    A. K-feldspar and biotite
    B. Na-plagioclase and muscovite
    C. quartz and Na-plagioclase
    D. quartz and olivine

    Hint: Refer to Figures 4.4, 4.6, and 4.7.

14. How would you distinguish a lava flow from a sill exposed at the Earth's surface?
    A. Sills tend to be coarser grained than lava flows because they cool slower.
    B. The chemical compositions of the lava flow and the sill (that is, the minerals present) would be very different.
    C. Sills tend to be finer grained because of slower rates of crystallization.
    D. Lava flows are coarser grained because of very rapid rates of cooling.

15. The rock type of most batholiths found in the continental crust is
    A. gabbro.
    B. obsidian.
    C. granite.
    D. basalt.

16. How does a rising magma make space for itself as it moves through the solid crust?
    A. by breaking off large blocks of rock that sink into the magma chamber
    B. by wedging open the overlying rock
    C. by melting surrounding rocks
    D. by all these processes

17. The source for most mafic magmas is thought to be
    A. partial melting of felsic and intermediate rocks in the upper continental crust.
    B. partial melting of ultramafic rocks within the upper mantle.
    C. melting of preexisting granites and sediments.
    D. the molten core of the Earth.

18. If lava flows on the slopes of a volcano are derived from one large magma chamber, which crystallizes slowly and feeds eruptions over a period of many thousands of years, how would you predict the gross composition of the lava would change as the lava flows become younger?
    A. Younger lava flows would become progressively enriched in iron and more mafic.
    B. Younger lava flows would become progressively enriched in silica and more felsic.
    C. Lava flows would be the same composition since they all came from the same magma chamber.
    D. Lava flows would alternate in composition.

    Hint: Use Bowen's reaction series in Figure 4.6 and review the textbook section *Magmatic Differentiation.*

19. The production of basalt can be achieved by the partial melting of
    A. gabbro.
    B. ultramafic rocks.
    C. a mixture of gabbro and oceanic sediments.
    D. rhyolite.

    Hint: Refer to Figures 4.13 and 4.15.

20. Andesites—intermediate magmas—are typically associated with
    A. divergent plate margins, like the mid-oceanic ridges.
    B. fractures in the crust that allow magmas from the upper mantle to rise to the surface.
    C. hot spots, like Hawaii.
    D. convergent plate margins, like the western edge of South America—the Andes.

21. An ophiolite suite contains the following combination of rocks:
    A. granite, gneiss, sandstone, limestone, and shale.
    B. deep sea sediments, pillow basalts, gabbro, and peridotites.
    C. dikes, sills, and plutons of peridotites.
    D. plutonic rocks and surrounding sediments characteristic of a magma chamber.

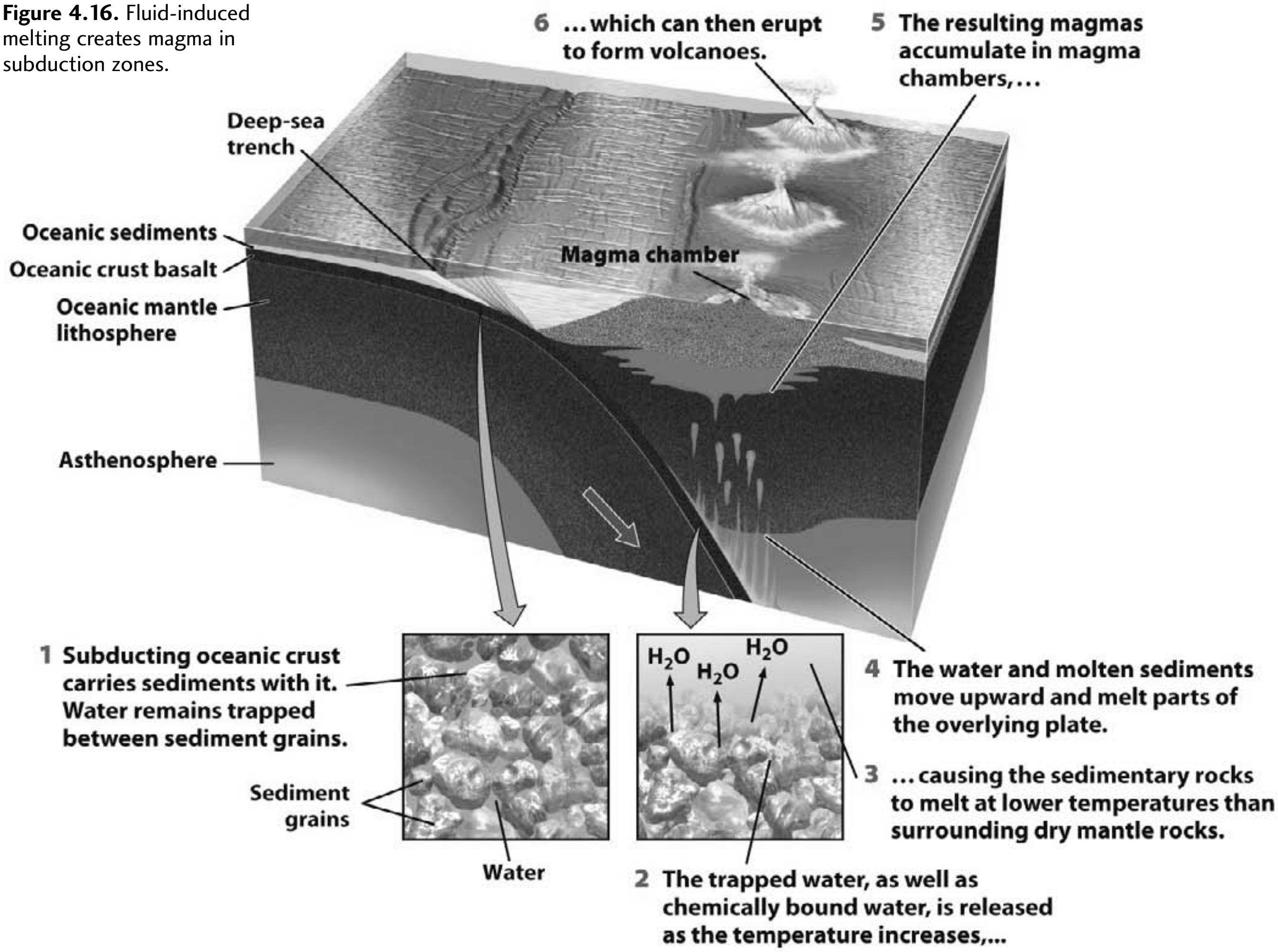


Figure 4.16. Fluid-induced melting creates magma in subduction zones.

22. Which flowchart characterizes the magmatic processes that occurr at spreading centers?
    A. peridotite → decompression melting → basalt
    B. ophiolite → fluid-induced melting → basalt
    C. deep ocean sediments → fluid-induced melting → andesites
    D. basalt → decompression melting → peridotite

23. Which of the following hypotheses for the origin of granite is NOT reasonable?
    A. mixing of magmas with different compositions
    B. decompression melting within a magma plume
    C. partial melting
    D. melting of sedimentary and metamorphic rocks

24. Which set of conditions will result in basalt melting at the lowest temperature?
    A. dry basalt at low pressure
    B. dry basalt at high pressure
    C. wet basalt at low pressure
    D. wet basalt at high pressure

CHAPTER 5

Sedimentation: Rocks Formed by Surface Processes

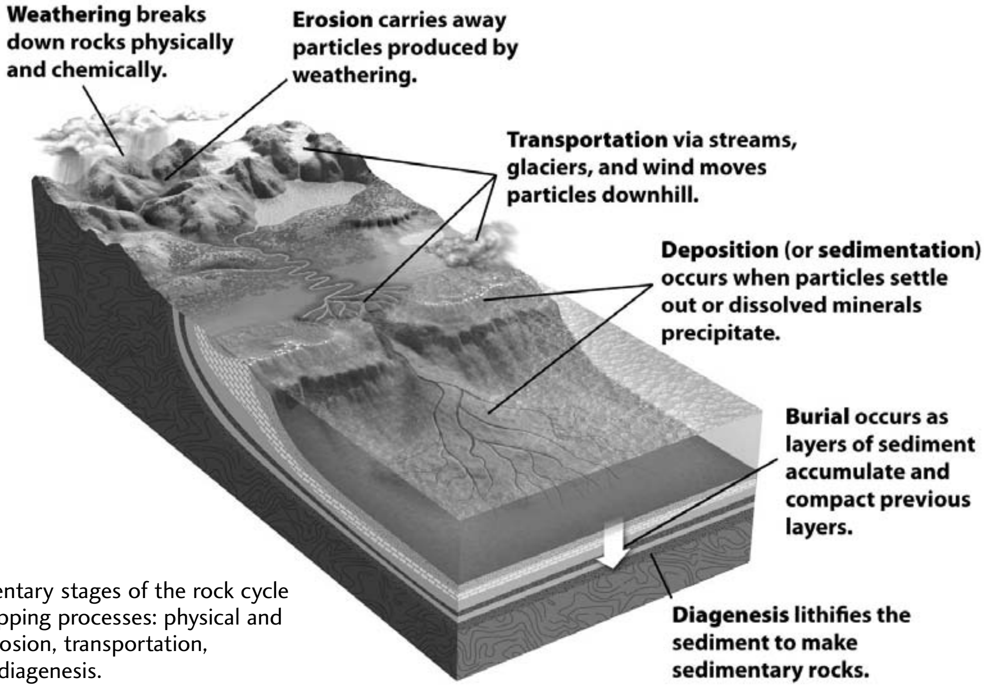


Figure 5.1. The sedimentary stages of the rock cycle comprise several overlapping processes: physical and chemical weathering, erosion, transportation, deposition, burial, and diagenesis.

Before Lecture

Chapter Preview

- **What are the major processes in the formation of sedimentary rocks?**
  Brief answer: weathering, erosion, transportation, deposition, burial, and diagenesis. Study Figure 5.1.

- **How does plate tectonics relate to sedimentary rock?**
  Brief answer: Environments of deposition, composition, and texture of sediments, as well as the shape and depth of sedimentary basins, are influenced by plate tectonics. Refer to Figure 5.8.
- **What is the relationship between sediments and environments on the Earth's surface?**
  Hint: Refer to Figure 5.9.
- **What are the major types of sediments and sedimentary rocks?**
  Brief answer: siliciclastic (sandstone) versus chemical (evaporites) and biochemical (limestone). Study Tables 5.3 and 5.4, and Figures 5.9, and 5.16.

Vital Information from Other Chapters

Review Figure 3.24 and preview Chapter 16.

During Lecture

Note-Taking Tip: Some features to watch for in sedimentary rock samples and formations

In this lecture you will be introduced to a variety of sedimentary rocks, formations, and sedimentary environments. Since they will probably be new to you, it is smart to prepare. Spend a few minutes of your preview time becoming familiar with the most important sedimentary rock features:

- Bedding and other sedimentary structures: pages 124–126
- Bedding sequences (stratigraphy): Figure 5.15 on page 126
- Grain size: Figures 5.7 and 5.19 and Table 5.3
- Mineral content and major groups of sandstones: Figure 5.20 on page 132
- Chemical and biological sedimentary rocks: Figure 5.21
- Carbonate platform systems: Figure 5.22

One goal for lecture should be to leave the room with good answers to the preview questions. To avoid getting lost in the details, keep the big picture in mind: Chapter 5 tells the story of how sedimentary rocks are created by the processes of the rock cycle. It may be helpful to have Figure 5.1 with you so that you can refer to it during lecture.

Note-Taking Tip: Use abbreviations to speed up your note taking

bed → bedding	lith → lithification
carb → carbonate	sed → sediment or sedimentary
clast → clastic	sed r → sedimentary rock
chem → chemical	carb sed → carbonate sediment
biochem → biochemical	sed base → sedimentary basin
env → environment	sed env → sedimentary environment

After Lecture

Review Notes

Right after lecture, while the material is fresh in your mind, is the perfect time to review your notes. Review to be sure you understood all the key points and wrote them down in a form that will be readable later.

Check Your Notes: Have you…

- ☐ included the chapter overview? Figure 5.1 is the "big picture." Consider adding your own version, including the six sedimentary rock-forming steps.
- ☐ developed a chart like the one in Exercise 1 to help you learn the sedimentary environments?

Intensive Study Session: Focus on chunking the information into a solid overview

In earlier chapters we have used the metaphor of building a house for studying geology. *Chunking* is a mental process that will help you construct a good frame. The idea is to group the important information. Later you hang details on this framework of basic information.

If you have sometimes wondered how some of your professors can rattle off tons of complicated material without even looking at their lecture notes, chunking (see box) provides an explanation. Over the years they have chunked (connected) more and more bits of information about geology. Chapter 5 provides a great opportunity for you to develop your memory efficiency. Use the clues and aids in the box to group the details of sedimentary rocks into a format that is easy to remember.

Memory and Learning Tip: Chunking

It's easier to remember a three-item list than a 30-item list. If you have 30 things to remember, the first thing you need to do is to divide the long list into a small number of shorter lists. Group similar items together, name the groups, and then associate the items in each list with the group to which it belongs. Instead of trying to remember 30 things, you have reduced your task to remembering a much smaller number.

Example: Figure 5.9 illustrates the different **sedimentary environments** on Earth. Note that while 11 sedimentary environments are discussed, they are organized into three general kinds of environments: continental, shoreline, and marine. You are likely to remember the information better if you chunk it into the three categories rather than trying to absorb the details of all eleven examples. The authors of *Understanding Earth* must agree. Notice that they have organized the information to help you think in terms of just three general categories (continental, shoreline, marine) for sedimentary environments. Note also the color coding. Why did the authors choose particular colors for each environment. Use these clues to study more effectively and improve your retention of the information.

First, overview the processes involved in forming sedimentary rocks. Study Figure 5.1 and commit the six steps in the figure to memory.

Next, work on Figure 5.9 on text page 121, which illustrates common sedimentary environments on Earth. Note that although 11 sedimentary environments are discussed, they are organized into just three kinds of environments. For now focus most of your attention on understanding the three and don't get lost in the details of all 11.

Move on to diagenetic processes on pages 126–128. Figure 5.16 provides a great visual overview. It chunks lots of information. Here's a little memory trick: You can recall all the information in this figure story by remembering just two words: *process* and *sediments.* Here's how it works. First, notice that Steps 1–2 describe the three simple processes (pressure, compaction, and cementation) that are a part of diagenesis. Next look at Step 3. Observe how pressure transforms different sediments into different kinds of rocks with very different textures. There are four sediments (mud, sand, gravel, and organic matter). So you have two short lists to remember: the list of three processes and the list of four sediments. If you can remember the sediments (mud, sand, gravel, organic matter) you can easily guess the rock that each turns into. So you can commit the entire table to memory by memorizing a very short two-word list: *processes (3)* and *sediments (4).* You should be able to remember the rest of the table by association. Try it!

Move on to classification on page 129. Sedimentary rock classification involves many, many details. Notice, however, that you can reduce all these details to two basic categories: (1) clastic sedimentary rocks (Table 5.3 and Figure 5.19) and (2) chemical/biochemical sedimentary rocks (Table 5.4 and Figure 5.21). **Hint:** If you are a visual or kinesthetic learner, it may help to work up your own simplified version of these tables.

If you want to test your knowledge of the chapter, the following materials can be used for self-testing and applying your new knowledge to some very interesting geologic problems.

- **Practice Exercises and Review Questions.** At the very least do Exercise 1. It gets to the key information you need to learn in this chapter.

- **Text.** Read Earth Issues on page 136. Study it to learn more about the formation of coral reefs. This is a must if you like to scuba dive! Answer Exercises 1, 2, and 5. Also work on Thought Questions 3, 5, 7, 10, and 12. When you visit the Grand Canyon in Arizona, you will be able to understand the geology better and impress your traveling partners after completing these exercises and questions.

- **Web Site Study Resources**
  http://www.whfreeman.com/understandingearth6e
  In the **Geology in Practice** exercises on the Web site, you can try your hand at identifying and reconstructing the interesting story told by sedimentary rocks. *Identifying Sedimentary Environments, Common Sedimentary Environments,* and *Depositional Environments* are Web site exercises that will also provide you an opportunity to practice using information and skills highlighted in this chapter.

Exam Prep

Materials in this section are most useful during your preparation for quizzes and exams. The **Chapter Summary** and the **Practice Exercises** and **Review Questions** should simplify your chapter review. Read the **Chapter Summary** to begin your session. It provides a helpful overview that should refresh your memory.

Next, work on the **Practice Exercises** and **Review Questions.** Complete the exercises and questions just as you would an exam, to see how well you have mastered this chapter. After you answer the questions, score them. Finally, and most important, review each question you missed. Identify and correct the misconception(s) that resulted in your answering the question incorrectly.

Chapter Summary

What are the major processes in the formation of sedimentary rocks?

- Weathering and erosion produce the clastic particles and dissolved ions that compose sediment. Water, wind, and ice transport the sediment to where it is deposited. Burial and diagenesis harden sediments into sedimentary rocks. Refer to Figure 5.1.

How does plate tectonics relate to sedimentary rock?

- Sedimentary environments, the composition and texture of sediments, and the geometry of the basins in which sediments accumulate are all related to plate tectonic settings. For example, the formation of a new ocean basin by rifting along a divergent plate boundary creates a rift basin and ultimately a stable continental margin and ocean basin. Refer to Figure 5.8.

What is the relationship between sediments and environments on the Earth's surface?

- Sedimentary environments are often grouped into three general locations: on the continents, near the shoreline, and in the ocean.
- Factors that influence the sediments in these environments include (1) kind and amount of water, (2) topography, and (3) biological activity.
- Sedimentary structures and fossils provide information about the agent of transport (water, wind, or ice) and the environment of deposition for the sediment.

What are the major types of sediments and sedimentary rocks?

- The two major types of sediments are siliciclastic and chemical/biochemical. Siliciclastic (also known as clastic) sediments are formed from rock particles and mineral fragments. Chemical and biochemical sediments originate from the ions dissolved in water. Chemical and biochemical reactions precipitate these dissolved ions from solution.
- Classification and the name of clastic sediments and sedimentary rocks (conglomerate, sandstone, shale) are based primarily on the size of the grains within the rock. The classification and name of chemical and biochemical sediments (evaporites, limestones, and dolostone) in sedimentary rocks are based primarily on their composition.

How is sediment transformed into hard rock?

- Burial and diagenesis transform loose sediments into hard rock. Burial promotes this transformation because buried sediments are exposed to increasingly higher pressures and temperatures. Diagenesis involves many physical and chemical processes. For example, cementation is an important chemical diagenetic change in which minerals are precipitated in the open spaces within clastic sediments, forming cements that bind the sediments together.

- Figure 5.16 summarizes how diagenetic processes produce changes in composition and texture.

Practice Exercises

Answers and explanations are provided at the end of the Study Guide.

Exercise 1: Common sedimentary environments

Using Figures 5.1 and 5.9 as a guide, fill in column 2 in the following table with the clastic or chemical sediment (e.g., sand, silt, mud, salts, carbonate, peat) that best match the environments of deposition.

Environment of deposition	Sediment deposited
Alpine or glacial river channel	
Dunes in a desert	
Flood plain along a broad meander bend	
River delta along a marine shoreline	
Continental shelf	
Deep sea adjacent to a continental shelf	
Shoreline sand dunes	
Tidal flats	
Organic reef	

Exercise 2: Grain sizes for clastic sedimentary rocks

Using the terms for sediments and rocks listed in Table 5.3, fill in the blanks in columns 3 and 4 with the appropriate names of the sediments and rocks that match the typical particle size of the *common object.* A few answers have been filled in as a reference.

Grain size	Common object	Sediment	Rock type
Coarse	football or bus	*boulder gravel*	
↑	plum or lime		*conglomerate*
	pea or bean		
	coarse-ground pepper or salt		*sandstone*
↓	fine-ground pepper or salt		
Fine	talcum powder or baby powder		

Exercise 3: Clastic and chemical sediments and sedimentary rocks

Given the descriptive statements in column 1, fill in columns 2 and 3 of the table with the appropriate sediment types and rock types from the list of common sediment types and sedimentary rocks.

Sediment types	**Sedimentary rocks**			
biochemical	arkose	dolostone	limestone	sandstone
clastic	chert	evaporite	peat	shale
chemical	conglomerate	graywacke	phosphorite	siltstone

Descriptive statement	Sediment type	Sedimentary rock example
Composed largely of rock fragments		
Precipitated in the environment of deposition		
Important source of coal		
Often formed by diagenesis	*chemical*	*dolostone and phosphorite*
Formed from abundant skeleton fragments of marine or lake organisms, such as coral, seashells, and foraminifers		
Produced by physical weathering		
Produced from rapidly eroding granitic and gneissic terrains in an arid or semi-arid climate		

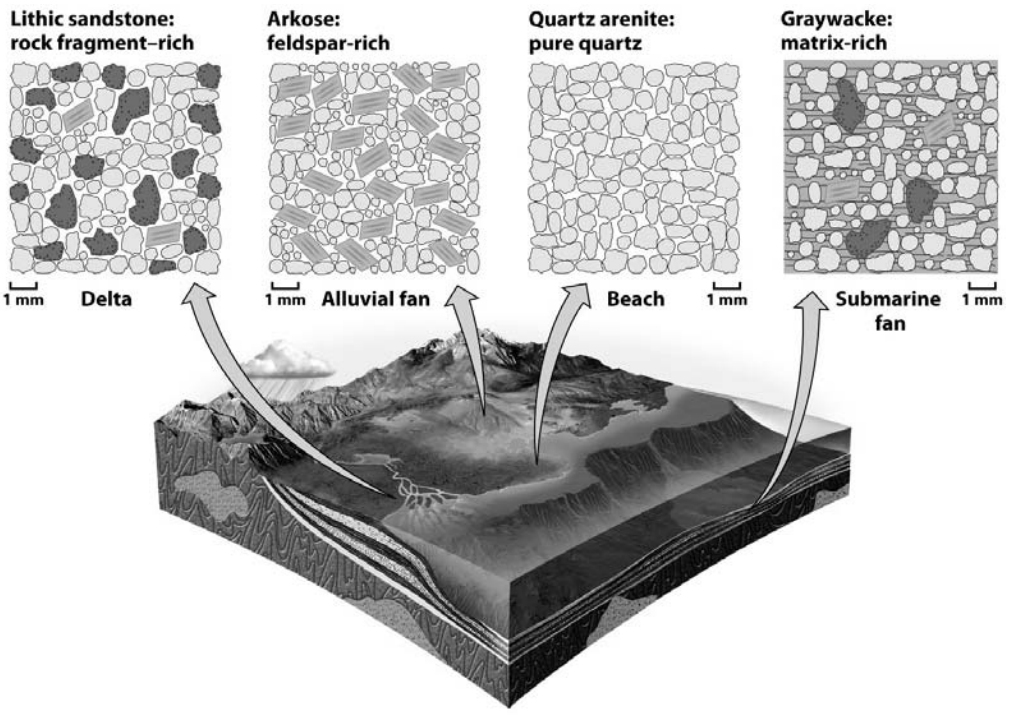


Figure 5.20. The mineralogy of four major groups of sandstones and the sedimentary environments where they are most likely to be found.

Review Questions

1. Which of the following rock groups includes only clastic sedimentary rocks?
   A. dolomite, gypsum, and limestone
   B. cherts, sandstone, and shale
   C. dolomite, coal, and limestone
   D. shale, sandstone, and conglomerate
2. Which sequence of rock names has the correct arrangement in order of decreasing particle diameters?
   A. conglomerate, shale, sandstone
   B. shale, siltstone, sandstone
   C. sedimentary breccia, shale, sandstone, claystone
   D. conglomerate, sandstone, claystone
3. The grains in a sandstone may include
   A. rock fragments.
   B. quartz.
   C. feldspar.
   D. all of the above.
4. Sedimentary rocks are produced through which of the following sequences of events?
   A. erosion, weathering, transportation, deposition, burial, and diagenesis
   B. weathering, erosion, transportation, burial, diagenesis, and deposition
   C. erosion, weathering, deposition, transportation, and cementation
   D. weathering, erosion, transportation, deposition, burial, and diagenesis
5. Dolomite is the primary mineral found in dolostone. It is formed by
   A. foraminifera extracting minerals from seawater.
   B. diagenetic alteration of calcite.
   C. direct precipitation in lake water.
   D. coral reef exposure to direct sunlight.

Test-Taking Tip for Multiple-Choice Exams

When taking a multiple-choice test, treat each alternative answer as a true–false question. Rule out any alternative that is false. For example in Question 4, A and C are false because erosion must follow weathering. B is false because deposition must preceed burial and diagenesis. Therefore, D must be the correct answer.

6. What are the two most important diagenetic processes that transform loose sediments into hard sedimentary rocks?
   A. compaction, cementation
   B. transportation, burial
   C. erosion, transportation
   D. uplift, erosion

7. What are two chemical or biochemical sedimentary rocks formed by the diagenetic process?
   A. dolostone, phosphorite
   B. limestone, chert
   C. sandstone, limestone
   D. siltstone, graywacke
8. Where are most sediments deposited?
   A. on the continental shelf and adjacent ocean floor
   B. in lakes
   C. along streams
   D. in deserts
9. In which of the following materials would you least expect to find cross-bedding?
   A. sand dunes
   B. delta sediment
   C. river bar deposits
   D. evaporites
10. The most widespread environment of deposition for carbonates in the world today is
    A. the deep sea, e.g., the Arctic Ocean.
    B. the tidal flat environment, e.g., the Mississippi Delta.
    C. in river channels.
    D. a warm, shallow-water marine environment, e.g., the Florida Keys.
11. A sandstone made of pure quartz grains is likely to be deposited
    A. along the shore of a continent.
    B. in the deep sea.
    C. in river channels.
    D. along the edges of a coral reef and atolls.
    Hint: Refer to Figure 5.20.
12. Chemical weathering is most dominant in
    A. warm, dry climates.
    B. warm, wet climates.
    C. cool, dry climates.
    D. cool, wet climates.
    E. at the shoreline.
13. The coast of Alaska is known for its high mountainous relief, active volcanoes, and glaciers that reach to the sea. What types of sediments would you expect to be commonly deposited offshore from this landscape?
    A. arkose
    B. carbonate sand
    C. quartz sand
    D. graywacke
    Hint: Refer to Figure 5.20 and the text that precedes it.
14. When a granite is subject to intense chemical weathering, it is most likely to result in a sediment composed of
    A. feldspar and clay.
    B. quartz and calcium carbonate.
    C. quartz and clay.
    D. quartz and feldspar.

Study Tip

Review Chapter 16, Weathering, Erosion, and Mass Wasting.

15. Feldspar is the most abundant silicate mineral in the crust of the Earth; the most common sedimentary rock is
    A. sandstone.
    B. conglomerate.
    C. limestone.
    D. shale.
16. A coarse sandstone with asymmetrical ripples and small-scale cross-bedding is exposed in a cliff between layers of siltstone above and gravels below. What is the environment of deposition for the coarse sandstone layer?
    A. beach
    B. river channel
    C. lake
    D. offshore.
    Hint: Refer to Figure 5.15.
17. Reefs and atolls are built by coral and algae
    A. on subsiding oceanic volcanoes and continental margins.
    B. on islands in the middle of lakes.
    C. in the deep ocean floor and later uplifted to sealevel.
    D. where dolostone is transformed to limestone.
18. As seawater evaporates, precipitation of soluble salts occurs in which order?
    A. halite, carbonates, calcium sulfate
    B. calcium sulfate, halite, carbonates
    C. iron oxide, quartz, peat
    D. carbonates, calcium sulfate, halite
19. Mechanisms by which plate tectonic processes produce sedimentary basins are
    A. rifting, thermal sag, and flexure of the lithosphere.
    B. heating and compression of the crust.
    C. weathering and erosion.
    D. diagenesis and turbation.

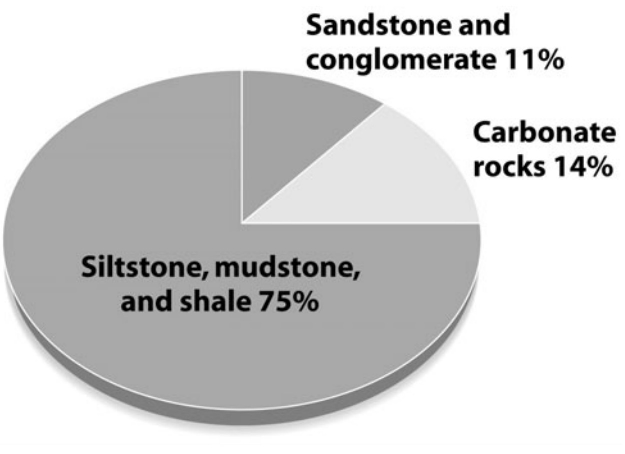


Figure 5.18. The relative abundance of the major sedimentary rock types. In comparison with these types, all other sedimentary rock types—including evaporites, cherts, and other chemical sedimentary rocks—exist in only minor amounts.

CHAPTER 6

Metamorphism: Modification of Rocks by Temperature and Pressure

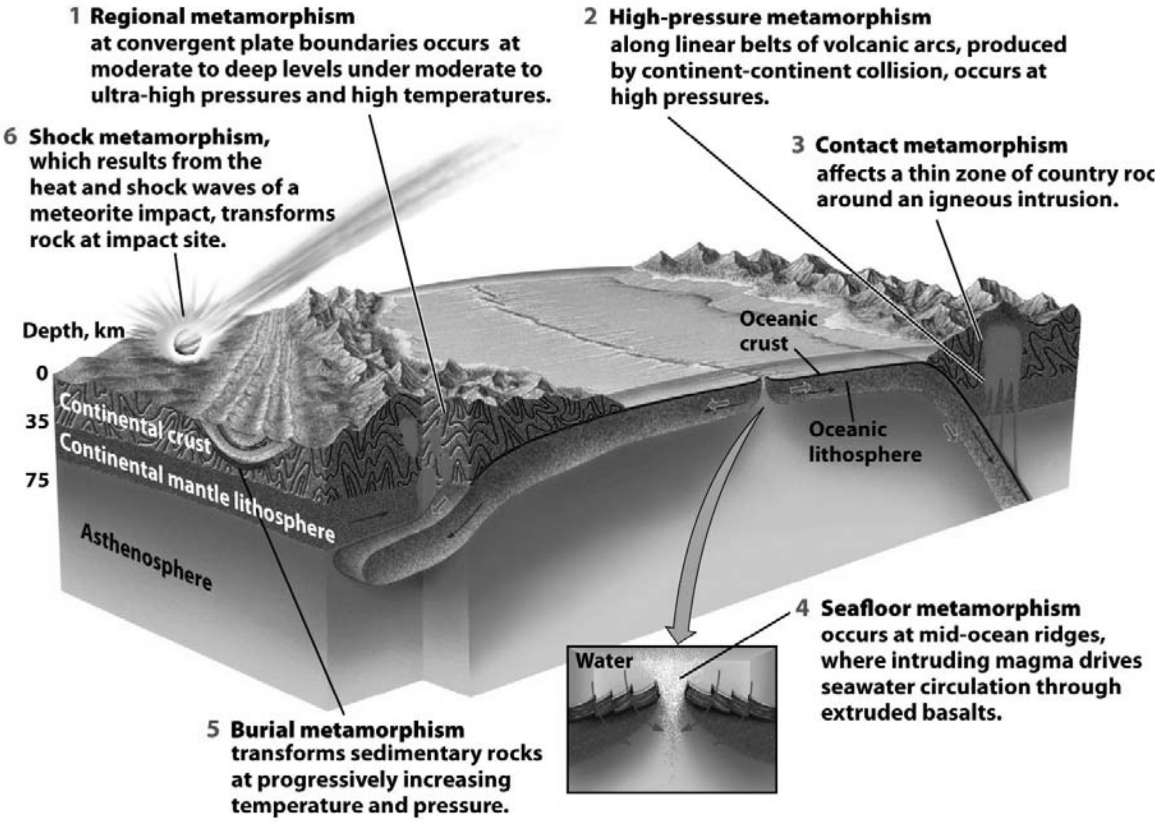


Figure 6.4. Different types of metamorphism occur in different settings.

Before Lecture

Chapter Preview

- **What causes metamorphism?**
  Brief answer: Metamorphism—alteration of preexisting rocks in the solid state—is caused by increases in pressure and temperature and by reaction with chemical components introduced by migrating fluids. See Figure 6.2.
- **What are the various kinds of metamorphism?**
  Brief answer: Regional and contact metamorphism are the most common. See Figures 6.4, 6.5, and 6.6.
- **What are the chief types of metamorphic rocks?**
  Brief answer: Metamorphic rocks fall into two major textural classes called foliated with minerals oriented in some preferred direction such as the grain in wood and nonfoliated with no preferred mineral orientation. See Table 6.1.
- **How is metamorphism linked to plate tectonics?**
  Hint: Refer to Figure 6.4.

Vital Information from Other Chapters

Review the sections Metamorphic Rocks and The Rock Cycle. These sections are short and well worth your review.

During Lecture

Keeping up with a fast-speaking lecturer can be a challenge.

- Take as many notes as you can.
- Don't stop writing when you become confused and you want to ponder a concept. You can do that later.
- If you miss something, leave a space so that you can fill it in later.

Note-Taking Tip: Use abbreviations to speed up your note taking

met rock → metamorphic rock
sed rock → sedimentary rock
sl → slate or slaty
sl cleave → slaty cleavage
shl → shale
shst → schist
fol → foliated
unfol → unfoliated
gran → granular
reg m → regional metamorphism
con m → contact metamorphism

Feel free to make up your own abbreviations. The important thing is to develop shorthand that is meaningful to you, while being quick, easy to use, and easy to remember.

After Lecture

Review Notes

Review your notes right after lecture while material is fresh in your mind. Here is some metamorphic rock material to add to your notes.

Check Your Notes: Have you…

- ☐ added key figures to focus your attention? The most important figures are Figure 6.2 (pressure and temperature), Figure 6.4 (types of metamorphism), Figures 6.5 and 6.6 (foliation). Table 6.1 (classification) is the most important table.
- ☐ added helpful sketches? Suggestion for Chapter 6: Metamorphic rocks are classified in part by texture. Draw simple sketches of textures (slaty cleavage, phyllite, schist, gneiss) to help you remember the grades of metamorphism. Close study of the photo at the beginning of the chapter and Figures 6.5 and 6.6 will help you see how to do this.
- ☐ added a summary of the graphs? Chapter 6 contains some important information in graphic form. Review P-T Figures 6.1, 6.9, 6.10, 6.11, 6.12, and 6.13. Note that all show different grades of metamorphism resulting from increasing pressure and temperature. Can you summarize all these figures on a single page of your notes? What does your summary sketch tell you about the formation of metamorphic rocks?
- ☐ created a brief big picture overview of this lecture (a sketch or written outline)? Suggestion for Chapter 6: Figure 6.4 is key to understanding the tectonic settings that drive metamorphism. Sketch a simplified version that clearly shows six geologic settings for metamorphism. Write a caption for this figure in your own words.

Intensive Study Session

We recommend giving the highest priority to activities that involve answering questions. Answering questions while using your text and lecture notes as reference material is far more efficient than rereading chapters or glancing over notes. As always, you have three sources from which to choose questions.

- **Practice Exercises and Review Questions.** Use the Practice Exercises and Review Questions at the end of this Study Guide chapter. Exercise 1 will help you sort out the kinds of rock discussed in this chapter. Now that you have studied the three rock types in detail, it's time to integrate the information. Exercise 2 will help you rise above the details and gain an overview by comparing igneous, sedimentary, and metamorphic rocks.
- **Text.** For this chapter, the most important figures are Figure 6.2 (pressure and temperature), Figure 6.4 (types of metamorphism), and Figure 6.13 (plate tectonics). The most important table is Table 6.1 (classification). Complete Exercises 1, 6, 8, and 9 and Thought Questions 4, 5, 6, and 9 at the end of the chapter.
- **Web Site Online Review Exercises and Study Tools**
  http://www.whfreeman.com/understandingearth6e
  Complete the **Graded Online Quiz.** Pay particular attention to the explanations for the hints and answers. **Flashcards** will help you learn new terms. The **Geology in Practice** exercises provide an opportunity to practice identifying metamorphic rocks and reviewing geologic settings in which they occur.

Exam Prep

Materials in this section are most useful during your preparation for exams. The **Chapter Summary** and the **Practice Exercises** and **Review Questions** should simplify your chapter

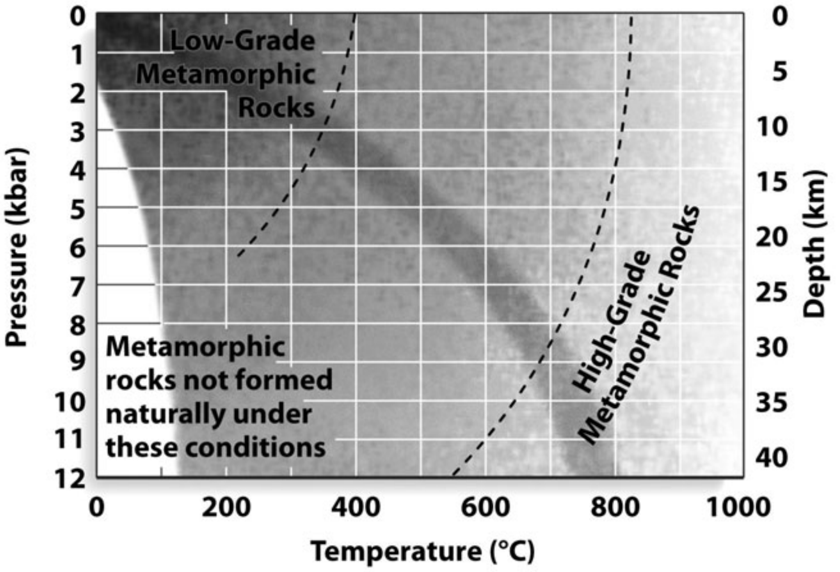


Figure 6.1. Temperatures, pressures, and depths at which low-grade and high-grade metamorphic rocks form. The dark band shows the rates at which temperature and pressure increase with depth over much of the continental lithosphere.

review. Read the **Chapter Summary** to begin your session. It provides a helpful overview that should refresh your memory.

Next, work on the **Practice Exercises** and **Review Questions.** Complete the exercises and questions just as you would an exam, to see how well you have mastered this chapter. After you answer the questions score them. Finally, and most important, review each question that you missed. Identify and correct the misconception(s) that resulted in your answering the question incorrectly.

Chapter Summary

What causes metamorphism?

- Metamorphism is the alteration in the solid state of preexisting rocks, including older metamorphic rocks. Increases in temperature and pressure and reactions with chemical-bearing fluids cause metamorphism. Metamorphism typically involves a rearrangement (recrystallization) of the chemical components within the parent rock. Rearrangement of components within minerals is facilitated by (1) higher temperatures that increase ion mobility in the solid state; (2) higher confining pressure that compacts the rock; (3) directed pressure associated with tectonic activity that can cause the rock to shear (smear), which orients mineral grains and generates a foliation; and (4) chemical reactions with migrating fluids may remove or add materials and induce the growth of new minerals.

What are the various kinds of metamorphism?

- An overview of six types of metamorphism is provided in Figure 6.4. Regional metamorphism (associated with convergent plate boundaries), contact metamorphism (caused by the heat from an intruding body of magma), and seafloor metamorphism (caused by seawater percolating at mid-ocean spreading centers) are the three most common types of metamorphism within the Earth's crust. Other types of metamorphism are low-grade, high-grade, and shock metamorphism.

What are the chief types of metamorphic rocks?

- Metamorphic rocks fall into two major textural classes: foliated (displaying a preferred orientation of minerals, analogous to the grain in wood) and the nonfoliated. The composition of the parent rock and the grade of metamorphism are the most important factors controlling the mineralogy of metamorphic rock. Metamorphism usually causes little to no change in the bulk composition of rock. The kinds of minerals and their orientation do change. Mineral assemblages within metamorphic rocks are used by geoscientists as a guide to the original composition of the parent rock and the conditions during metamorphism. Refer to Figures 6.9 and 6.10.

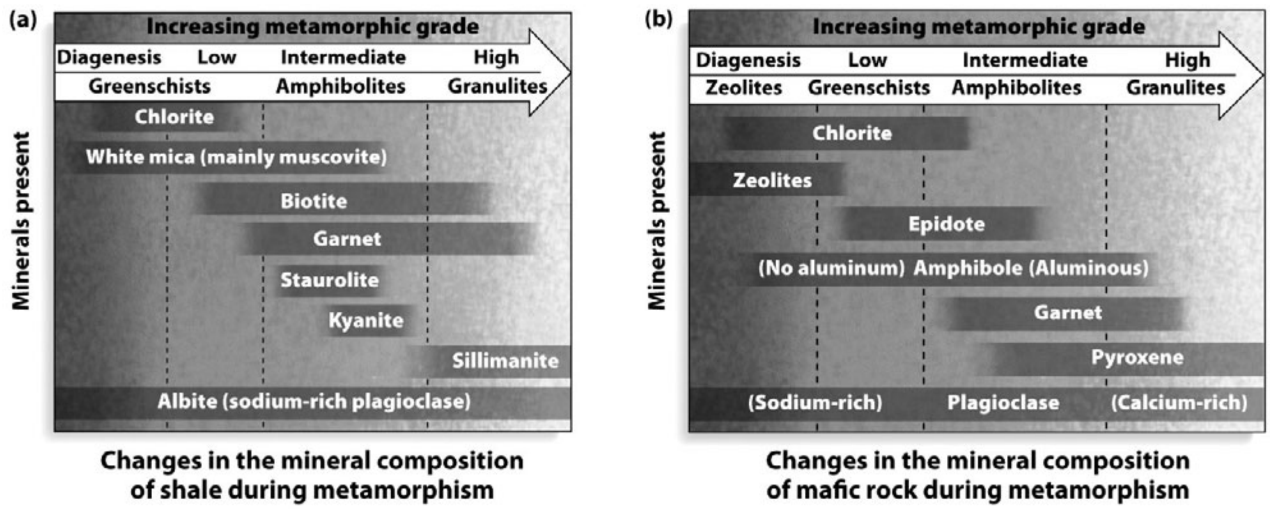
- Mineral assemblages in metamorphic rocks provide a basis for reconstructing the conditions that caused metamorphism and understanding more about the associated geologic setting. Figure 6.10 summarizes major minerals of metamorphic facies. Figures 6.9, 6.10, 6.12, and 6.13 illustrate how geologists study and interpret metamorphic rocks and reconstruct the conditions that formed them.

How is metamorphism linked to plate tectonics?

- Regional and high-pressure metamorphism occur at convergent plate boundaries. Refer to Figures 6.5, 6.6, and 6.13.
- Seafloor metamorphism occurs at spreading centers.
- Contact metamorphism occurs in a variety of plate tectonic settings where magma bodies are generated.

The important thing is not to stop questioning.

—ALBERT EINSTEIN



(c)

Metamorphic Facies	Minerals Produced from Shale Parent	Minerals Produced from Basalt Parent
Greenschist	Muscovite, chlorite, quartz, albite	Albite, epidote, chlorite
Amphibolite	Muscovite, biotite, garnet, quartz, albite, staurolite, kyanite, sillimanite	Amphibole, plagioclase feldspar
Granulite	Garnet, sillimanite, albite, orthoclase, quartz, biotite	Calcium-rich pyroxene, calcium-rich plagioclase feldspar
Eclogite	Garnet, sodium-rich pyroxene, quartz/coesite, kyanite	Sodium-rich pyroxene, garnet

Figure 6.10. Changes in the mineral composition of mafic rocks during metamorphism.

Practice Exercises

Exercise 1: Classification of metamorphic rocks by texture

Complete the table by filling in the blank spaces.

Parent rock	Metamorphic rock	Texture (foliated/granoblastic)
shale		*foliated*
quartz-rich sandstone		
	granulite	
granite		
limestone		
	hornfels	
	amphibolites and greenstones	
	migmatite	

Study Tip: Putting it all together

Now you have been introduced to all three major rock types, igneous, sedimentary, and metamorphic. This is a good time to assemble what you have learned into a comparison chart. A chart is an excellent way to ensure that you remember details about these rock types. Exercise 2 will help you do this.

Exercise 2: Comparing igneous, sedimentary, and metamorphic rocks

Complete the table by filling in the blank spaces. Note that there may be more than one reasonable answer for some blanks.

Major mineral composition	Texture	Rock type (igneous, sedimentary, metamorphic)	Rock name (granite, sandstone, marble)
calcium carbonate	*nonfoliated*		
quartz, K and Na feldspar, mica, and amphibole	*phaneritic*		
clay	*fine-grained clastic*		

(continued)

Major mineral composition	Texture	Rock type (igneous, sedimentary, metamorphic)	Rock name (granite, sandstone, marble)
pyroxene, calcium feldspar, and olivine			*basalt*
quartz	*monfoliated*		
pebbles and cobbles of a variety of rock types			
fragments of seashells and fine mud		*sedimentary*	
quartz, muscovite, chlorite, and garnet		*metamorphic*	*schist*

Review Questions

1. When existing rocks undergo metamorphism, they become changed by
   A. the weathering process at or near the surface.
   B. color and hardness.
   C. melting and crystallization from the melt.
   D. the application of heat and pressure.
2. Metamorphic rocks exposed at the surface are mainly products of processes acting on rocks
   A. near the Earth's surface.
   B. at depths ranging from the upper to lower crust.
   C. within the mantle.
   D. within the center of continents.
3. Generally there are two types of metamorphic rocks:
   A. regional and contact.
   B. foliated and granoblastic.
   C. compacted and cemented.
   D. clastic and porphyritic.
4. Foliated metamorphic rocks typically occur in association with regional metamorphism because the
   A. orientation of rocks involved in regional metamorphism favors the development of foliation.
   B. rock is softened by heat and squeezed by compressive forces.
   C. parent rock is the correct type to produce foliation.
   D. pressure is very low, which allows foliation to develop.
   Hint: Refer to Figures 6.5 and 6.6.
5. Foliation develops
   A. perpendicular to compressive forces.
   B. parallel to compressive forces.
   C. due to high water content.
   D. due to low temperatures and pressures.

6. Some metamorphic rocks are distinguishable from igneous and sedimentary rocks because their constituent grains
   A. interlock, forming a continuous mosaic.
   B. have quite different chemical compositions.
   C. tend to be lined up in a preferred direction.
   D. are rounded and cemented together.
7. Chemical compositions of metamorphic rocks are determined by the
   A. pressures to which they have been subjected.
   B. effects of both temperature and pressure.
   C. temperature to which they have been raised.
   D. composition of the original rocks and fluids that percolate through the rock during metamorphism.
8. Metamorphism affects
   A. only older igneous rock.
   B. any younger igneous and metamorphic rock.
   C. only older sedimentary rock.
   D. any older igneous, sedimentary, or metamorphic rocks.
9. Which metamorphic sequence correctly shows increasing grain size?
   A. schist → gneiss → phyllite → slate
   B. slate → phyllite → schist → gneiss
   C. gneiss → phyllite→ slate → schist
   D. phyllite → slate → gneiss → schist
10. Starting with the lowest temperature zone, which series of index minerals is characteristic of increasing metamorphic grade?
    A. chlorite, biotite, garnet, sillimanite
    B. garnet, chlorite, biotite, kyanite
    C. biotite, garnet, chlorite, sillimanite
    D. chlorite, biotite, sillimanite, kyanite, garnet
    Hint: Refer to Figures 6.9 and 6.10.
11. On the Moon, the major cause of metamorphism is
    A. burial.
    B. subduction.
    C. meteor impacts.
    D. very cold temperatures.
12. Of the metamorphic rocks listed, which one is formed at the highest temperature?
    A. slate
    B. schist
    C. phyllite
    D. gneiss
    Hint: Refer to Figures 6.9 and 6.10.
13. The difference between a gneiss and a granite is that the gneiss
    A. has a different bulk chemical composition.
    B. shows a distinct foliation.
    C. has a different mineral composition.
    D. is generally less coarse grained.
14. Schist and slate are distinguishable in that
    A. schist is fine grained, whereas slate is coarse grained.
    B. schist is foliated, whereas slate is not foliated.
    C. slate is fine grained, whereas schist is coarse grained.
    D. slate is foliated, whereas schist is not foliated.

15. Regional metamorphism is found in association with
    A. lava flows.
    B. hot springs.
    C. very low pressures.
    D. subduction zones and cores of mountain ranges.
16. If gneiss or another metamorphic rock is heated to a degree that it begins to melt,
    A. the quartz, K-feldspar, and Na-rich plagioclase would start to melt first.
    B. Na-Ca plagioclase, biotite, and minerals (such as garnet) would melt first, leaving a residue rich in felsic minerals.
    C. all the minerals in the rock would start to melt at essentially the same temperature to form a magma of the same composition of the gneiss.
    D. the ferromagnesian minerals would start to melt first.

    Hint: Refer to Figures 4.6 and 4.7.
17. As magma intrudes into a host or country rock (the preexisting rock that is in contact with the intrusion), it is transformed into a new rock. What is this process called?
    A. regional metamorphism
    B. contact metamorphism
    C. recrystallization
    D. schistosity formation
18. In the Web **Geology in Practice** exercise, *Gravels to Metaconglomerate,* oval quartz pebbles apparently become converted into cigar-shaped features within a metaconglomerate. How would you explain the transformation?
    A. The cigar-shaped features formed as larger quartz pebbles were tumbled in a stream channel before metamorphism.
    B. As the oval quartz pebbles became exposed to elevated temperatures, they softened and stretched out in response to directed pressure. Some of the quartz may have also recrystallized along directions perpendicular to the directed pressure.
    C. Quartz is an index mineral for high-grade metamorphism associated with burial of sedimentary rocks. Therefore, this conglomerate must have been uplifted from near the bottom of the crust.
    D. The conglomerate melted and the large cigar-shaped features are large quartz crystals.
19. You are on a summer backpacking trip in Alaska with friends and find an outcrop of mica schist with large garnet porphyroblasts, like the sample shown in Figure 6.6. Your friends quickly scramble to collect some garnet crystals. They then ask you about the conditions under which the beautiful garnet crystals formed. What is your response to their query?
    A. Garnet-bearing schists are formed from iron-rich magmas that solidify underground.
    B. Garnet is an index mineral for low-temperature and low-pressure metamorphism associated with meteor impact craters. So we must be within an ancient impact crater.
    C. Garnet commonly occurs in mica schists and is an index mineral for intermediate- to high-grade metamorphism, associated with regional metamorphism. This rock may have at one time been in the roots of a huge mountain.
    D. Garnets occur only in eclogites. Therefore, this rock must have begun at the base of the crust and been exposed by extensive uplift and erosion occurring in this region.
20. While studying some metamorphic rock samples for an undergraduate research project, you discover evidence that the rocks were exposed to high-grade metamorphic conditions. Further study reveals that the garnets within the rock show a history of prograde followed by retrograde P-T paths. You check the field notes from the geologist who collected the samples and are not surprised to find mention of ophiolites in the region (refer to Figures 4.14 and 6.12). You conclude from this information that metamorphic rocks formed when
    A. continents collided.
    B. magma intruded into a volcano associated with a subduction zone.
    C. a meteorite hit the Earth.
    D. hydrothermal fluids altered rock in an area with numerous hot springs and geysers.

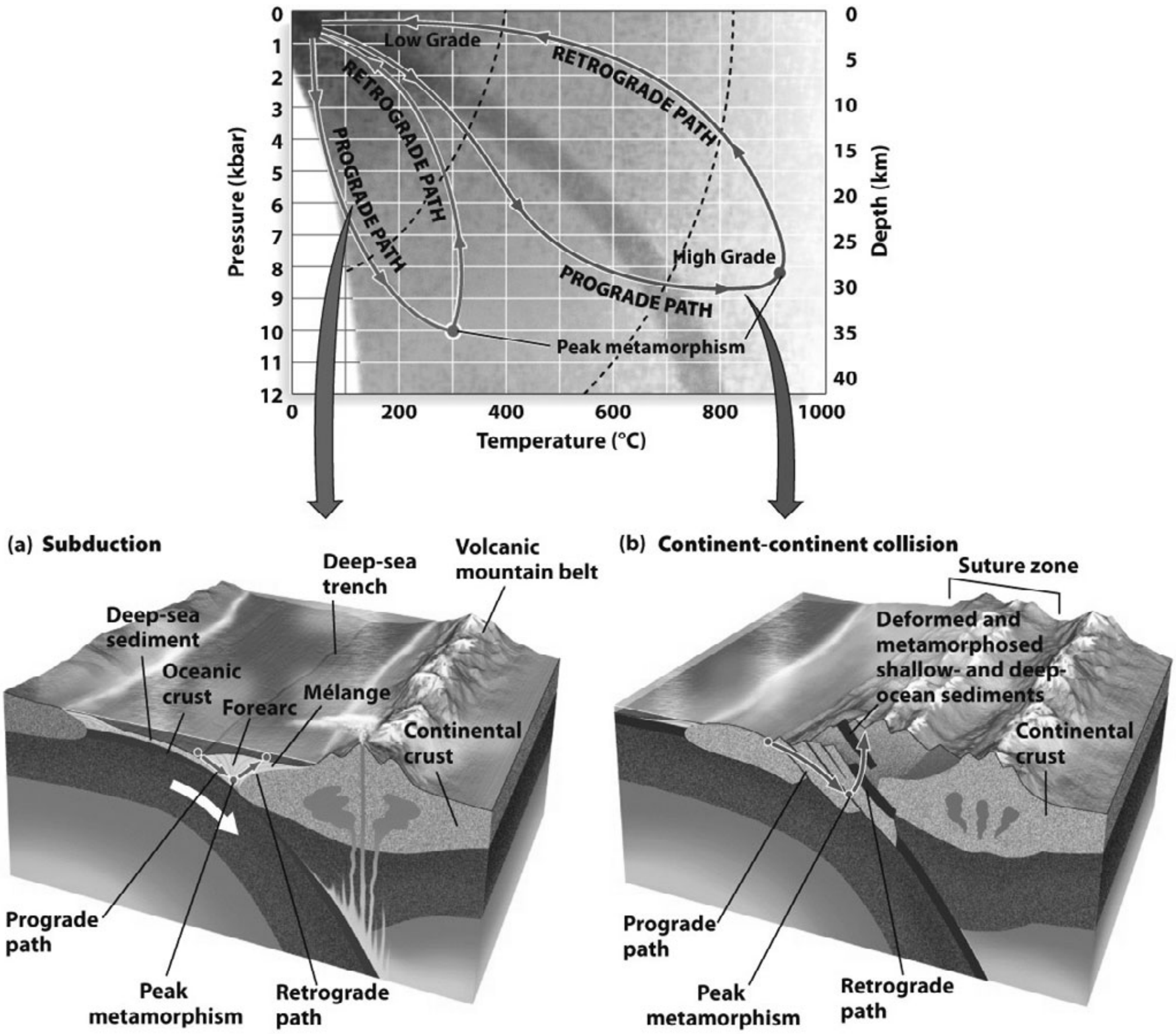


Figure 6.13. P-T paths indicate the trajectory of rocks during metamorphism. (a) Metamorphism of mélange at an ocean-continent convergence zone. (b) Metamorphism at a continent-continent convergence zone. The different P-T paths of rocks formed in these different plate tectonic settings indicate differences in geothermal gradients. Rocks transported to similar depths—and pressures—beneath mountain belts become much hotter than rocks transported to an equivalent depth by subduction.

CHAPTER 7

Deformation: Modification of Rocks by Folding and Fracturing

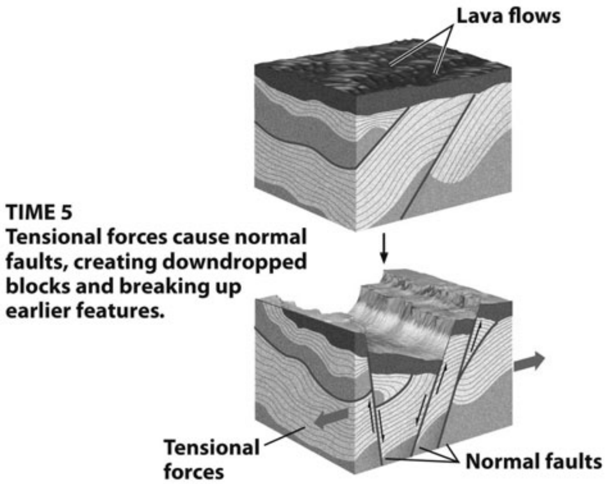


Figure 7.23. Last stage in the development of a geologic region. Refer to Figure 7.19 (a) for a more regional perspective on this type of deformation.

Before Lecture

Before you attend lecture, be sure to spend some time previewing the chapter. For an efficient preview, use the Study Guide **Chapter Preview** questions as a framework for understanding the chapter. Previewing works best if you do it just before lecture. With the main points in mind, you will understand the lecture better. This in turn will result in a better and more complete set of notes.

Study Tip

Rock deformation lectures are particularly visual. Slide material on folds and faults can be confusing if you have never seen these geologic features before. So be sure to preview the figures before attending lecture. For an overview, start with Figure 7.8. Notice how three kinds of force produce three kinds of faults if the material is brittle. What happens if the material is ductile or plastic?

How much time should you devote to previewing? Obviously, more time is better than less. But even a brief (five- or ten-minute) preview session just before lecture will produce a result that you will notice. For a refresher on why previewing is so important, see Study Guide, Part 1, Chapter 3, How to Be Successful in Geology.

Chapter Preview

- **What are geologic maps and cross sections?**
  Brief answer: Geologic maps represent the rock formations exposed at the Earth's surface. Geologic cross sections are diagrams showing how the geologist interprets or projects the geology at the surface into the subsurface. Refer to Figure 7.4.
- **How do rocks deform (break or bend)?**
  Brief answer: Rocks typically break (fault) when the temperature is low, burial is shallow, and the force is applied quickly. Rocks typically bend (fold) when the temperature is higher, burial is deeper, and the force is applied over a long period. See Figures 7.8, 7.12, and 7.14.
- **What geologic features are produced when rocks deform?**
  Brief answer: Folds, faults, and joints are common geologic structures produced when rocks are deformed.
- **What do geologic structures produced by rock deformation tell geologists about the geologic history of a region?**
  Brief answer: The type(s) of folds, faults, and joints and their spatial orientation provide geologists with clues for deciphering the kinds of forces affecting a region over time. See Figure 7.23.

Vital Information from Other Chapters

After each lecture you need to thoroughly master the concepts covered before you attend the subsequent lecture. The ideas of geology are like a stack of boxes. Each new idea rests on all ideas (boxes) stacked beneath it.

Another look at Chapter 3 would serve you well. Since there is a strong connection between deformation and metamorphism, review Figures 6.5 and 6.6 and the section on Plate Tectonics and Metamorphism in Chapter 6.

Web Site Study Resource

http://www.whfreeman.com/understandingearth6e

During Lecture

One goal for lecture is to leave class with good answers to the preview questions.

- To avoid getting lost in details, keep the big picture in mind. Chapter 7 tells the story of three kinds of forces (compressive, tensional, and shearing) and how geologists find evidence of these forces in rock structures (folds and faults).
- Deformation lectures are particularly visual. Slide material on folds and faults can be confusing if you have never seen these geologic features before. Keep Figures 7.8, 7.12, and 7.14 on hand during lecture.

Note-Taking Tip

Figures of faults and folding can be drawn very simply once you understand them. But until you do, make it easy on yourself. Photocopy Figures 7.8, 7.12, and 7.14. Three-hole-punch them for easy insertion into your three-ring notebook. If they are already in your notebook before lecture, you cannot be distracted drawing them during lecture.

Education is a voyage in self-discovery.

—LAURENCE M. GOULD

After Lecture

Review Notes

The perfect time to review your notes is right after lecture. The following checklist contains both general review tips and specific suggestions for this chapter.

Check Your Notes: Have you…

☐ added visual material? Suggestion: Test your understanding of Chapter 7 by adding to your notes simple sketches of important geological features such as normal, reverse, and thrust faults, and an anticline, syncline, asymmetric fold, and overturned fold. Add captions to help you keep things straight. (For example, “Associate the word ‘sink’ to the ‘s’ in syncline. ‘Sink’ is what a syncline resembles.”)

☐ created a brief big picture overview of this lecture (a sketch or written outline)? Suggestion: Figure 7.8 is a good summary of brittle rock deformation.

Intensive Study Session

Because there is a lot to learn in this chapter, be sure to set priorities for studying. There is probably more material than you will have time to study in one intensive study session. We recommend that you give highest priority to activities that involve answering questions. Answering questions while using your text and lecture notes as reference material is far more efficient than reading chapters or glancing over notes. As always, you have three sources from which to choose questions:

- **Practice Exercises and Review Questions** Be sure to do Exercise 1. It involves the key information you need to learn in this chapter.
- **Text.** This is a very visual chapter, so focus your attention on understanding the figures. Most of the really essential material for this chapter is in Figures 7.8, 7.12, and 7.14, so focus on understanding these illustrations first. Answer Exercises 1 and 5 at the end of the chapter.
- **Web Site Study Resources**
  http://www.whfreeman.com/understandingearth6e
  Complete the **Online Quiz.** The **Geology in Practice** exercise *Folds, Faults, and Other Records of Rock Deformation* provides an opportunity for you to practice your skills identifying and interpreting classic examples of rock deformation. The **Flash Cards** will help you learn the new terminology.

Exam Prep

Materials in this section are most useful during your preparation for quizzes and exams. The **Chapter Summary** and the **Practice Exercises** and **Review Questions** should simplify your chapter review. Read the **Chapter Summary** to begin your session. It provides a helpful overview that should refresh your memory.

Next, work on the **Practice Exercises** and **Review Questions.** Complete the exercises and questions just as you would an exam, to see how well you have mastered this chapter. After you answer the questions, score them. Finally, and most important, review each question you missed. Identify and correct the misconception(s) that resulted in your answering the question incorrectly.

Chapter Summary

What are geologic maps and cross sections?

- Geologic maps represent the rock formations exposed at the Earth's surface. The orientation of rock layers is measured as strike and dip. Refer to Figure 7.3.
- Geologic cross sections are diagrams showing how the geologist interprets or projects the geology at the surface into the subsurface. Refer to Figure 7.4.

How do rocks deform (bend and break)?

- All rocks may bend (ductile behavior) and break (brittle behavior) in response to the application of forces. Laboratory experiments have revealed that whether a rock exhibits ductile or brittle behavior depends on its composition, temperature, depth of burial (confining pressure), and the rate with which tectonic processes apply force.
- Ductile behavior is more likely when a rock is sedimentary and exposed to higher temperatures, deeper burial, and slower application of tectonic forces. Brittle behavior is favored when rocks are igneous or high-grade metamorphic and cooler, closer to the Earth's surface, and exposed to more rapid application of tectonic forces.

What geologic features are produced when rocks deform?

- Folding is a result of ductile deformation. From the type of fold and its orientation, geologists can interpret the orientation of the tectonic forces and characteristics of the rock layers during deformation.
- Faulting and jointing are a result of brittle deformation. Jointing occurs when a rock fractures but there is little movement along the fracture planes. Faults are fractures along which there is appreciable movement (offset). The type and orientation of faults and joints provide valuable information about the tectonic forces and the characteristics of the rock layers at the time of deformation.

What do geologic structures produced by rock deformation tell geologists about the history of a region?

- The type of fold or fault provides a means for geologists to interpret the type of tectonic force acting on the rock during deformation. Tectonic forces can be of three types: compressive, tensional, and shearing forces. These forces are active at all three types of plate tectonic boundaries: compressive forces dominate at convergent boundaries (where plates collide or subduct); tensional forces dominate at divergent boundaries (where plates are pulled apart); and shearing forces dominate at transform faults (where plates slide horizontally past each other).
- Geologic structures such as folds, faults, and joints occur on all scales from microscopic to the size of a mountainside. Geologists deduce the geologic history of a region in part by unraveling the history of deformation, thereby reconstructing what the rock units looked like before deformation.
- Regional deformational fabrics (the types of faults and folds in evidence) can help geologists decipher the plate tectonic history of the region. For example, normal faulting suggests that a region is being stretched like a rubber band by tensional forces. Refer to Figures 7.19, 7.20, 7.22, and 7.23. Consider how the geologic circumstances in Figure 7.20 are similar but also somewhat different from those depicted in Figure 7.19 (1 Tensional tectonics).

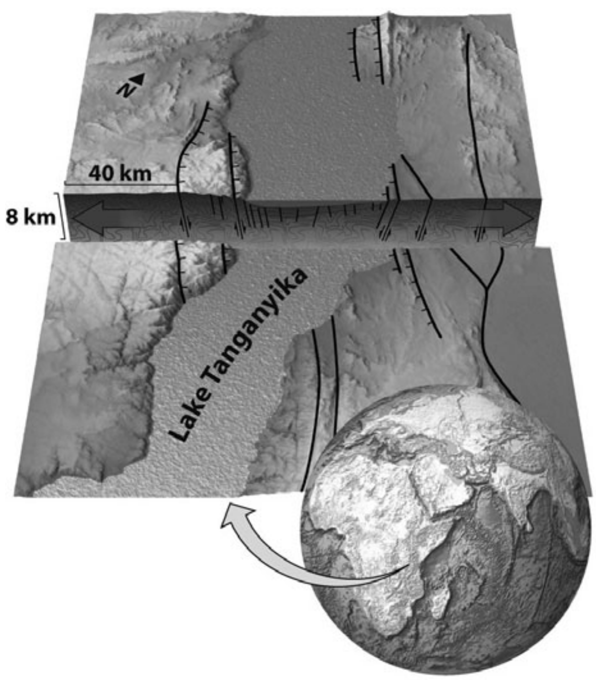


Figure 7.20. In East Africa, tensional forces are pulling the Somali subplate away from the African Plate creating rift valleys bounded by normal faults (see Figure 2.8b). The rift valley shown here is filled by sediments and Lake Tanganyika, on the boundary between Tanzania and the Democratic Republic of Congo. The cross section has been vertically exaggerated by a factor of 2.5:1, which exaggerates the fault dips; the actual dips of the normal faults are about 60°.

Practice Exercises

Exercise 1: Silly Putty

Silly Putty is a popular teaching aid with geologists because, at room temperature, it exhibits all three deformation characteristics of solids. If you pull on the putty quickly, it will snap into two pieces. Handled slowly, the putty can be easily bent and molded into many shapes. Plus, a ball of it thrown on the floor will bounce. Compare the properties of Silly Putty with the behavior of rocks by completing the table.

Behavior of Silly Putty	Behavior of rock	Type of force	Geologic structure produced by this style of deformation
Snaps into pieces		*tensional*	
Bends	*ductile*		
Bounces	*elastic*		
		compressional *The ball of putty is compressed by the impact with the floor.*	

Rocks do exhibit elastic behavior. More on this when we study earthquakes. (Earthquakes are attributed to the elastic properties of rocks.)

Exercise 2: Geologic structures

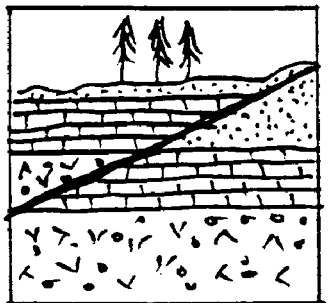
For each of the following five illustrations of deformed rocks, name the (A) geologic structure (normal fault, syncline); (B) type of force (compressional, tensional, shearing) responsible for producing each geologic structure; and (C) the plate tectonic boundary (convergent, divergent, or shear) with which the geologic structure is commonly associated.

A. Geologic structure ______________________

B. Type of force ______________________

C. Commonly associated plate tectonic boundary

____

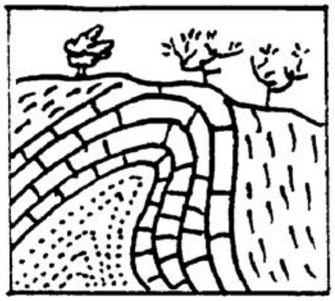


D. Geologic structure ______________________

E. Type of force ______________________

F. Commonly associated plate tectonic boundary

____

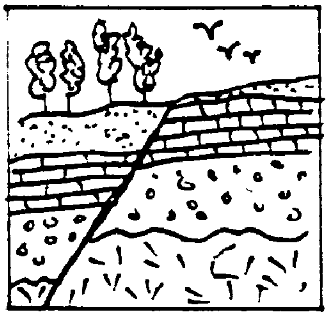


G. Geologic structure ______________________________

H. Type of force ______________________________

I. Commonly associated plate tectonic boundary

____



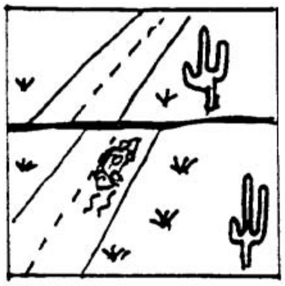
Vertical section

J. Geologic structure ______________________________

K. Type of force ______________________________

L. Commonly associated plate tectonic boundary

____



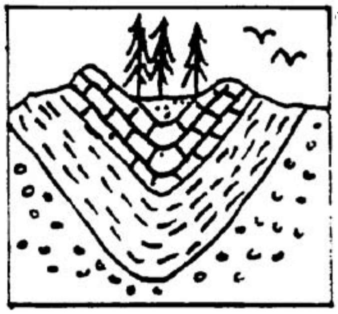
Oblique view

M. Geologic structure ______________________________

N. Type of force ______________________________

O. Commonly associated plate tectonic boundary

____



Vertical section

Exercise 3: Anticline versus syncline

A. Briefly describe the diagnostic differences between an anticline and a syncline.

____

____

____

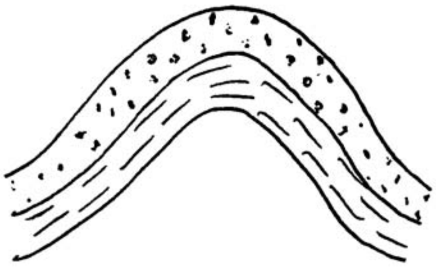
____

B. Draw a picture of a typical outcrop pattern for a plunging syncline exposed at the surface. Refer to Figure 7.13.

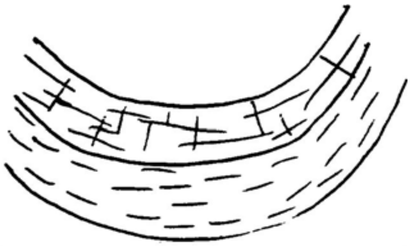
Exercise 4: Identifying geologic structures

Fill in the blanks with the correct names for the geologic structures illustrated.

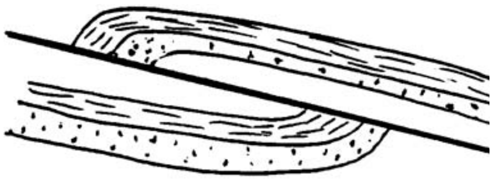
A. This fold is called a(n) ________________________.



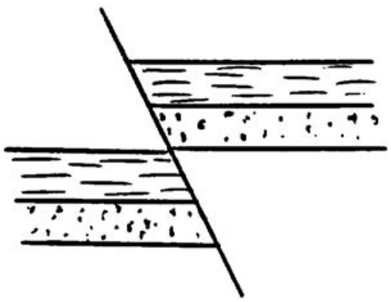
B. This fold is called a(n) ________________________.



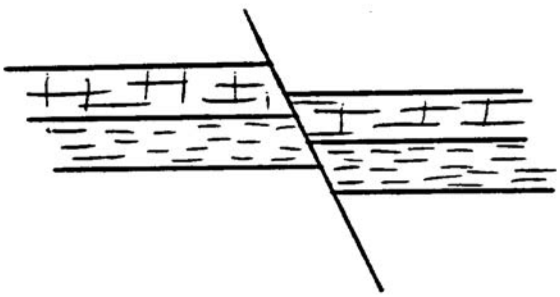
C. This fault is called a(n) ________________________.



D. This fault is called a(n) ________________________.



E. This fault is called a(n) ________________________.



Review Questions

1. A rock that breaks suddenly in response to the application of forces is
   A. elastic.
   B. plastic.
   C. brittle.
   D. ductile.
2. The two measurements that define the orientation of an exposed rock layer are
   A. strike and dip.
   B. strike and slip.
   C. slip and dip.
   D. fold axis and tilt.
3. The sense of motion along the San Andreas fault in California is
   A. left lateral strike slip.
   B. right lateral strike slip.
   C. dip slip.
   D. thrust.
4. As tensional forces are applied to a continental region, the resulting geologic feature will be a(n)
   A. anticline.
   B. rift valley.
   C. thrust fault.
   D. dome.
   Hint: Refer to Figures 7.8 and 7.19.
5. When no offset can be detected along a fracture in a rock, the fracture is called a
   A. stress plane.
   B. joint.
   C. fault.
   D. rupture.
6. Which of the following conditions promotes ductile deformation of rocks?
   A. old igneous rocks within the interior of a continent
   B. rocks deforming at a relatively low temperature
   C. stress building up rapidly to a very high level
   D. rocks subjected to high confining pressures and temperatures
7. When deformed, which of the following rocks is more likely to fracture brittlely instead of flow ductilely?
   A. basalt
   B. shale
   C. pure limestone
   D. muddy sandstone
8. As molten rock cools near or at the surface, it can develop shrinkage fractures that extend vertically down into the rock body. These crisscrossing, regularly patterned fractures create long thin rods of rock we call
   A. shrinkage palisades.
   B. tension faults.
   C. columnar joints.
   D. elongate joints.
   Hint: Refer to the photo at the beginning of Chapter 4.

9. Which of the following geologic structures is caused by tensional forces?
   A. thrust fault
   B. reverse fault
   C. anticline
   D. normal fault
10. Thrust faults commonly form
    A. around hot spots.
    B. where continents are colliding.
    C. where continents are pulling apart.
    D. along a transform fault.
11. The direction of dip is defined by a line
    A. at right angles to the strike line.
    B. north of the strike line.
    C. parallel to the strike line.
    D. parallel to plunge.
    Hint: Refer to Figure 7.3.
12. From an airplane you notice that the outcrops of tilted layers of rock make a distinct zigzag pattern across a plain. You reasonably conclude that the
    A. area has been cut by numerous normal faults.
    B. layers are folded into a series of plunging folds.
    C. layers are folded into a series of nonplunging folds.
    D. layers have been tilted so that all the layers dip in the same direction.
    Hint: Refer to Figures 7.13.

CHAPTER 8

Clocks in Rocks: Timing the Geologic Record

Strata, no matter how different they may appear, are of the same age if they contain the same assemblage of fossils.

—WILLIAM "STRATA" SMITH
(1769–1839)

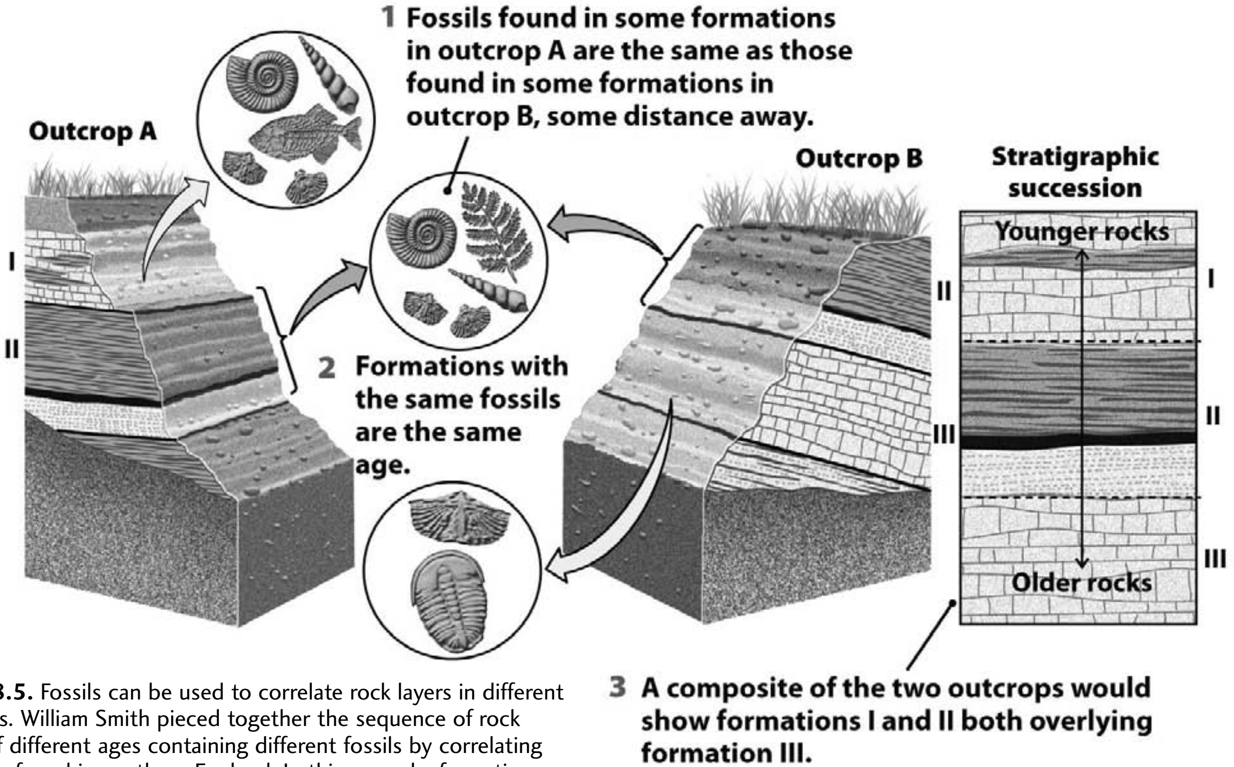


Figure 8.5. Fossils can be used to correlate rock layers in different outcrops. William Smith pieced together the sequence of rock layers of different ages containing different fossils by correlating outcrops found in southern England. In this example, formations I and II were exposed at outcrop A and formations II and III at outcrop B.

Before Lecture

Time-Management Tip: Something is always better than nothing

How much time should you devote to previewing? Obviously, the more time, the better. However, even a brief (five or ten minutes) preview session just before lecture will produce noticeable results. Arrive ten minutes early for lecture. Use the time to preview the chapter for the day's lecture. Even if you have only a minute or two you can read the preview questions and brief answers and gain a rough idea of what the chapter is about. The time just before lecture is precious, because whatever you preview will remain in short-term memory and help you understand lecture.

Chapter Preview

- **How can the relative ages of rocks be determined from rock outcrops?**
  Brief answer: The principles of superposition, fossils, and cross-cutting relationships provide a basis for establishing the relative age of a sequence of rocks at an outcrop. For example, in Figure 8.4 and Earth Issues 8.1, the youngest sedimentary rock layers are on top and the oldest are at the bottom. And in Figure 8.10, magma intrusions and a fault are younger than the rock they cut through.
- **How can the relative ages of rock outcrops at two or more locations be determined?**
  Brief answer: Stratigraphic and fossil succession, plus radiometric dates of rock units, provide a basis for establishing how rock outcrops at different localities may be related to each other (correlate), even if they are hundreds or thousands of miles apart. See Figure 8.5.
- **What is the Geologic Time Scale and how is it calibrated?**
  Brief answer: The Geologic Time Scale is the internationally accepted reference for Earth's geologic history. Using relative and absolute dating methods, geologists have calibrated (divided) Earth's history into four eons: Hadean, Archean, Proterozoic, and Phanerozoic. Because more evidence is available for the most recent eon, the Phranerozoic, it has been possible to divide it more finely into eras, periods, and epochs. See Figures 8.10 and 8.14.
- **How are the Geologic Time Scale and geochronological methods, like radiometric dating, applied to geologic problems?**
  Brief answer: We understand Earth's history to the degree to which we can place the record of geologic events in time. The Geologic Time Scale is the accepted standard for how geologic time is subdivided.

Vital Information from Other Chapters

Review Figure 1.17 (the ribbon of geologic time from the formation of the solar system to present). Review the text section The Rock Cycle: Interactions between Plate Tectonic and Climate Systems in Chapter 3. Reread the Atomic Structure of Atoms section in Chapter 3 before reading about radiometric dating methods. Also preview Figure 9.11.

Time is simply nature's way of keeping everything from happening at once.

—GRAFFITI ON A WALL

During Lecture

Here's an overview that should help you take good notes for this lecture.

- **Big Picture.** The big picture for this lecture is the entire Geologic Time Scale! Geologic time is wondrously huge. It is so expansive that at first it seems incomprehensible. The lecturer will describe the 4.5-billion-year expanse of geologic time and may use examples and exercises designed to help you grasp geologic time.
- **New Terms.** It is difficult to talk about the Geologic Time Scale without referring to its time intervals. So you may feel barraged with new terms: epochs, periods, eras, eons, Holocene, Pleistocene, Pliocene. To avoid getting lost, keep a copy of Figures 8.11 and 8.14 at hand. Refer to Figure 8.14 to check terms as needed. Note how different-sized chunks of time are used for different eons: huge chunks (eons) are used for events early in Earth's history when there is less geological evidence for what happened, and smaller chunks (epochs) are used for intervals of time closer to the present. Because more evidence is available for the most recent eon, the Phanerozoic, it has been divided more finely into eras, periods, and epochs. See Figure 8.14.
- **Succession of Geologic Events.** You will work through how the *relative* ages of rocks are determined. By the end of lecture you will be able to use two basic principles (superposition and cross-cutting) to determine the relative age of a sequence of rocks such as that shown in Figure 8.10.
- **Absolute Dating.** Carbon-14 has a short half-life. It works for dating younger samples of tissue attached to bone, charcoal, and wood because these materials all contain carbon. Other isotopes (uranium-238, potassium-40, rubidium-87) have much longer half-lives and are used to date rocks that are geologically older. Table 8.1 shows how half-life is related to the effective dating range of each method.

After Lecture

Review Notes

The perfect time to review your notes is right after lecture. The following checklist contains both general review tips and specific suggestions for this chapter.

Check Your Notes: Have you…

- ☐ shown clearly how superposition and cross-cutting features can be used to sequence rock units and geologic events? **Hint:** A simple sketch is the best way to show this.
- ☐ shown clearly the characteristics of (1) an unconformity and (2) an angular unconformity? Check Figures 8.6, 8.7, and 8.8 against your notes. Add sketches to your notes if you need to.

Intensive Study Session

The two big tasks for this study session are to master the skill of dating outcrops using the principles of superposition and cross cutting and to learn the Geologic Time Scale.

Begin your work on outcrops with Study Guide Exercise 1. The other exercises and the review questions will allow you to test your skills further. Refer to your notes and relevant text figures to help you.

> *We are like the butterflies who flutter*
> *for a day and think it is forever.*
>
> —Carl Sagan

Unless you happen to have spent your summer working on an archeology dig, tossing around terms like Paleocene, Eocene, and Oligocene, the epochs of the Cenozoic may look like a steep memory curve. Here are four different strategies for learning the Geologic Time Scale.

1. **Marker events** are simply interesting things that happened: animals or plants that evolved, creatures that dominated the Earth, large extinction events. Look at Figure 8.11. Select some marker events you already know about. **Example:** Can you guess one of the periods during which dinosaurs were dominant? The movie *Jurassic Park* has made this an easy question to answer. When did complex life begin? Find some other marker events of particular interest to you. You may find yourself surprised at how early some events occurred. Marker events will help you remember the Geologic Time Scale. Try Exercise 3.

2. **Logical chunks.** Group the information into short lists you can remember. Study the groupings of the time scale with Figures 8.11 and 8.14 in front of you. Learn it as a series of short lists. Understand the following logic.

   - **Eons (Figure 8.14)** are the biggest time chunks. There are only four (Hadean, Archean, Proterozoic, Phanerozoic) to remember. Only the most recent (Phanerozoic eon) is broken down further. Hadean sound like Hades (hell), not a bad description of the young planet with its molten surface and asteroids crashing into it.
   - **Eras (Figure 8.11)** are next biggest. You have to learn eras only for the Phanerozoic eon. That's because geological evidence is too limited to justify the division of earlier eons. There are only three Phanerozoic eras to remember: Old Life, Middle Life and New Life. Think of them that way first; you can tack on the Greek stems later.
   - **Periods (Figure 8.11)** are next. All three eras of the Phanerozoic eon are further divided into periods. No periods for earlier eons: not enough evidence.
   - **Epochs** are the smallest divisions of geologic time. You have to learn epochs only for the most recent era (Cenozoic, or New Life). All epochs of the Cenozoic end in *-cene* (for "Cenozoic").

Now that you understand the divisions, return to Figure 8.14, which clarifies how they all fit together and adds the absolute dates that have been determined by reading the radiometric rock clocks.

3. **Word Stems.** Word stems are clues to meaning. Greek and Latin stems are used a great deal by scientists. You can look them up in any good dictionary. A few helpful stems for the Geologic Time Scale follow.

   Eras
   Paleo- = Greek: "old"
   Meso- = Greek: "middle"
   Ceno- = Greek: "new"
   -zoic = Greek: "life"

   Epochs: Don't worry about the middle epochs for now. Just remember the first and last ones.
   Paleo = Greek: "old"
   Pleisto = Greek: "much." Remember that there was *much* ice in the Pleistocene.
   Holo = Greek: "recent." Remember that the Holocene is the present or most recent epoch.
   Note that all epochs of the Cenozoic epoch end in *-cene*.

4. **Mnemonic (catch phrase).** When there are long lists of unfamiliar terms to learn (such as the epochs of the Cenozoic), many learners find making catch phrases helpful. Try this. Do Exercise 4, Geologic Time Scale mnemonic.

Web Site Study Tools
http://www.whfreeman.com/understandingearth6e
Take the **Graded Online Quiz** and pay particular attention to the feedback for answers.
Flashcards will help you learn new terms.

No vestige of a beginning, no prospect of an end.

—James Hutton
(1726–1797)

Exam Prep

Materials in this section are most useful during your preparation for examinations. The **Chapter Summary** and **Practice Exercises** and **Review Questions** should simplify your chapter review. Read the **Chapter Summary** to begin your session. It provides a helpful overview that should refresh your memory.

Chapter Summary

How can the relative ages of rocks be determined from rock outcrops?

- The principles of superposition and cross-cutting relationships provide a basis for establishing the relative age of a sequence of rocks at an outcrop. Using these two principles, geologists can order (determine what happened first, second, third, and so on) the geologic events represented by the rocks and geologic features in rock outcrops. The principle of original horizontality for sedimentary layers provides a starting point for identifying sequences of sedimentary rocks affected by tectonic forces after they were deposited.

How can the relative ages of rock outcrops at two or more locations be determined?

- To reconstruct the geologic history of the Earth, geologists need to correlate the geologic events represented by rocks at one locality with the geologic events represented by rocks at other localities. The stratigraphic and fossil succession and the radiometric dates of rock units show how rock outcrops at different localities may be related to each other, even if they are hundres or thousands of miles apart.

What is the Geologic Time Scale and how is it calibrated?

- The Geologic Time Scale is the internationally accepted reference for the sequence of events represented by Earth's rock record. Geologists constructed it over about the last 200 years using mainly fossils, superposition, and cross-cutting relationships to establish the relative ages of thousands of rock outcrops around the world. In about the last 60 years, the Geologic Time Scale has been calibrated using radiometric methods derived from the discovery of radioactive isotopes by physicists in the early part of the twentieth century.
- The Geologic Time Scale, like the theory of plate tectonics or any other scientific theory or tool, is always open to the challenge of new evidence. But it is important to understand that the Geologic Time Scale is rooted deeply not just in geology but in physics, chemistry, biology, and paleontology. It is one of science's great foundations, a concept that if seriously challenged by hard evidence (it has not been) would force reappraisal of many disciplines of solid working science. For it to be wrong, much of geology would have to be wrong, and substantial areas of physics would have to be wrong, and most of biology and paleontology would have to be wrong. An error of this magnitude is very unlikely. Thus (for most practical purposes) the Geologic Time Scale is assumed as fact by virtually all scientists and scientifically literate people.

How are the Geologic Time Scale and geochronological methods like radiometric dating applied to geologic problems?

- We understand Earth's history to the degree to which we can place the record of geologic events in time. The Geologic Time Scale is the accepted standard for how geologic time is subdivided. Earth Issues 8.1 provides an example.

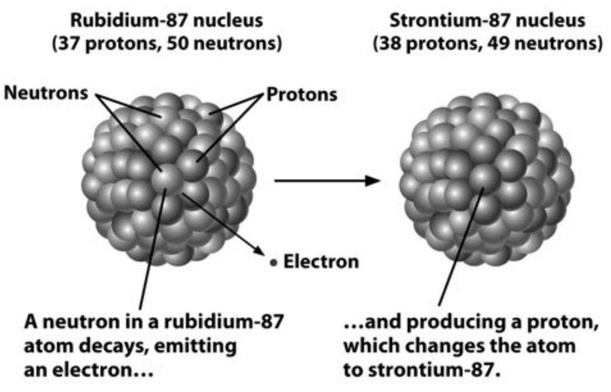
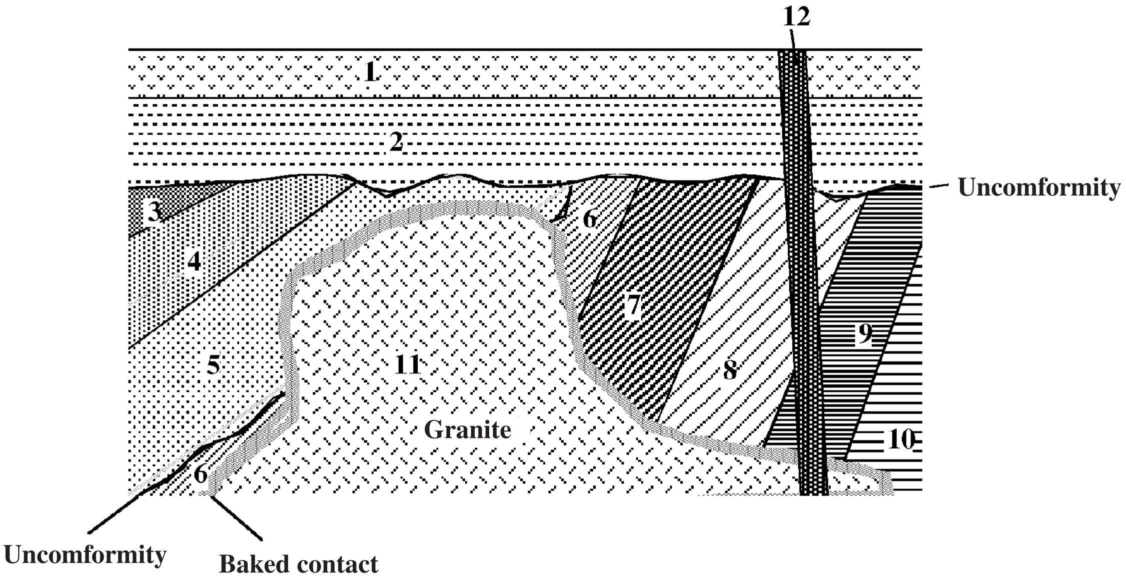


Figure 8.12. The radioactive decay of rubidium to strontium.

Practice Exercises

Exercise 1: Determining the succession of geologic events

The following block diagram illustrates the geology of an area in Argentina. Answer the questions regarding the geological history of this area. Circle the correct answer when a choice is provided.



Unit 2 contains clasts of units 3 through 10.
Unit 5 contains clasts of units 6 through 10.
Units 5 through 10 are baked along their contacts with unit 11.
Units 1, 2, 8, 9, and 11 are baked along their contacts with dike 12.

A. Which unit is the youngest rock in this area? 1 2 3 4 5 6 7 8 9 10 11 12

B. Which unit is the oldest rock in this area? 1 2 3 4 5 6 7 8 9 10 11 12

C. 1. Is unit 3 older than unit 12? Yes No Not possible to know
   2. Explain the logic you used to answer question C-1.

____

____

D. 1. Is unit 1 younger than unit 11? Yes No Not possible to know
   2. Explain the logic you used to answer question D-1.

____

____

E. 1. In an attempt to further work out the geologic age relationships in this area, samples of units 1, 11, and 12 (igneous rocks) were collected for radiometric dating. The resulting counts of radioactive parent atoms and daughter atoms are listed in the table.

Rock unit	No. Parent atoms	No. Daughter atoms
1	500	500
11	250	750
12	750	250

Using this information, unit 1 is

a. older than unit 12 but younger than unit 11.

b. younger than unit 12 but older than unit 11.

c. older than unit 11 but younger than unit 12.

2. Explain the logic you used to answer question E-1.

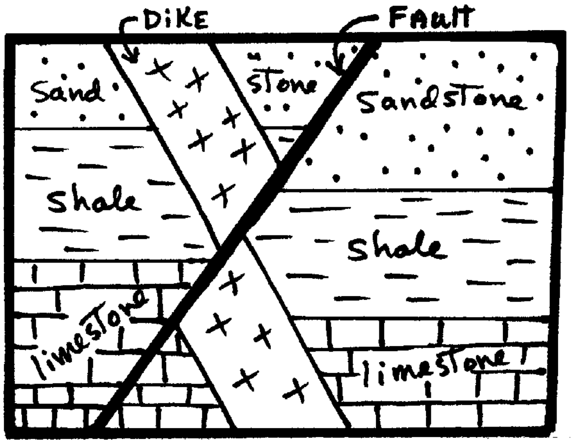
____

____

Exercise 2: Ordering geologic events

In the illustration, a geologic outcrop reveals three layers of sedimentary rocks, one fault, and a single igneous dike intrusion.

A. Order the sequence of geologic events from youngest to oldest.



Youngest ____________________

____

____

____

Oldest ____________________

B. Briefly describe the geologic history represented by the rock sequence.

____

____

____

____

____

Exercise 3: Marker events for the Geologic Time Scale

A. Enter each event in the list in the appropriate eon box in the table. When there is more than one event in a box, order them so that the oldest is at the bottom and the youngest is at the top.

Significant (Marker) Events in Earth History

Dinosaur extinction	Major phase of continent formation completed
Earliest evidence of life	Moon forms
End of heavy bombardment of the Earth	First nucleus-bearing cells develop
Evolutionary Big Bang	Oxygen buildup in atmosphere
Humans evolve	

B. Fill in the names of eras, periods, and epochs in the correct sequence from oldest at the bottom to youngest at the top. Refer to both Figures 1.17 and 8.11 to complete this exercise.

Eon	Era	Period	Epoch
Phanerozoic		*Quaternary*	*Holocene*
Humans evolve	________	*Tertiary*	*Pleistocene*
________			________
	Mesozoic	________	________
		Jurassic	________
		________	________
	________	________	________
		Pennsylvanian	
		________	
		________	
		________	
		Ordovician	
________		________	
Proterozoic			
________			
First nucleus-bearing cells develop			
Archeon			
________			
________			
Hadean			
________			
________			
Earth accretion begins			

Nothing lives long but the earth and the mountain.

—CHARLES BALLARD

Exercise 4: Geologic Time Scale mnemonic

Construct a mnemonic device for remembering the Geologic Time Scale names. The first letter of each word must match the first letter of the corresponding period or epoch in the proper order. You may use your native language, but be careful not to mix up the words when you do so.

Examples (refer to Figures 8.11 and 8.14 for the Geologic Time Scale):

Periods of the Geologic Time Scale

__C__hronically __O__verworked __S__tudent __D__ecks __M__onotonous __P__hysics __P__rofessor __T__o __J__ustify __C__ontradictory __T__est __Q__uestions.

Epochs of the Cenozoic:

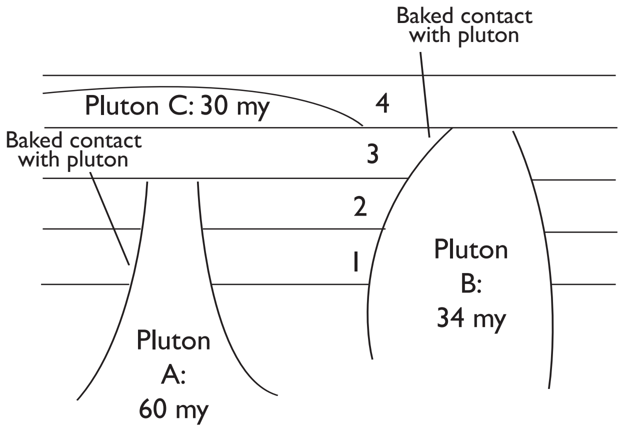
__P__lease __E__at __O__ur __M__ushroom __P__ot __P__ie __H__ot.

Now invent your own mnemonic to help you remember the Geologic Time Scale.

Review Questions

1. The principle of superposition holds that for any unfolded series of sedimentary layers,
   - A. overlying strata extend over a broader area than the layers beneath them.
   - B. the layer at the top of the pile is always younger than the layers beneath it.
   - C. sediments generally accumulate in the vertical sandstone–shale–limestone sequence.
   - D. the layer at the top of the pile is always older than those beneath it.
2. From youngest to oldest, the correct sequence of eras dividing the Phanerozoic eon is
   - A. Paleozoic, Cenozoic, Mesozoic.
   - B. Mesozoic, Cenozoic, Paleozoic.
   - C. Mesozoic, Paleozoic, Cenozoic.
   - D. Cenozoic, Mesozoic, Paleozoic.
3. The epochs of the Tertiary period progress from oldest to youngest in which sequence?
   - A. Eocene, Oligocene, Paleocene, Miocene, Pliocene
   - B. Paleocene, Eocene, Oligocene, Miocene, Pliocene
   - C. Paleocene, Eocene, Miocene, Pliocene, Oligocene
   - D. Paleocene, Eocene, Oligocene, Miocene, Pliocene, Pleistocene
4. From oldest to youngest, the correct order of periods for the Paleozoic era is
   - A. Cambrian, Ordovician, Devonian, Silurian, Mississippian, Permian, Pennsylvanian.
   - B. Cambrian, Ordovician, Silurian, Devonian, Mississippian, Pennsylvanian, Permian.
   - C. Cambrian, Silurian, Ordovician, Pennsylvanian, Mississippian, Devonian, Permian.
   - D. none of the above.
5. Sandstone and shale rock layers immediately below and above an angular unconformity imply a history of
   - A. erosion, deposition, and deformation erosion.
   - B. erosion, deformation, deposition, and erosion.
   - C. deformation, erosion, deposition, and deformation.
   - D. deposition, deformation, erosion, and deposition.

   Hint: Refer to Figure 8.8.
6. From the diagram, one can infer age limits for rock layer 3 of
   - A. between 34 and 60 million years.
   - B. between 30 and 60 million years.
   - C. less than 20 million years.
   - D. more than 60 million years.



7. What makes the isotopes of a given element different from each other?
   - A. their atomic numbers
   - B. their number of electrons
   - C. their number of neutrons
   - D. their number of protons
8. Naturally occurring ________________ that decay(s) into other materials at known rates can be used to estimate the actual age of a rock.

A. organic matter
B. minerals
C. radioactive elements
D. silicon

9. The Phanerozoic time is divided into three intervals: (1) the interval of old life, (2) the interval of middle life, and (3) the interval of modern life. These intervals correspond (from oldest to youngest) to the
   A. Archean, Mesozoic, and Paleozoic.
   B. Paleozoic, Precambrian, and Proterozoic.
   C. Precambrian, Cambrian, and Neocambrian.
   D. Paleozoic, Mesozoic, and Cenozoic.

10. Which radiometric dating method would be most effective in determining the age of charcoal at an archeological site?
   A. rubidium–strontium
   B. radiocarbon
   C. uranium–lead
   D. potassium–argon

   Hint: Refer to Table 8.1 in your textbook.

11. Only geologically young materials can be dated using radioactive C-14 isotopes because
   A. the decay rate varies widely over time.
   B. they have a very short half-life.
   C. within decades all the C-14 is decayed away.
   D. they are a very rare isotope.

12. If the half-life of some radioactive element is 1 billion years and a mass of rock originally contained 1000 atoms of the radioactive element, how many atoms of the radioactive element would be left after 3 billion years had passed?
   A. 500 atoms
   B. 250 atoms
   C. 125 atoms
   D. no radioactive atoms

13. Small pieces of charcoal from an ancient ruin yield a carbon-14 date of 3000 years. This age best represents the approximate interval of time that has elapsed since
   A. a fire burned the wood.
   B. humans inhabited the ruin.
   C. humans cut the wood.
   D. the wood died.

14. Radiometric dates have been attached to the Geologic Time Scale by the determination of radiometric ages of
   A. igneous rocks younger and older than sedimentary formations.
   B. shales.
   C. fossil skeletons.
   D. metamorphosed sediments.

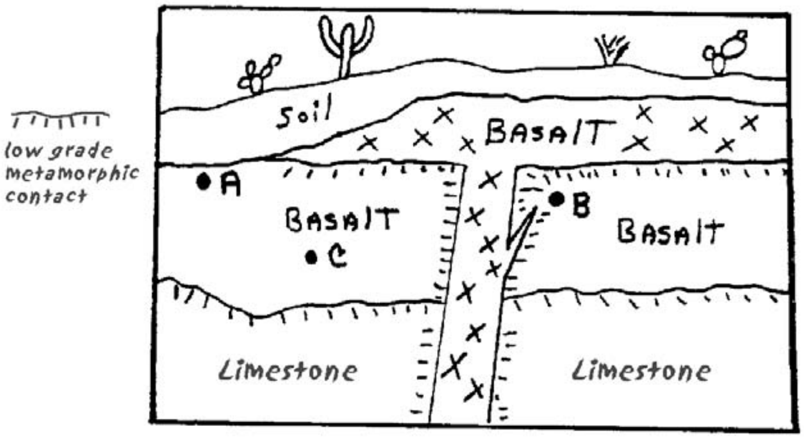
15. For the most part, radiometric dates for rocks represent only the last time the rock
   A. crystallized from a magma or was metamorphosed.
   B. was eroded.
   C. became cemented.
   D. was deposited.

16. One method that geologists use to study buried sediments and unconformities is
   A. seismic stratigraphy.
   B. radiometric stratigraphy.
   C. depositional stratigraphy.
   D. metamorphic stratigraphy.

   Hint: Refer to Figure 8.16.

17. If a rock is heated by metamorphism and the daughter atoms generated by the decay of the radioactive parent atoms migrate out of a mineral that is subsequently radiometrically dated, the date will be __________________ the actual age.
   A. younger than
   B. older than
   C. the same as
   D. none of the above

18. Which sample of basalt in the diagram is likely to yield the most accurate K/Ar radiometric date?

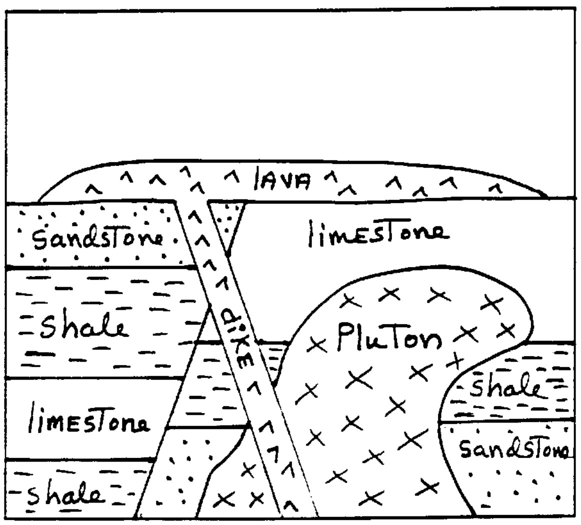


A. A B. B C. C

19. A layer of conglomerate contains cobbles of an igneous rock. One of the cobbles was dated radiometrically at 35 million years old. From this radiometric age, the conglomerate layer can be inferred to be

A. more than 35 million years old.
B. less than 35 million years old.
C. 35 million years old.
D. none of the above.

20. In the illustration, what is the most recent geological event depicted?



A. eruption of the lava
B. faulting
C. intrusion of the pluton
D. deposition of shales, sandstones and limestones

21. Pieces of charcoal were found in a paleosoil layer covering an ancient fire pit with stone tools including arrowheads and axes. The charcoal was radiometrically dated using carbon-14 and yielded an age of approximately 10,500 years. What can you infer about the age of the archeological site?

A. The archeological site is about 10,500 years old.
B. The archeological site is younger than 10,500 years.
C. The archeological site is older than 10,500 years.
D. The age of the archeological site is unresolved but may be older than 10,500 years.

CHAPTER 9

Early History of the Terrestrial Planets

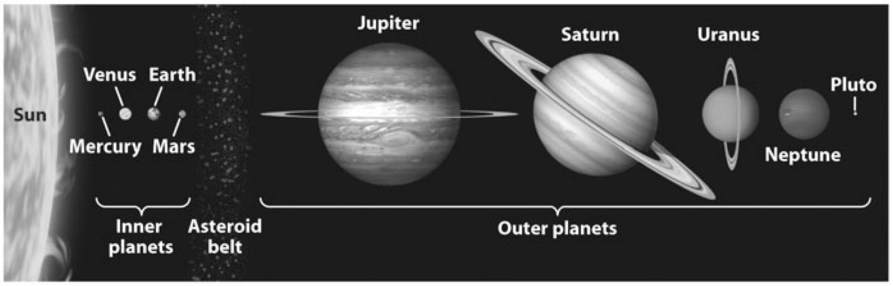


Figure 9.3. The solar system. This figure shows the relative sizes of the planets and the asteroid belt separating the inner and outer planets.

Before Lecture

Chapter Preview

- **How did our solar system form?**
  Brief answer: It accreted from gas and dust about 4.5 billion years ago.
  Figure 9.2 shows this process beautifully. Look it over before lecture.
- **How did the Earth form and change over time?**
  Brief answer: The Earth's core, mantle, crust, oceans, and atmosphere evolved as the interior of the planet heated up, melted, and differentiated. Study Figures 9.5 and 9.6.

- **What are some major events in the history of our solar system?**
  Brief answer: The age of the solar system as determined from meteorites is about 4.56 billion years. The major planets formed within about 10 million years, and they differentiated into a core–mantle–crust layering in less than 100 million years. The Moon formed from a giant impact at about 4.5 Ga. Minerals as old as 4.4 billion years have survived in the Earth's crust.
- **What do planetary surfaces tell us about their age?**
  Brief answer: Samples from the surface of the Moon have been dated by isotopic methods. The age of other planetary surfaces is estimated from the density of impact craters.
- **What have we learned from recent planetary probes?**
  Brief answer: Venus is the only planet other than Earth that has active tectonics controlled by global convection of its mantle. Water is present on Mars only as ice at its poles and in the shallow subsurface. In the past, water may have been present as a liquid on the Marian surface.

After Lecture

The perfect time to review your notes is right after lecture, while the material is still fresh in your mind. Review to be sure you noted all the key points and wrote them down in a form that will be readable later. As you review, you can also add useful visual material and a summary.

Check Your Notes: Have you…

- ☐ annotated your notes for focused learning? Usually the most efficient way to do this is by (1) underlining or highlighting key points and (2) adding headings or key words in the margin (you do set up your notes with a left-hand margin, don't you?). **Hint:** Preview questions make great headings.

  For additional ideas about annotating notes go to the following link: http://www.csbsju.edu/academicadvising/help/lec-note.htm
- ☐ added a simple sketch or two to clarify the key points?
- ☐ written a brief (one-paragraph) summary of the most important concept you learned from this lecture? Feel free to use your notes and the figures in your text as needed. Reviewing preview questions may help.

Intensive Study Session

For this chapter the most efficient study approach is to start with the two practice exercises. Practice Exercise 1 will help you master the basics of planet formation. Then turn to Practice Exercise 2. When we are learning about a new subject, we all have a tendency to focus on the "what" (what we know) rather than the "how" (how do we know it)—the supporting evidence. Yet to carry out an intelligent conversation and write a good response to a discussion question in homework or on an exam, we need to be able to explain the evidence for our statements and observations. The observation that there is water on Mars begs for a detailed explanation. How do we know there is water on Mars? Before the next lecture, rough out an answer to Practice Exercise 2 (also refer to Exercise 5 at the end of Chapter 9 in the textbook). As questions arise about how a line of evidence serves to support the presence of water on Mars, write the questions down and ask the instructor about them via e-mail or during the next class meeting.

Web Site Study Resources

http://www.whfreeman.com/understandingearth6e

Check out the study aids available on the Web site. You will find **Graded Online Quiz** and **Flashcards** (to help you learn new terms).

Exam Prep

Materials in this section are most useful during your preparation for exams. The **Chapter Summary** and **Practice Exercises** and **Review Questions** should simplify your chapter review. Begin your review with the **Chapter Summary.** It provides a helpful overview that should refresh your memory.

Next, work on the **Practice Exercises** and **Review Questions.** Complete the exercises and questions just as you would an exam, to see how you have mastered this chapter. After you answer the questions, score them. Finally, and most important, review each question you missed. Identify and correct the misconception(s) that resulted in your answering the question incorrectly.

Chapter Summary

How did our solar system form?

- Our solar system probably formed when a cloud of interstellar gas and dust condensed about 4.5 billion years ago. The planets vary in chemical composition in accordance with their distance from the Sun and with their size.

How did the Earth form and change over time?

- Earth probably grew by accretion of colliding chunks of matter. Very early after the Earth formed, it is thought that our Moon formed from material ejected from the Earth by the impact of a giant meteorite.
- Heat generated from the Moon-forming impact and the decay of radioactive elements probably caused much of the Earth to melt. Melting allowed iron and other dense matter to sink toward the Earth's center and form the core. Lower density (lighter) matter floated upward to form the mantle and crust. Release of trapped gases (mostly water) from within the Earth gave rise to the oceans and an early atmosphere. In this way, the Earth was transformed into a differentiated planet with chemically distinct zones: an iron core; a mantle of mostly magnesium, iron, silicon, and oxygen; and a crust rich in oxygen, silicon, aluminum, calcium, potassium, sodium, and radioactive elements.
- As the Earth cooled, an outer relatively rigid shell called the lithosphere formed on top of a hotter and softer asthenosphere. Volatiles trapped within the mantle escaped through volcanoes to form Earth's atmosphere and oceans. Life evolved and developed the capability of extracting carbon dioxide out of surface environments and releasing oxygen as a by-product of photosynthesis. Refer to Chapter 11.

  The interaction of major components of Earth's system continues to this day.

What are some major events in the history of our solar system?

- The age of the solar system as determined from meteorites is about 4.56 billion years. The major planets formed within about 10 million years, and they differentiated into a core–mantle–crust layering in less than 100 million years. The Moon formed from a giant impact at about 4.5 Ga. Minerals as old as 4.4 billion years have survived in the Earth's crust. Refer to Figure 9.11.

What do planetary surfaces tell us about their age?

- Samples from the surface of the Moon have been dated by isotopic methods. The age of other planetary surfaces is estimated from superposition and the density of impact craters.

What have we learned from recent planetary probes?

- Venus is the only planet other than Earth that has active tectonics controlled by global convection of its mantle. Refer to Figure 9.16.
- Water is present on Mars only as ice at its poles and in the shallow subsurface. In the past, water may have been present as a liquid on the Marian surface.
- The Cassini-Huygens probe found that Saturn's rings extended hundreds of kilometers from the planet and were made up of billions of particles of ice and rock—particles ranging in size from grains of sand to houses.

Practice Exercises

Exercise 1: The evolving early Earth

Fill in the blanks in the following flowchart, which characterizes a popular hypothesis for the early history of the Earth after the Sun and planets had formed (refer to parallel flowchart).

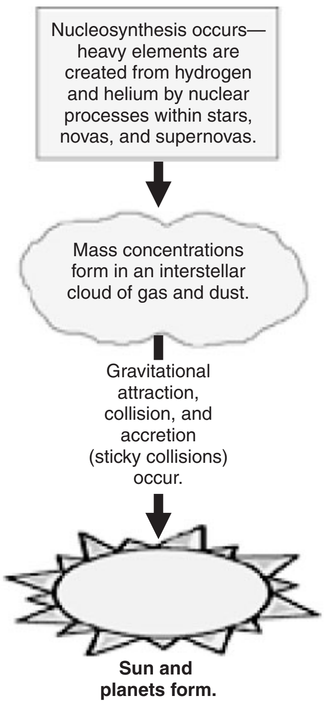
The Sun and planets form.

↓

Earth's interior heats up due to
- *decay of radioactive elements*
- ______________________________

↓

Consequences of the Earth heating up include
- *formation of an iron core*
- ______________________________
- ______________________________
  ____



Exercise 2: Evidence of water on Mars

Discuss four lines of evidence revealed by recent Marian probes of water (past and present) on Mars.

Hint: Start by making a list of lines of evidence mentioned in this chapter. Pick the four that you understand the best and then discuss how each supports the presence of water on Mars, both in the past and at present.

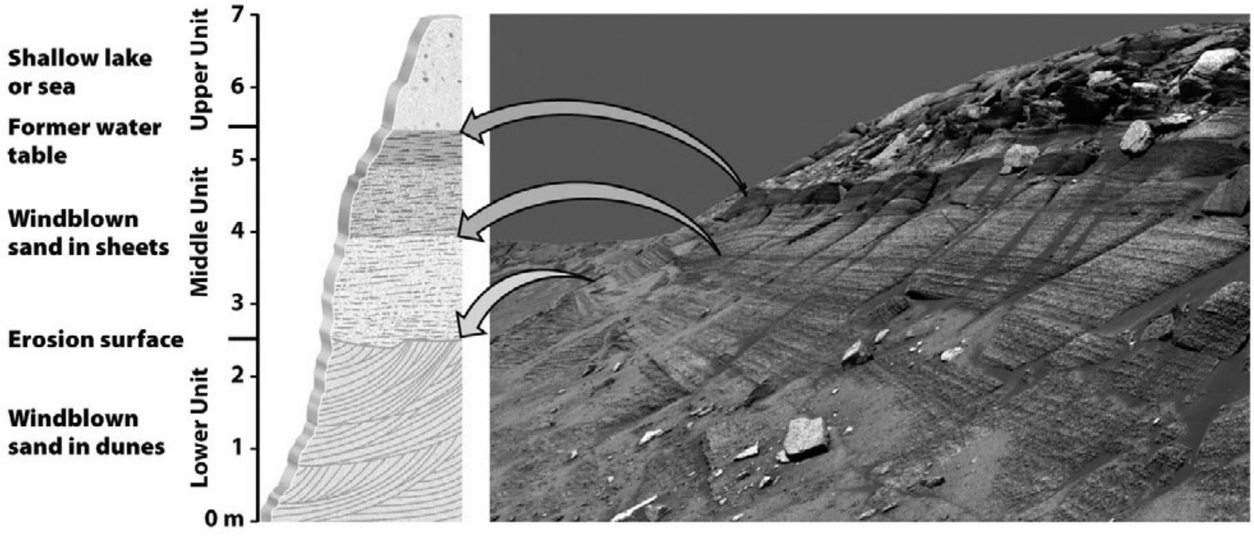


Figure 9.26. A sedimentary sequence exposed along the flank of Endurance Crater, photographed by the rover *Opportunity*. (a) An interpretive drawing showing each stage in the history of the outcrop. (b) The vertical succession of layers in the outcrop preserves an excellent record of early Martian environments. [NASA/JPL/Cornell.]

Review Questions

1. During the formation of our solar system, what was the process that caused dust and condensing material to accrete into planetesimals?
   A. nuclear fusion
   B. rapid spin of the protosun
   C. heating of gases
   D. gravitational attraction and material collisions
2. A major source of internal heat in the Earth today is
   A. ocean tides.
   B. radioactivity.
   C. solar energy.
   D. volcanoes.

Test-Taking Tip

When taking a test, be alert to items that give away the answers to other items.
Example: Question 12 provides a hint for answering question 3.

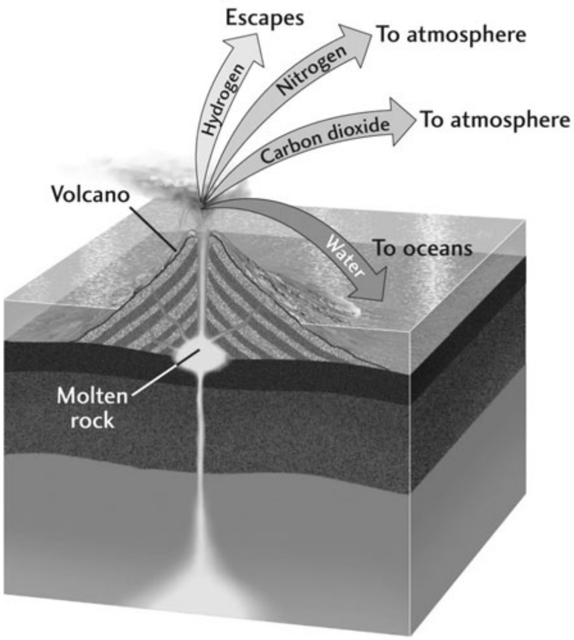


Figure 9.6. Early volcanic activity contributed enormous amounts of water vapor, carbon dioxide, and nitrogen to the atmosphere. Hydrogen, because it is lighter, escaped into space.

3. Which of the following processes is thought to be responsible for the formation of the present Earth's atmosphere?
   A. chemical breakdown of minerals
   B. capture of oxygen and nitrogen from space
   C. both degassing of Earth's interior and liberation of oxygen by photosynthesis
   D. degassing of Earth's interior
4. From radiometric dates of lunar rock samples and meteorites, how old is the Earth estimated to be?
   A. 45 million years old
   B. 4.5 billion years old
   C. 10 billion years old
   D. 100 billion years old
5. Geochemists have determined that differences in the distribution of chemical elements in the present Earth's crust, mantle, and core—in contrast to the distribution of chemical elements in the initial solar nebula—may be due in part to
   A. inhomogeneities within the initial interstellar dust cloud.
   B. early melting and differentiation of materials of varying density.
   C. cosmic ray bombardment over 4.5 billion years.
   D. nuclear synthesis within our Sun.
6. Why do geoscientists think tectonic plates move across the Earth's surface?
   A. Centrifugal force of Earth's rotation spins plates across the Earth's surface.
   B. Volcanic eruptions on the seafloor push tectonic plates apart.
   C. Tidal forces drive plate motion.
   D. Movement of the plates is the surface manifestation of convection in the mantle.
   Hint: Refer to Figure 9.16.
7. Within our solar system, one big difference between the inner and outer planets—besides size and position relative to the Sun—is their
   A. density.
   B. color.
   C. rate of formation.
   D. time of formation.

8. Earth's Moon is thought to have formed by
   A. capture of a large planetary object traveling past Earth.
   B. accretion, just like the planets.
   C. material ejected from Earth by volcanic eruptions.
   D. the impact of a Mars-sized object on Earth very early in Earth's history.
9. The nebular origin of our solar system is characterized as
   A. a proven fact.
   B. a theory.
   C. a hypothesis.
   D. pure guesswork.
10. Bombardment from space may be disastrous for life, but it is also an essential process in the history of a planet. Why?
    A. Bombardment is how a planet grows, and residual heat from impacts may help to create a dynamic planet.
    B. The oceans and atmosphere formed on Earth as a result of bombardment.
    C. Impacts drive plate tectonics.
    D. Impacts keep planets from getting too big.
11. The impacting object that caused the extinction of the dinosaurs 65 million years ago is estimated to have had a radius of about
    A. 100 meters.
    B. 1 kilometer.
    C. 10 kilometers.
    D. 100 kilometers.
    Hint: Refer to Table 9.2.
12. Oxygen released into Earth's atmosphere by photosynthesis is vital for our existence not only because we need it to breathe but also because
    A. it is essential for all life on Earth.
    B. it combines with free hydrogen gas in our atmosphere to produce water.
    C. life would not have evolved without oxygen.
    D. it forms an ozone layer in the upper atmosphere that protects us from UV radiation.

It is in the stars.
The stars above us, govern our condition.

—W. SHAKESPEARE
King Lear, IV, iii

CHAPTER 10

History of the Continents

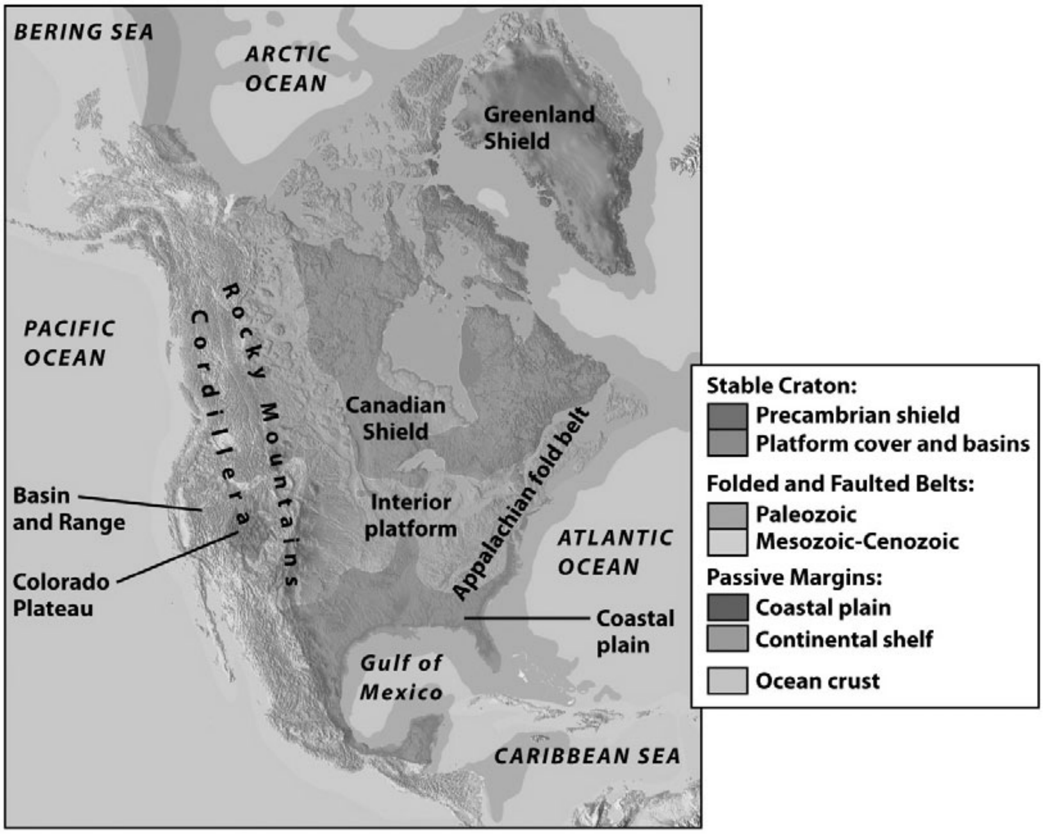


Figure 10.1. The major tectonic provinces of North America reflect the processes that formed the continent.

Before Lecture

Before you attend lecture, be sure to spend some time previewing the chapter. For an efficient preview, use the following questions.

Chapter Preview

- **What are the major geologic features of North America?**
  Brief answer: Review Figure 10.1. Pay particular attention to the location and characteristics of the active tectonic belt in western North America and the relatively stable continent of the ancient orogenic belts, platform, and shield. Look for patterns in age and location.
- **How do continents grow?**
  Brief answer: The silica-rich, iron-poor rocks in continents are produced mostly in subduction zones by magmatic differentiation and metamorphism of silica-rich sediments. Once produced, the continental rocks are difficult to subduct and recycle into the mantle because they are more buoyant than mantle material. Rifting and transform faulting typically break continents into small pieces while terrane accretion and continent collisions assemble pieces into larger continents. Refer to Figures 10.11 and 10.12.
- **How does orogeny modify continents?**
  Brief answer: Much as a styrofoam float resists being dragged under water, silica-rich, low-density continental crust is more buoyant than the mantle, and therefore continents resist being subducted. Instead, continental crust is damaged (deformed) and piles up (thickens) at convergent plate boundaries. Intense folding, faulting, detachment, and thrust transport of sedimentary wedges and the formation of huge granitic batholiths thicken the overriding continental lithosphere. These processes can deform continental crust hundreds of kilometers from the convergence zone. Thicker continental crust tends to stand higher.
- **What is epeirogeny?**
  Brief answer: Gradual downward and upward movements of broad regions of the crust, without significant folding or faulting, involves a set of processes called epierogeny. Heat, loading and unloading, and flow within the mantle may all cause epierogeny.
- **What is the Wilson cycle?**
  Brief answer: The Wilson cycle characterizes the sequence of events in the opening and closing of an ocean basin. A new ocean basin forms when a continent is rifted apart. As an ocean basin closes due to subduction of its ocean lithosphere, continents grow. A few times in Earth's history, the closure of a series of ocean basins resulted in the formation of a supercontinent, like Pangaea in the early Permian. Refer to Figures 10.17 and 10.18.
- **How have the Archean cratons survived billions of years of plate tectonics?**
  Brief answer: Like giant sailboats, continents have cratonic keels that stabilize the raft of continental lithosphere against the effects of convective currents in the mantle and plate tectonic processes. It is hypothesized that the keels consisted of somewhat less dense mantle rocks that are about the same age as the Archean crust above them. Refer to Figure 10.24.

Study Tip

When confronted with new scientific terminology, sometimes the dictionary can help. For example, if you look up the terms *epeirogeny* and *orogeny* you will find the following origins for the roots of these terms:

epeirogeny—Gk. *epeiros*, continent
orogeny—Gk. *oros*, mountain

Vital Information from Other Chapters

To understand the evolution of the continents, you will need to draw on diverse information from many chapters. While working on Chapter 10, Evolution of the Continents, keep the following concepts in mind and review them as much you need to.

Plate Tectonics

Divergent boundaries (Figure 2.8)

Convergent boundaries (Figure 2.8)

The forces that drive plate tectonics (Figure 1.15)

Igneous Rocks

Magma differentiation (Figures 4.5 and 4.11)

Formation of igneous rocks at divergent and convergent plate boundaries (Figures 4.15 and 4.16)

Rock Deformation

Folding and faulting (Figures 7.8)

Thrust faulting (Figure 7.21)

Folding (Figures 7.12 and 7.14)

Appalachian Fold belt (Figure 7.22)

Development of a fictitious geologic province (Figure 7.23)

During Lecture

One goal for lecture should be good answers to the preview questions.

- To avoid getting lost in the details, keep the big picture in mind. Chapter 10 examines the geologic history of the continents.
- Make a copy of Figure 10.18, the Wilson cycle, and have it handy during lecture.

After Lecture

Review Notes

The perfect time to review your notes is right after lecture. The following checklist contains both general review tips and specific suggestions for this chapter.

Check Your Notes: Have you…

☐ added notes or sketches of material from previous chapters that you need to understand your class notes? This is a good idea for this chapter because the chapter draws heavily on previous material. **Hint:** Refer to the Study Guide section **Vital Information from Other Chapters.** There you will find a helpful list of material you may want to review or include as you rework your notes.

☐ created a brief big picture overview of this lecture? **Hint:** The Wilson cycle provides a useful overview of this chapter. Refer to Figure 10.18 and consider adding sketches and text from that figure to your notes.

Intensive Study Session

Set priorities for studying this chapter. Try to give highest priority to activities that involve answering questions. We recommend the following strategy for learning this chapter.

- **Preview the following Figures:** 10.1, 10.4, 10.8, 10.11, 10.12, 10.13, 10.15, 10.16, 10.18, 10.20, and 10.24. You will need to understand these figures to answer the **Review Questions.**

- **Complete Practice Exercises 1 and 2.** These exercises will help you remember the most important ideas in this chapter.
- **Work in some review time as you study the evolution of the continents.** Reviewing is always a good idea, and it is especially important for this chapter because it draws on so many ideas in previous chapters. Refer to **Vital Information from Other Chapters** for a list of helpful figures to review.
- **Answer the Review Questions.** Try answering each question to check your understanding of the lecture. Check your answers as you go, but try to answer the questions before you look at the answers. Pay attention to the test-taking tips we provide. They will help you do better on your midterm.
- **Sometime before your exam, answer all the exercises at the end of the chapter.** They require short answers and won't take long if you know the material. A helpful animation, *Accretion of a Buoyant Fragment of a Continent,* is provided on the Web site for Exercises 5 and 6 at the end of Chapter 10 in the textbook.
- **Web Site Study Resources**
  http://www.whfreeman.com/understandingearth6e
  Complete the **Online Quiz.** Pay particular attention to the feedback. The **Geology in Practice Exercises** address the question "Do continents float on the mantle?" **Flashcards** will help you learn the new terminology in this chapter.

Exam Prep

Materials in this section are most useful during your preparation for quizzes and exams. The **Chapter Summary** and the **Practice Exercises** and **Review Questions** should simplify chapter review. Begin your session with the **Chapter Summary.** It provides a helpful overview that should refresh your memory.

Next, work on the **Practice Exercises** and **Review Questions**. Complete the exercises and questions just as you would for an exam, to see how well you have mastered this chapter. After you answer the questions, score them. Finally, and most important, review each question you missed. Identify and correct the misconception(s) that resulted in your answering the question incorrectly.

Chapter Summary

What are the major geologic features of North America?

- Figure 10.1 shows the major tectonic features, including the Canadian Shield, interior platform, Cordillera and Appalachian mountain belts, coastal plain, and continental shelves.
- Figure 10.3 shows the sedimentary basins and domes of North America.
- The Appalachian fold belt and western Cordillera mountain belt are characterized in Figures 10.4, 10.5, and 10.11.

How do continents grow?

- Magmatic differentiation. Magmas generated in subduction zones tend to be more silica-rich because (1) crustal material, like sediments, can be incorporated into the melt and (2) partial melting and crystal settling differentiate the iron-rich and silica-rich materials.
- Continental accretion. Plate motions accrete buoyant (silica rich) rocks to con-

tinental margins by (1) transfer of fragments from a subducting plate to a continental plate, (2) closure of marginal basins to add thickened island-arc crust to the continent, (3) lateral transport via strike-slip faulting along continental margins, and (4) suturing of two continental margins during their collision. Refer to Figures 10.11, 10.12, 10.15, 10.17, and 10.18 for illustrations and examples.

What are epeirogeny and orogeny?

- Epeirogeney refers to simple up-and-down movements without significant folding and faulting. Proposed mechanisms for vertical crustal movements are (1) isostatic adjustments caused by loading or unloading of the crust via accumulation and melting of glacial ice and (2) heating or cooling the crust in association with continental rifting or a hot spot. Refer to Figure 10.20.
- Orogeny usually results from plate convergence and is characterized by sever deformation including extensive faulting and folding. Examples of orogeny include the Appalachian and Rocky Mountains of the United States. But the most spectacular example on the planet is the Alpine–Himalayan belt. Refer to Figures 10.15 and 10.16 and the related section of text describing the formation of the Himalayas.

How does orogeny modify continents?

- Like a styrofoam float, the buoyant continental crust resists being dragged under water; silica-rich, low-density continental crust is more buoyant than the mantle, and therefore continents resist being subducted. Instead, continental crust is damaged (deformed) and piles up (thickens) at convergent plate boundaries.
- Intense folding, faulting, detachment and thrust transport of sedimentary wedges and the formation of huge granitic batholiths thicken the overriding continental lithosphere.
- These processes can deform continental crust hundreds of kilometers from the convergence zone. Thicker continental crust tends to stand higher.

What is the Wilson cycle?

- The Wilson cycle, named after J. Tuzo Wilson, is a flowchart that summarizes the general sequence of events in the evolution of continental crust. Refer to Figure 10.18.
- The cycle begins when the edges of continental cratons are rifted during the breakup of a supercontinent such as Pangaea. Rifting creates a new ocean basin with passive margins that collect ocean sediment. Eventually convergence begins, creating an active margin, with accompanying subduction, mountain building, and terrain accretion.
- From time to time during Earth's history, plate convergence produced supercontinents like Rodina and Pangaea.

How have the Archean cratons survived billions of years of plate tectonics?

- The formation of silica-rich continental crust goes back at least 4.0 billion years.
- Cratons (older and more stable parts of the continents) have keels that, like the hull of a sailboat, extend into the mantle.
- Cratonic keels appear to consist of somewhat lower density rock, called peri-

dotite, that is depleted of heavier constituents, such as the element iron and the mineral garnet.

- Keels appear to form at about the same time as the continental crust above it.
- It is hypothesized that the cold, strong, mantle keel more than 200 km thick helps to preserve the cratons from disruption by mantle convection and plate tectonic processes.

Refer to Figure 10.24 .

Nothing lives long but the earth and the mountain.

—Charles Ballard

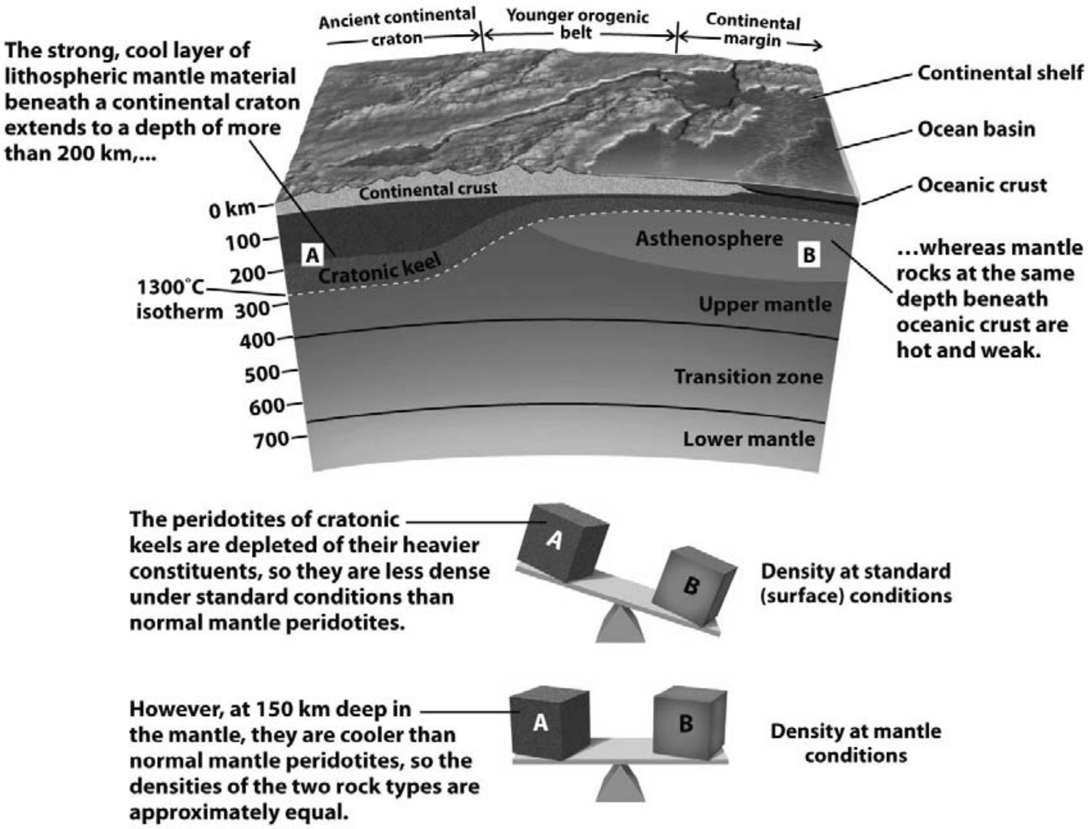


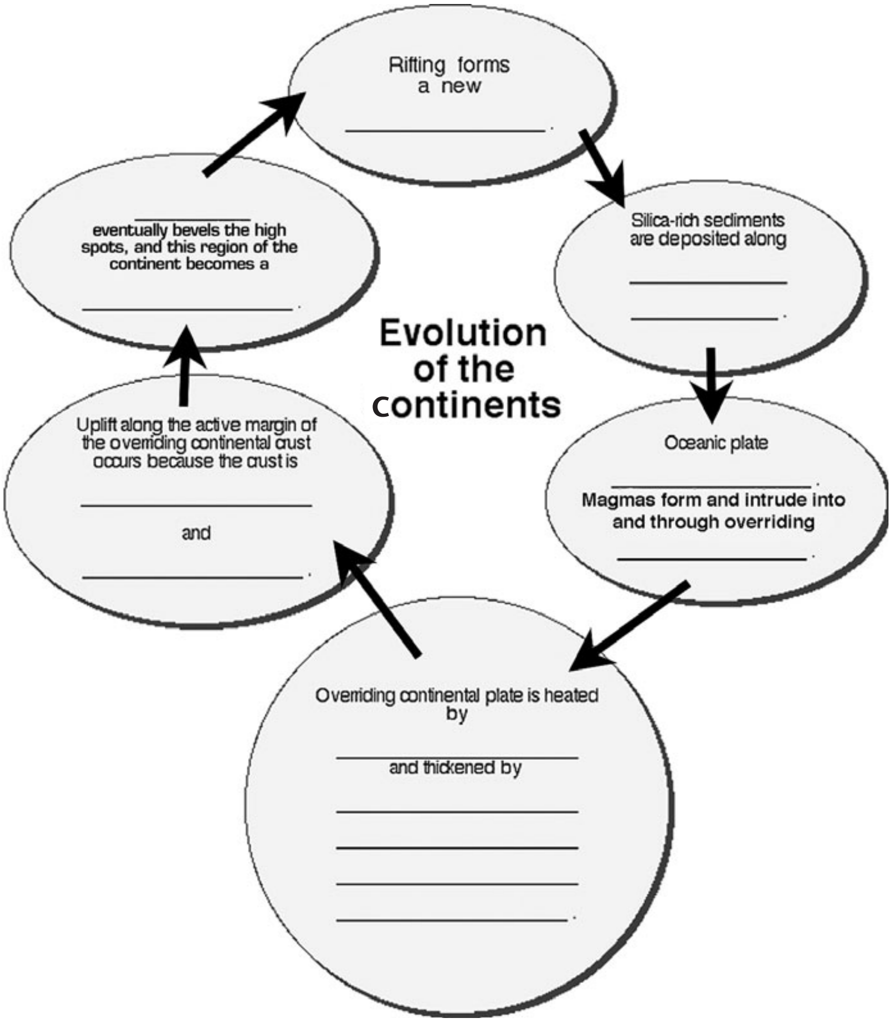
Figure 10.24 The chemical composition of cratonic keels counterbalances the effects of temperature to stabilize them against disruption by plate tectonic processes. [After T. H. Jordan, "The Deep Structure of Continents," *Scientific American* (January 1979): 92.]

Practice Exercises

Exercise 1: Evolution of the Continents

Complete the sentences in the flowchart with words from the list. Refer to Figures 10.12, 10.15, and 10.18.

accretion and collision	intrusion of magmas	subducts
continental plate	magmatism	thick
erosion	ocean basin	thrust faulting
folding	passive margin	
hot	stable craton	



Exercise 2: Ocean crust versus continental crust

Using information in Chapters 2, 4, and 10, complete the table.

Characteristics	Ocean crust	Continental crust
Composition		
Rock type(s)		*Very heterogeneous—can contain any rock, but granitic and gneissic with a cover of sediments are dominant.*
Density	*3.0 g/cm*^{3}	*2.7 g/cm*^{3}
Thickness	*10 km*	
Age		*The ages of continental crust span 4 billion years.*
Topographic features	*Abyssal floor* *Ridge with axial rift* *Trenches* *Seamounts* *Hot-spot island chains* *Plateaus*	
Structure/Architecture	*A model for the structure of the ocean crust is the ophiolite suite: deep-sea sediments, basaltic pillow lavas and dikes, and gabbro. (**Note:** Peridotites are part of the mantle lithosphere, not the ocean crust.)*	*The architecture of the continents is complex. It consists of preexisting cratons, accreted microplates, island arcs, volcanic arcs, suture zones, ophiolite suites, and belts representing ancient orogenic zones. Sediments cover basement rock in the interior platform of the continent.*
Origin		*Orogenic processes and accretion of pre-existing crustal blocks along convergent plate boundaries*

Review Questions

1. The massive, interior regions of continents that have been stable for extensive periods of time are called

   A. mountains. C. cratons.
   B. plateaus. D. plains.

2. Intense deformation and accretion of continental crust occurs at

   A. convergent plate margins. C. hot spots.
   B. transform margins. D. divergent plate margins.

3. Which of the following features is not associated with orogeny?

   A. thrust faulting C. passive continental margin
   B. intrusion of plutons D. metamorphism

4. The oldest rocks found on the continents are about

   A. 200 million years old. C. 4 billion years old.
   B. 1 billion years old. D. 4.5 billion years old.

   Hint: Refer to Figures 10.8 and 10.22.

5. Which of the following processes produces continental growth?
   A. suturing of margins during a continental collision
   B. transfer of crust during subduction
   C. transfer of crust during strike-slip faulting
   D. all the above
6. The Wilson cycle is
   A. a model for the evolution of landscapes.
   B. the sequence of events for the differentiation of magmas.
   C. the cycle of tectonic events related to continental evolution.
   D. a high-performance mountain bike developed in the Appalachian Mountains.
7. Much of the crust within the Cordillera of western North America ________________ over the last 200 million years.
   A. accreted
   B. eroded
   C. subsided
   D. subducted

   Hint: Refer to Figures 10.11 and 10.12.
8. Cratonic and other continental interior rocks are typically ______________________ those rocks found at active continental margins.
   A. much younger than
   B. older than
   C. younger than
   D. the same age as

   Hint: Refer to Figure 10.8.

Test-Taking Tips for Multiple-Choice Exams*

10. **Answer the questions you know first.** Mark items where you get stuck. Come back to harder questions later. Often you will find the answer you are looking for embedded in another, easier question.
9. **First try to answer the item without looking at the options.**
8. **Eliminate the distracters.** Treat each alternative as a true–false item. If "False," eliminate it.
7. **Use common sense.** Reasoning is more reliable than memory.
6. **Underline key words in the stem.** This practice can be helpful when you are stuck. It may help you focus on what question is really being asked.
5. **If two alternatives look similar,** it is likely that one of them is correct.
4. **Answer all questions.** Unless points are being subtracted for wrong answers (rare), it pays to guess when you're not sure. Research indicates that items with the most words in the middle of the list are often the correct items. But be cautious. Your professor may have read the research too!
3. **Do not change answers.** Particularly when you are guessing, your first guess is often correct. Change answers only when you have a clear reason for doing so.
2. **If the first item is correct, check the last.** If it says "all (or none) of the above," you obviously need to read the other alternatives carefully. Missing an "all of the above" item is one of the most common errors on a multiple-choice exam. It is easy to read carelessly when you are anxious.
1. **READ THE DIRECTIONS BEFORE YOU BEGIN!**

* For optimal exam performance, review and use the **Final Exam Prep Worksheet** (Appendix B). The idea is to organize a systematic review of material divided into short study sessions.

9. Interior continental shields, or cratons, are traversed by ancient orogenic belts, but younger orogenic belts are different from ancient orogenic belts because
   A. their sediments have been subjected to extensive regional metamorphism.
   B. the crust is much thinner and cooler.
   C. they consist of hotter and thicker crust.
   D. they consist almost entirely of volcanic rocks.
10. A large portion of the Cordilleran orogenic belt may consist of
   A. accreted terranes.
   B. hot-spot volcanism.
   C. ophiolite suites.
   D. an ancient craton.
   Hint: Refer to Figure 10.11.
11. Orogeny is taking place today
   A. along the east coast of North America.
   B. along the west coast of South America.
   C. in the center of North America.
   D. in the Canadian Shield.
12. Which of the following statements about orogenic systems is NOT valid?
   A. Orogeny is initiated by rifting as extension begins to open up a new ocean basin.
   B. Orogeny is initiated by subduction and the evolution of an active convergent margin.
   C. Large volumes of granite are intruded during orogenies.
   D. Folding and thrusting of preexisting rocks contributes to crustal thickening in the orogen.
13. The ______________________________ were produced by convergent plate boundary processes, including collision, during the Paleozoic.
   A. Cascade Mountains of northwestern North America
   B. Rocky Mountains of Colorado
   C. Appalachian Mountains along the eastern margin of North America
   D. Cordillera of western North, Central, and South America
   Hint: Refer to Figures 10.4 and 10.17.
14. The Cordilleran orogeny was initiated by formation of
   A. a continental rift in western North America.
   B. a subduction zone and convergent plate boundary along the western edge of North America.
   C. an impact of a comet-size object in the Pacific Ocean adjacent to the western edge of North America.
   D. a line of mantle or hot spots, which causes doming and rifting throughout western North America.
15. The western Cordillera of North America is topographically higher than the Appalachians mainly because
   A. orogeny occurred more recently in the Cordillera, so the crust is thicker.
   B. granite batholiths were intruded in the Cordilleran belt.
   C. the Appalachians eroded faster because they consist mostly of soft, sedimentary rocks.
   D. the Appalachians never reach the elevation of the Cordillera because collisions do not generate high mountains.
16. Your assignment as a geologist is to map out ancient orogenic zones in what is now the stable interior of a continent. Recent epeirogenic uplift has resulted in good exposures of the ancient basement rocks. Which of the following features would NOT be evidence of an ancient orogenic zone?
   A. intensely deformed sedimentary rocks
   B. lava flows and thick layers of volcanic tuff
   C. many granitic plutons that are all about the same radiometric age
   D. widespread and relatively thick accumulations of coral-rich limestone, sandstones, and shales

17. Why are the Sierra Nevada Mountains so much higher than the continental surfaces west and east of them?
    A. The crust is proably thicker and/or hotter beneath the Sierra Nevada.
    B. The crust beneath the Sierra Nevada is very thin and hot.
    C. The crust beneath the Sierra Nevada is probably denser than that to the east and west.
    D. The Sierra Nevadas are most probably part of an ancient spreading center that is no longer active.
18. Mountains are both the source and product of sediments because
    A. most sediments are subducted with the ocean lithosphere and thereby contribute to subduction zone magmatism.
    B. most sediments shed off mountains end up on the margin of a continent and are eventually accreted to the edge of continental crust by orogenic processes associated with convergent plate margins.
    C. the melting of sediments results in mafic igneous rocks characteristic of continental crust.
    D. most sediments end up on the deep ocean floor where they sit for billions of years.
19. In the context of plate tectonics, a reasonable sequence of events for an orogenic "cycle" is
    A. hot spots → subduction → rifting → orogeny.
    B. rifting → passive margin → subduction → orogeny → uplift.
    C. rifting → collision → subsidence → erosion → uplift.
    D. transform faulting → uplift → volcanism → orogeny.
    Hint: Refer to Figure 10.18.
20. The Earth's oldest continental crust can be found
    A. in active orogenic zones.
    B. on the ocean floor.
    C. in continental shield regions.
    D. along the margins of the continents.
21. The growth of continents occurs at
    A. hot spots.
    B. subduction zones.
    C. rift zones.
    D. transform faults.
22. Where on Earth could you go today to find an orogenic system with strong similarities to the Cordillera of North America? The study of this active orogenic system would provide you with a better understanding of the geologic history of western North America.
    A. Andes
    B. Himalayas
    C. Appalachians
    D. East Africa Rift
23. Epeirogeny is associated with
    A. subduction zones where convergence causes rapid vertical uplift.
    B. stable interior platforms within continents where isostatic adjustments result in gradual uplift or subsidence.
    C. continental collisions where the highest mountains form.
    D. the Wilson cycle for the evolution of continents.
    Hint: Refer to Figure 10.20.
24. Continental cratons seem relatively immune from deformation by plate tectonic processes because
    A. of deep, strong, mantle keels beneath them.
    B. they are always located at the center of the continent far from active plate boundaries.
    C. the continental crust is very strong.
    D. they are covered with sediments.
    Hint: Refer to Figure 10.24.
25. A modern example of how crust can be transported laterally along a continental margin is the
    A. amalgamation of the southwestern Pacific islands.
    B. mid-Atlantic Ridge.
    C. Appalachian orogeny.
    D. San Andreas strike-slip fault.
    Hint: Refer to Figure 10.6.

CHAPTER 11

Geobiology: Life Interacts with Earth

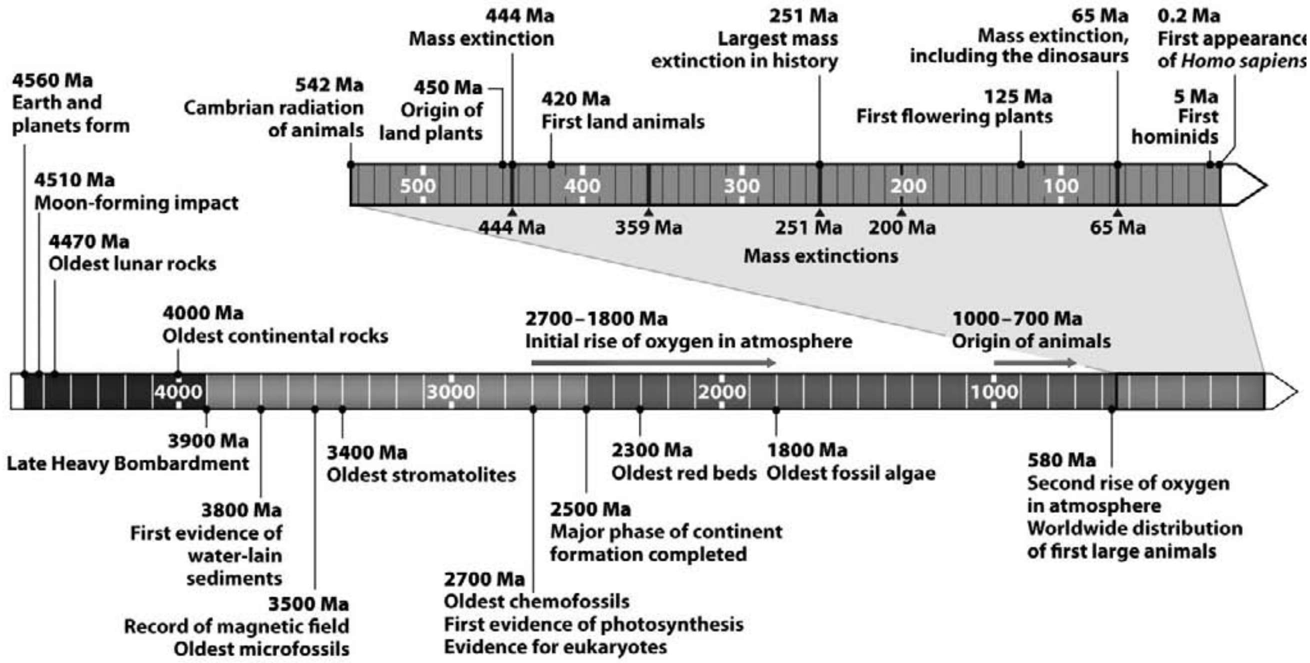


Figure 11.12. The geologic time scale, showing major events in the history of life. (Ma, million years ago.)

Before Lecture

Before you attend lecture be sure to spend some time previewing the chapter. For an efficient preview use the **Chapter Preview** questions, which constitute the framework for understanding the chapter. Previewing works best if you do it just before lecture. With the main points in mind you will understand the lecture better. This in turn will result in good and complete notes.

Study Tip

To understand this chapter, focus on systems and cycles. Study inputs and outputs: what goes into and what comes out of each process described.

How much time should you devote to previewing? Obviously, more time is better than less. But even a brief (five- or ten-minute) preview session just before lecture will produce a result you will notice. For a refresher on why previewing is so important, see Part 1, Chapter 3, How to Be Successful in Geology.

Chapter Preview

- **How do organisms and the Earth interact?**
  Brief answer: Life processes influence weathering, precipitate minerals, and modify the composition of the atmosphere and oceans. Geobiology is the study of these interactions.
- **What is the biosphere?**
  Brief answer: The biosphere is the part of our planet that contains all living organisms. It is characterized by metabolic processes that influence and even control geologic processes.
- **What is metabolism?**
  Brief answer: Metabolism is the process that all organisms use to convert inputs into outputs. For example, photosynthesis by plants uses three inputs (sunlight, carbon dioxide, and water) to produce two outputs, sugar and oxygen gas.
- **How important are microbes?**
  Brief answer: Microbes are the must abundant and diverse organisms on Earth. They regulate geologic processes such as weathering of minerals and rocks, precipitation of certain sedimentary minerals, and production of gases such as oxygen and carbon dioxide.
- **How did life originate, and what signs do we have of life on the young Earth?**
  Brief answer: Simple molecules of methane, ammonia, and water on the primitive Earth are thought to have combined to form amino acids, which then combined to form proteins. The oldest signs of life on Earth are shown in Figure 11.14.
- **What is the difference between radiation and extinction?**
  Brief answer: Radiation is the relatively rapid development of new types of organisms. When groups of organisms are no longer able to adapt to changing environmental conditions or to compete with a superior group of organisms, they become extinct.
- **Can life exist on other planets?**
  Brief answer: For every star, there is a habitable zone where water will be stable. If a planet is within a habitable zone, there is a chance that life might have originated there. Refer to Figure 11.24.

Vital Information from Other Chapters

After each lecture, you need to thoroughly master the concepts covered before you attend the subsequent lecture. The ideas of geology are like a stack of boxes. Each new idea rests on all ideas (boxes) stacked beneath it.

There is a good deal of geological time material in this chapter in the section Geologic Events in Earth's History. Review Figure 11.12 in the context of Figures 8.11 and 8.14; refer to Figures 8.11 and 8.14 in Chapter 8, Clocks in Rocks: Timing the Geologic Record. These three figures supplement each other. It is vital that you understand the method of radiometric dating that has supplied the dates for the ribbon of time (review Table 8.1 and the section Isotopic Dating Methods. For atmospheric dating and climate work, different methods are required. Review Clocking the Climate System in Chapter 8. Review An Overview of Geologic Time in Chapter 1. Review Chapter 9, Early History of the Terrestrial Planets.

During Lecture

This lecture is likely to cover a series of processes. Listen carefully and try to get the key inputs and outputs of each process into your notes.

Note-Taking Tip

Copy Figure 11.12 and paste it at the beginning of your Chapter 11 lecture notes. Refer to it to help you stay oriented in geological time. Don't get bogged down with specific dates of events. When we are talking about a billion years, a difference of a few million years isn't worth worrying about. Instead, think in term of landmarks, and try to place them in the correct order. For example, single-celled life occurred a long time before multicelled life. Oxygen had to be present before multicelled life occurred. All extinctions are in the last 500 million years.

After Lecture

Review Notes

The perfect time to review your notes is right after lecture. The following checklist contains both general review tips and specific suggestions for this chapter.

Check Your Notes: Have you…

- ☐ added visual material? Suggestion: Test your understanding of Chapter 11 by adding simplified sketches of the important metabolic processes and Earth/organism cycles in this chapter. **Hint:** See Figures 11.4 and 11.10.
- ☐ labeled the inputs and outputs of specific processes that were discussed? If not, you need to look them up in the text.
- ☐ indicated events in geological time in an order you can make sense of? Refer to Figure 11.12.
- ☐ created a brief big picture overview of the lecture (using a sketch or written outline)?

Carefully rework your notes for this lecture with great attention to processes. For each process discussed, it may be helpful to make a simple flowchart specifying the input, the process, and the output.

Process
Input → Output

For cycles such as the sulfur cycle (Figure 11.10), it may help you to reduce the figure to a very simple version that will help you remember the essential biosphere part of the cycle elements.

> Decomposer microorganisms digest decaying animal/plant matter → hydrogen sulfide + iron in the soil → iron pyrite

Be sure to add the figure number (in this case Figure 11.10) so that you can review the process in its entirety.

Intensive Study Session

Because there is a lot to learn in this chapter, be sure to set priorities for studying. Quite likely, there is more material than you will have time to study in one intensive study session. We recommend that you give highest priority to activities that involve answering questions. Answering questions while using your text and lecture notes as reference material is far more efficient than reading chapters or glancing over notes. As always, you have three sources from which to choose questions.

- **Text.** Work out preliminary answers to Exercises 1, 2, 3, 5, 6, 7, and 10 at the end of the textbook chapter. Read each question. Then try to answer it. Finally, check your answer against the text. Check your answers with your fellow students, teaching assistant, and instructor.
- **Practice Exercises and Review Questions.** Learn by testing yourself on the processes covered in this chapter. Complete the **Review Questions,** referring freely to the text and recommended figures. Practice Exercise 1 will be a great help in sorting out some of the most important ways the biosphere interacts with important geological processes. Start there.
- **Web Site Study Resources**
  http://www.whfreeman.com/understandingearth6e

Exam Prep

Materials in this section are most useful during preparation for quizzes and exams. The **Chapter Summary** and **Practice Exercises** and **Review Questions** should simplify your chapter review. Read the **Chapter Summary** to begin your session. It provides a helpful overview that should refresh your memory.

Next work on the **Practice Exercises** and **Review Questions.** Complete the exercises and questions just as you would an exam, to see how well you have mastered the chapter. After you answer the questions, score them. Finally, and most important of all, review each question that you missed. Identify and correct the misconception(s) that resulted in your answering the question incorrectly.

Chapter Summary

What is the biosphere?

- The Earth's biosphere is the part of our planet that contains all its living organisms. It includes all the plants and animals as well as whole kingdoms of nearly invisible microorganisms such as fungi and bacteria that are astronomically more numerous than humans or the creatures that make up our visible world. Some microorganism live in the most extreme environments on Earth.

- Because the biosphere intersects with the lithosphere, hydrosphere, and atmosphere, it can influence or even control basic geologic and climatic processes. Geobiology is the study of the interaction of these biosphere organisms with the Earth.

What is metabolism and how does metabolism affect the Earth?

- Organisms can be subdivided into producers (autotrophs) or consumers (heterotrophs) according to the way they obtain their food. Autotrophs make their own food using sources of energy and nutrients. Heterotrophs feed directly or indirectly on autotrophs.
- Metabolism is the process that all organisms use to convert inputs (energy and nutrients) to outputs (stored energy as carbohydrates or fat and waste products). For example, a photosynthetic plant uses sunlight, carbon dioxide, and water to produce carbohydrates and oxygen gas as a byproduct. Refer to Table 11.2.
- As their metabolic processes operate, organisms continuously exchange energy and matter with their environment. Biochemical cycles are pathways that describe this exchange or flow. Important biochemical cycles include the carbon cycle (Figure 11.3 and Table 11.2), the phosphate cycle (Figure 11.4), and the sulfur cycle (Figure 11.10).

How important are microbes?

- Single-celled organisms including bacteria, some fungi and algae, and protozoa are known as microbes. Where there is water, there are microbes.
- Microbes are the most abundant and diverse group of organisms on Earth.
- Microbes were the first organisms to inhabit the Earth, and all other organisms are descended from them. Refer to Figure 11.5.
- Extremophiles are microbes that live in environments that would kill other organisms. Refer to Table 11.3.
- Microbes play a critical role in many geologic processes, such as mineral precipitation, mineral dissolution, and the flow of important elements through Earth's crust.

How did life originate, and what signs do we have of life on the young Earth?

- Geoscientists continue to explore the mechanisms for how life originated on the primitive Earth. Laboratory experiments, like those by Stanley Miller (Figure 11.13), and studies of meteorites (Figure 11.23), the fossil record (Figure 11.14), rock chemistry, and modern organisms (Figure 11.15) are all filling in pieces of this puzzle.
- The fossil record tells us that microbes originated first on Earth and that they evolved into all multicelled organisms. We can find fossil microbes in rocks 3.5 billion years old.

Where did the oxygen in Earth's atmosphere originate?

- Earth's atmosphere is thought to have been oxygenated by cyanobacteria that gave off oxygen gas as a byproduct of photosynthesis. The fossils and the occurrences of banded iron formations and red beds in the geologic record provide evidence for important mileposts in the history of interactions between life and environment.
- An oxygen-rich surface environment set the stage for the evolution of Eukarya, including all multicellular animals.

What is the difference between radiation and extinction?

- A radiation is the relatively rapid development of new types of organisms that derive from a common ancestor. In contrast, extinction occurs when groups of organisms are no longer able to adapt to changing environmental conditions or compete with a superior group of organisms. Refer to Figure 11.17.
- The Cambrian explosion, which marks the origination of all major animal groups, is an example of a radiation. Refer to Figure 11.19.
- When many groups of organisms become extinct at the same time it is called a mass extinction. Refer to Figure 11.17, Earth Issues 11.1, Figure 9.18, and Table 9.2.

How do we search for life on other planets?

- The presence of liquid water over long periods of time (hundreds of millions of years) is considered to be a prerequisite for life.
- On a planet too close to its star water will boil and become a gas, which can be lost to space over time. On a planet too far from its star, water will freeze into a solid. For every star, there is a habitable zone, marked by the distance away from the star to the point where water is stable as a liquid. If a planet is within the habitable zone, there is a chance that life might have originated there. Refer to Figure 11.24.

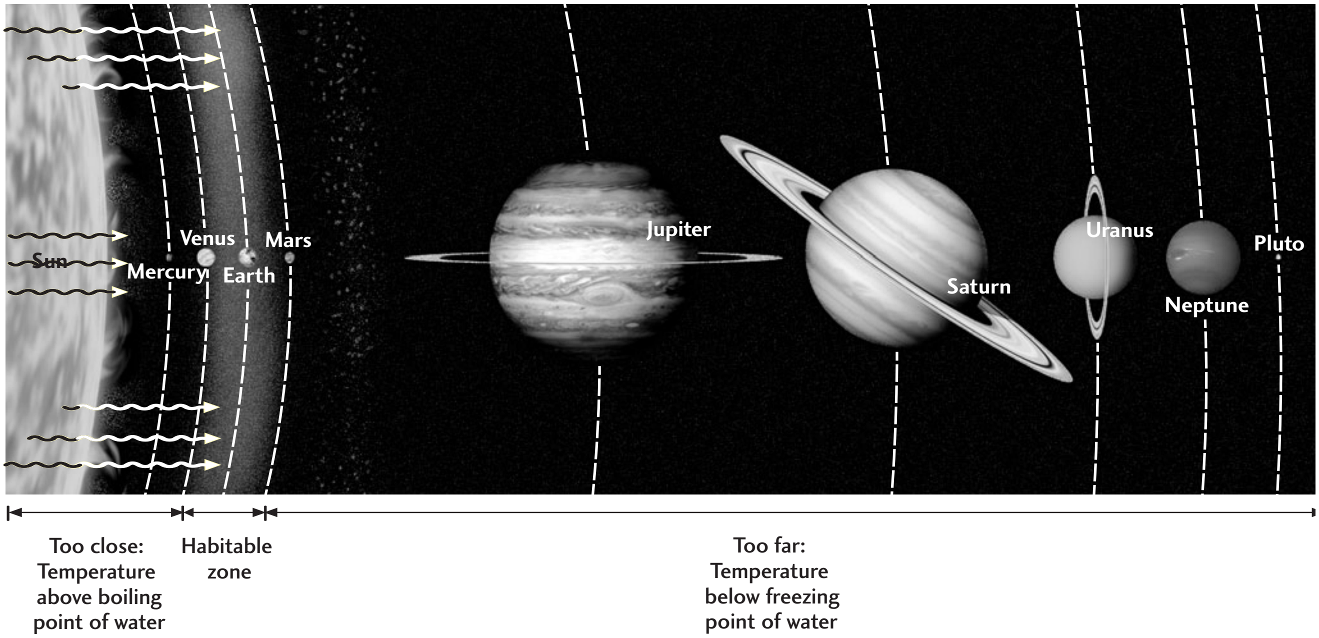


Figure 11.24. Stars have habitable zones where life on an orbiting planet could exist. The habitable zone is determined by distance from the star. It extends from the point at which water would boil away (too close to the star) to the point at which water would freeze solid (too far from the star).

Extinction is a difficult concept to grasp. It is an eternal concept. It's not at all like the killing of individual life forms that can be renewed through normal processes of reproduction. Nor is it simply diminishing numbers. Nor is it damage that can somehow be remedied or for which some substitute can be found. Nor is it something that simply affects our own generation. Nor is it something that could be remedied by some supernatural power. It is rather an absolute and final act for which there is no remedy on earth or in heaven. A species once extinct is gone forever.

—THOMAS BERRY

Practice Exercise

Exercise: How organisms and the Earth interact

Life processes influence weathering, precipitate minerals, and modify the composition of the atmosphere and oceans. Review some ways life processes affect the Earth by filling in the table.

Life's impact on Earth	Life process(es) generating the impact	Description of the interaction and impact
O_2 in Earth's atmosphere		
Greenhouse effect: Cooling	*Extraction of carbon from oceans and atmosphere by shell-producing and photosynthetic organisms*	
Greenhouse effect: Warming	*Respiration and metabolism of anaerobic microbes Refer to Table 11.2.*	
Mineral precipitation		
Mineral dissolution	*"Sulfate-eating" microbes*	*Hydrogen, hydrogen sulfide, and methane gases may be produced.*

Review Questions

1. Autotrophs are organisms that
   A. make their own food.
   B. get food by feeding directly or indirectly on producers.
   C. are multicellular.
   D. live only in anaerobic (oxygen-free) environments.
2. Living cells are composed primarily of the elements
   A. carbon, hydrogen, oxygen, and nitrogen.
   B. silicon, oxygen, hydrogen, and iron.
   C. carbon, phosphorous, iron, and calcium.
   D. silicon, nitrogen, iron, and magnesium.
3. Photosynthesis is a metabolic process that
   A. releases energy, CO_2, and water.
   B. stores energy, releases water, and precipitates calcium carbonate.
   C. stores energy as carbohydrates (sugars) and uses CO_2, and water.
   D. burns oxygen to create energy and releases water and CO_2.
4. Eukaryotic cells are
   A. very simple cells without nuclei.
   B. cells with a more complicated internal structure, including a nucleus.
   C. the earliest life form to appear in the fossil record.
   D. photosynthesizing.
5. The earliest record of eukaryotes occurred during the
   A. Phanerozoic.
   B. Proterozoic.
   C. Late Archean.
   D. Early Archean.
   Hint: Refer to Figures 8.14 and 11.5 and the section Chemofossils and Eukaryotes in Chapter 11.
6. Deposition of sedimentary banded iron formations correlates with the appearance of
   A. iron-rich basaltic lavas.
   B. animal life.
   C. coal swamps.
   D. abundant stromatolites.
   Hint: Refer to the textbook sections Microbial Mats, Stromatolites, and Origin of Earth's Oxygenated Atmosphere.
7. Banded iron formations (BIFs) are
   A. abundant in the Phanerozoic.
   B. precipitated by reacting with nitrogen.
   C. rare in the Archean.
   D. precipitated by reacting with oxygen.
8. Stromatolites represent sedimentary structures constructed by
   A. single-celled algae (cyanobacteria).
   B. horn corals.
   C. snails.
   D. burrowing trilobites.
9. Extremophiles are microbes that
   A. have a strong preference for oxygen-rich environments.
   B. are exclusively Eukaryotes.
   C. precipitate abundant calcium carbonate.
   D. live in environments with high salinity, acidity, temperature, or no oxygen.

10. Living things are able to grow and
    A. eat food.
    B. reproduce.
    C. calculate.
    D. precipitate.
11. What do the Murchison meteorite and the Miller experiment have in common?
    A. Both were exposed to nitrogen gas, a byproduct of life processes.
    B. Both contained abundant amounts of water.
    C. Both provide evidence for an atmosphere rich in oxygen on the primitive Earth.
    D. Amino acids, the fundamental building blocks of proteins, are abundant in the meteorite and the products produced by the Miller experiment.

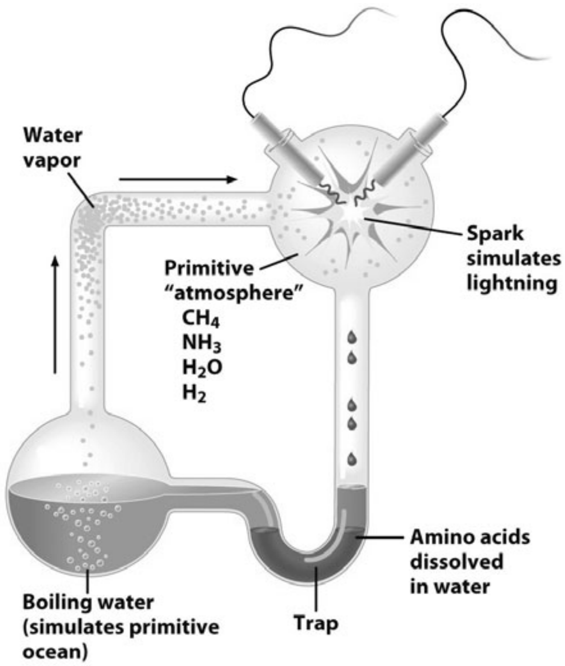


Figure 11.13. Stanley Miller used this simple experimental design to explore the origin of life. In this apparatus, ammonia (NH_3), hydrogen (H_2), water vapor (H_2O), and small carbon-bearing molecules such as methane (CH_4) were converted into amino acids—a key component of living organisms.

12. The Cambrian Explosion is
    A. the greatest mass extinction event in Earth history.
    B. a surprising rapid radiation of every major animal group.
    C. the first appearance of life on Earth.
    D. the rapid radiation of stromatolites across the Earth's surface.
13. As a planetary scientist studying potentially habitable planets outside our solar system, you would get very excited about finding evidence for
    A. a planetary atmosphere rich in nitrogen and ammonia gases.
    B. abundant oxygen gas and traces of methane in a planet's atmosphere plus water ice on the surface.
    C. an atmosphere rich in hydrogen and hydrogen sulfide gas.
    D. a surface covered with lava flows and few impact craters.

CHAPTER 12

Volcanoes

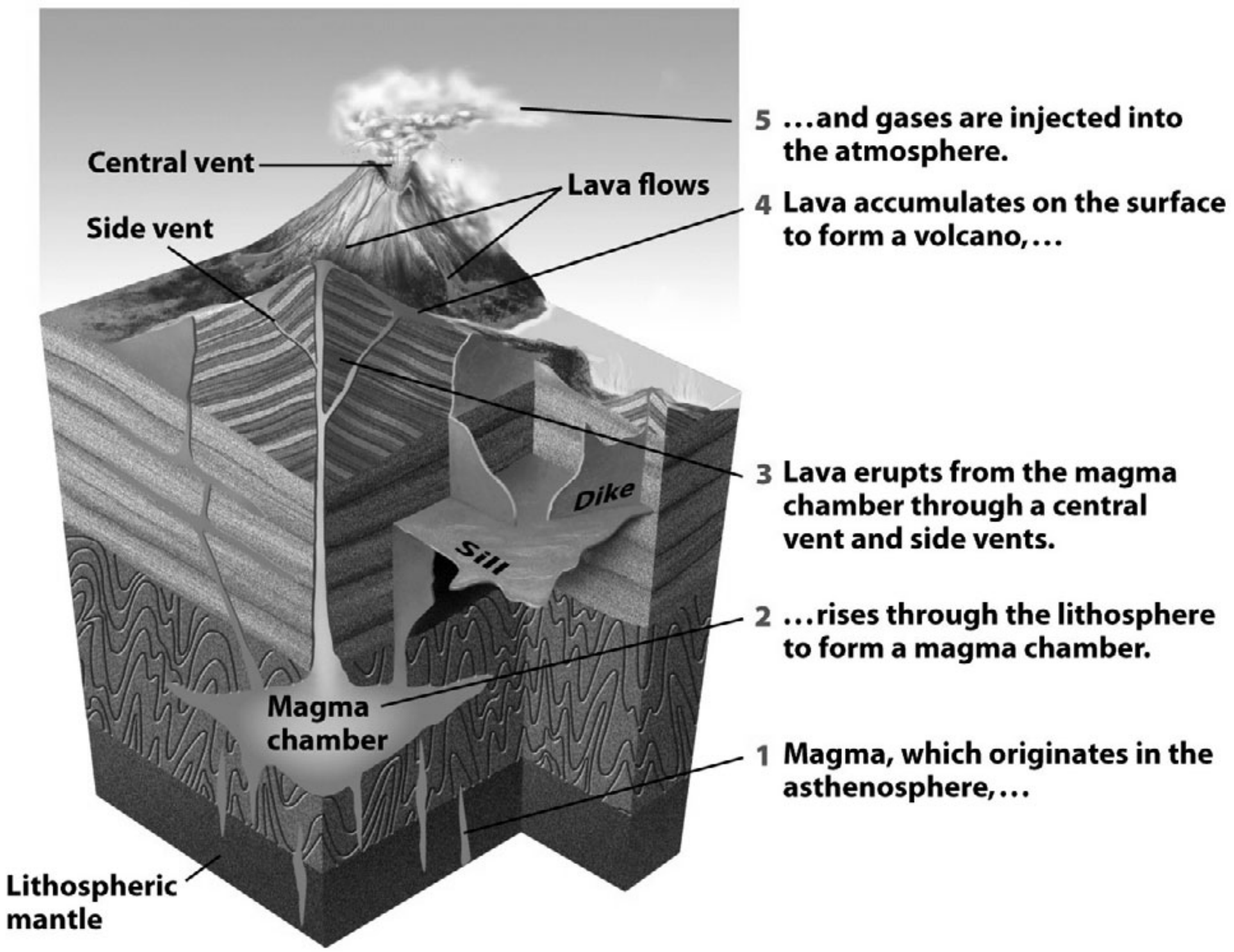


Figure 12.1. Volcanoes transport magma from the Earth's interior to its surface and gases are injected into its atmosphere (or hydrosphere, in the case of an underwater eruption).

Before Lecture

Chapter Preview

- **Why does volcanism occur? See Figure 12.1.**
  Volcanism occurs when magma rises buoyantly to the surface.
- **What are the three major lava types and how do they relate to eruptive style and volcanic landforms?**
  Mafic (basalt), intermediate (andesite), and felsic (rhyolite) lava types produce eruptions that range from relatively gentle basaltic flows to highly explosive rhyolitic eruptions. See Figure 12.14.
- **How is volcanism related to plate tectonics?**
  Volcanism is concentrated at convergent and divergent plate boundaries and hot spots. See Figure 12.23.
- **What are some of the beneficial effects of volcanism?**
  Volcanic processes create new ocean floor, our oceans and atmosphere, ore deposits, and geothermal energy.

Vital Information from Other Chapters

Review the following sections in Chapter 4: How Do Igneous Rocks Differ from One Another? and Igneous Activity and Plate Tectonics.

Previewing Tip

See the flowchart How to Study Geology in Part I of the Study Guide for additional ideas on previewing. The most useful answer to a preview question is one that you will actually remember during lecture. Simplify to something you can commit to memory.

Preview questions are like a fresh, undecorated Christmas tree. During lecture you decorate the tree.

During Lecture

One goal for lecture should be to leave the room with good answers to the preview questions.

- Focus on understanding how volcanoes work. Where the magma comes from (for example, iron-rich ocean crust or silica-rich continental crust) has everything to do with the explosiveness of the eruption and the shape of the resulting volcanic landform.
- Focus particularly on understanding Figures 12.1 (how a volcano system works) and 12.14 (volcanic eruptive styles and landforms). It may be helpful to bookmark these figures and have them handy during lecture for quick reference. Do annotate text figures with comments made by your instructor.
- Want ideas on taking good notes? If you haven't already done so, read the discussion of note taking in Part I, Chapter 3, of the Study Guide. You can use the **Note-Taking Checklist** before you go to lecture as a one-minute reminder of what to do to improve your note-taking skill. After lecture, use the checklist as a quality check.

Note-Taking Tip: Use abbreviations to speed up your note taking

ig rock → igneous rock
strat → stratovolcano
comp → composite volcano
HP → hot spot
V → volcanism or volcano
sh v → shield volcano
B → basalt
rhy → rhyolite or rhyolitic
mag → magma

Put these abbreviations in the margin to draw your attention to them later.

TQ (test question)

? areas where you feel lost or unclear about the material. Use these ? flags as a reminder that you need to follow up via further study or a conference with your instructor, tutor, or study partner.

After Lecture

Review Notes

Right after lecture, while the material is fresh in your mind, is the perfect time to review and improve your notes.

Check Your Notes: Have you…

- ☐ clearly identified important points? Example: You should have clear descriptions of the three lava types, information about the chemical composition and explosiveness of each type, and legible sketches of each landform discussed during the lecture.
- ☐ added sketches of the landforms associated with each eruptive style? Refer to Figure 12.14. Example: Compare the slope of a shield volcano with that of a composite volcano by drawing a simplified sketch of each one showing how steep each volcano is and the relative area each volcano is likely to cover. No fancy artwork is needed, just a steep inverted V for one and a flattened inverted V for the other. The shield volcano would be flattened and spread out and the composite (stratovolcano) steeper. Sketching provides a good check on how well you understand the differences.
- ☐ included a sketch of the basic features of a volcanic geosystem? Use Figure 12.1 as a reference.
- ☐ included a sketch similar to Figure 12.23 that shows how volcanism relates to plate tectonics?
- ☐ developed a table that summarizes the three lava types in terms of rock composition and associated landforms? Completing the table in Practice Exercise 1 will give you a summary of Chapter 12.

Intensive Study Session

Ready to work? Set priorities for studying this chapter.

- **Practice Exercises and Review Questions.** Be sure to do Exercise 1. It involves the key information you need to learn in this chapter.
- **Text.** Pay particular attention to Figures 12.1, 12.14, 12.15, 12.23, 12.27, and 12.29. These figures present the most important ideas in Chapter 12. Answer Exercises 1 and 5 and Thought Question 1 at the end of the chapter.
- **Web Site Study Resources**

  http://www.whfreeman.com/understandingearth6e

  Do the **Online Review Exercises** Where Do Volcanoes Occur? and Finding the Volcanic Hot Spots.

Motivation Tip

Chapter 12 contains material that should be of considerable interest to anyone living or planning to live in the northwestern United States. There is information in this chapter that could literally save your life. Also illustrated are landforms in Hawaii and some of our western national parks, for example, Mount Rainier, Crater Lake, and Yellowstone. Quite possibly you have visited one of these places and wondered at its beauty.

Give yourself permission to enjoy this particularly interesting chapter! Begin your study session by just browsing the artwork in Chapter 12 for ideas that interest you. Start reading wherever your interest takes you. Give yourself fifteen or twenty minutes just to enjoy the interesting illustrations before you plunge into studying text and doing exercises.

Exam Prep

Materials in this section are most useful during preparation for quizzes and exams. The **Chapter Summary** and the **Practice Exercises** and **Review Questions** should simplify your chapter review. Read the **Chapter Summary** to begin your session. It provides a helpful overview that should refresh your memory.

Next work on the **Practice Exercises** and **Review Questions.** Complete the exercises and questions just as you would an exam, to see how well you have mastered this chapter. After you answer the questions, score them. Finally, and most important of all, review each question that you missed. Identify and correct the misconception(s) that caused you to answer the question incorrectly.

Chapter Summary

Why does volcanism occur?

- Volcanism occurs when molten rock inside the Earth rises buoyantly to the surface because it is less dense than the surrounding rock. Volcanism is a surface expression of magma generation within the Earth.

What are the three major lava types and how do they relate to eruptive style and volcanic landforms?

- Silicate lavas can be classified in three major types—felsic (rhyolite), intermediate (andesite), and mafic (basalt)—based on decreasing amount of silica and increasing amounts of iron and magnesium.
- Eruption styles, volcanic deposits, landforms, and potential hazards are strongly linked to the chemical composition and gas content of the lava (refer to Exercise 1). Because basaltic lavas are relatively fluid and dry, they typically exhibit less explosive eruptions and erupt as lava flows. Rhyolite lavas are very viscous and usually wet. Therefore, they typically erupt very explosively as pyroclastic flows or form domes.

How is volcanism related to plate tectonics?

- There is a strong connection between major types of volcanism and crustal plate boundaries. Basaltic lavas occur at divergent plate boundaries and hot spots. The ocean crust is created by basaltic volcanism at the ocean ridge system. Basalt is thought to be generated by partial melting due to decompression of the ultramafic upper mantle. Basaltic, andesitic, and rhyolitic lavas erupt at convergent zones due to fluid-induced melting. The lavas generated along any particular convergent zone depend in large part on what type of rocks are being subducted and melted within the overriding crust.

How does volcanism interact with human affairs?

- There are both benefits and hazards associated with volcanism. Geothermal heat is growing in importance for electric energy generation. Earth's oceans and atmosphere are thought to have condensed from volcanic degassing of our planet's interior. Volcanic dust and gases can impact global climate. Volcanic eruptions and associated mudflows can have disastrous impacts on a region and its people. Important ore-forming processes occur when hot water circulates through the magma chamber and surrounding rock.

Practice Exercises

Exercise 1: Lava types—their properties, eruption styles, deposits, landforms, association with plate tectonics, and hazards

Fill in the blanks with the typical characteristics of each lava type. Keep in mind that different lavas exhibit a range of properties and behaviors. Give the best answer that generally characterizes each lava. Some answers have been provided as guidelines. Bullets mark spaces to fill in.

This table will provide you with a very useful study guide for much of Chapter 12. It makes an ideal summary of the chapter that should be very useful when you return to this chapter in preparation for your midterm exam.

	Lava types		
Characteristics	**Basalt (mafic)**	**Andesite (intermediate)**	**Rhyolite (felsic)**
Properties			
eruption temperature	•	*intermediate*	•
silica content	•	*intermediate*	*high (≈ 70%)*
gas content	*low, up to a few percent*	*variable*	*high (up to ≈ 15%)*
viscosity	*low-fluid magma*	*intermediate*	•
typical flow velocity	*0.7 to 30 m/minute*	*9 m/day*	*less than 9 m/day*
typical flow length	*10 to 160 km*	*8 km*	*less than 1.5 km*
typical flow thickness	*5 to 15 m*	*30 m*	*200 m*
Eruption styles	*typically not very explosive*	•	•
Deposits	*flood basalt* • • • •	*lava flow* *dome* *pyroclastic flow—* *tuff and welded tuff*	*obsidian dome* • •
Landforms	• • *cinder cone* *small caldera*	*composite volcano* *summit crater* *caldera* *cinder cone*	• • •
Association with plate tectonics	*hot spots* •	•	•
Hazards	• •	*lava flow* *pyroclastic/ash flow* *explosive blast* *hot gases* *mudflow*	*explosive blast* *hot gases* • •

The longest word in the English language is supposedly **pneumonoultramicroscopicsilicovolcanoconios**—a lung disease caused by breathing in particles of volcanic matter or a similar fine dust.

Exercise 2: Volcanoes at plate tectonic boundaries

Complete this exercise by filling in the blanks adjacent to the list of volcanic areas with the correct match of magmatic (plate tectonic) setting and characteristic magma type.

Use Figures 12.14, 12.15, 12.23, 12.24, and 12.31 and an atlas as a reference. Chapter 2 and Web site links provided at http://www.whfreeman.com/understandingearth6e will also help you. Sample answers are provided. Note that a volcanic area may have hybrid characteristics.

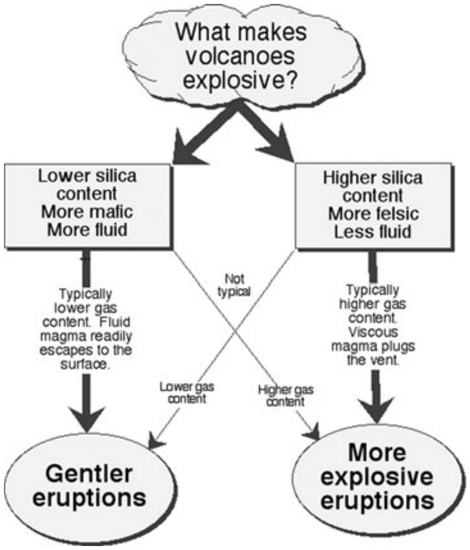
Volcano or volcanic area	Type of volcano (shield, composite, caldera)	Magma type (mafic, intermediate, felsic)	Magmatic (plate tectonic) setting—divergent, convergent, hot spot
Hawaii			
Tonga Islands	*composite*	*intermediate and felsic*	*convergent/subduction*
Columbia Plateau		*mafic*	*hot spot*
Santorini (Thera), Greece	*caldera*		
Mayon, Philippines			
Iceland			*divergent and hot spot*
Yellowstone			
Krakatoa, Indonesia			
North Island, New Zealand			
Crater Lake, Oregon			
Japan			
Aleutian Islands, Alaska			
Mariana Islands			
Kilimanjaro, Africa			
Pinatubo, Philippines			
Katmai, Alaska	*composite and caldera*		
Mount Rainier, Washington			
Tambora, Indonesia	*composite and caldera*		*convergent*
Vesuvius, Italy			

Review Questions

1. Lavas are almost always fine-grained rocks because
   A. the minerals they are made up of do not form large crystals.
   B. very little water is in the extruded magma.
   C. the lava crystallizes under pressure too low for large crystals to grow.
   D. they cool too rapidly for large crystals to grow.
2. Which extrusive rocks contain the most silica?
   A. andesite
   B. rhyolite
   C. granite
   D. basalt
3. During volcanic eruptions, the most common gas released is
   A. hydrogen.
   B. water.
   C. nitrogen.
   D. carbon dioxide.

4. A cloud of superheated steam and hot ash that is produced during a volcanic eruption and moves rapidly parallel to the ground is called
   A. a welded tuff.
   B. a pyroclastic flow.
   C. volcanic bombs.
   D. a cinder flow.
5. A good example of shield volcanoes can be found in
   A. northern California, Washington, and Oregon.
   B. the Hawaiian islands.
   C. the Caribbean islands, such as Mt. Pelée on Martinique.
   D. western South America.
6. Composite volcanoes (stratovolcanoes) are composed largely of
   A. basalt lava flows and basaltic cinders.
   B. pillow and pahoehoe lava flows.
   C. rhyolitic and intermediate lavas and pyroclastic flows.
   D. dikes and sills.
7. Compared to basalt, rhyolite lava flows are very thick and tend to form domes because rhyolite lava
   A. contains less gas than basalt lava and is therefore more fluid.
   B. is richer in silica than basalt lava and is therefore less fluid.
   C. cools more quickly than basalt lava.
   D. is less dense than basalt lava.
8. On a recent three-day hike up a gently sloping mountain, your friends describe to you features they encountered. Frequently they crossed lava flows and fissures, and occasionally they had to detour around large cinder cones. From your friends' description, you tell them they were hiking on a
   A. caldera.
   B. composite volcano.
   C. gabbro pluton.
   D. shield volcano.
9. Composite volcanoes are commonly associated with which tectonic setting?
   A. passive continental margins and deep ocean basins
   B. convergent plate boundaries, such as those of the circum-Pacific
   C. ocean spreading centers, such as Iceland
   D. transfer faults, such as the San Andreas fault
10. Of the following states, which is essentially all volcanic rock?
    A. Alaska
    B. Hawaii
    C. Oregon
    D. California
11. Typically, explosive volcanic eruptions are associated with
    A. basalt lavas.
    B. shield volcanoes.
    C. magmas that are poor in both silica and dissolved gases.
    D. magmas that are high in both silica and dissolved gases.
12. Shield volcanoes and composite volcanoes differ in shape because of
    A. the different compositions of their magma.
    B. the particular part of the ocean that each one forms in.
    C. the latitude at which each one forms.
    D. factors that are completely unknown to us at present.

    Hint: Refer to Figure 12.14.



13. Calderas usually form
   A. from molten material from the core that comes very near the Earth's surface at a thin point in the crust.
   B. after a steam explosion, when magma comes into contact with abundant underground water.
   C. when an eruption literally blows the top of a volcano off.
   D. after large volumes of magma erupt, leaving a void in the magma chamber into which the superstructure of a volcano can collapse.

   Hint: Refer to Figure 12.15.

14. Your friends have described to you an eruption that took place at an undisclosed location. The lava they described merely flowed out of a fissure and spread rapidly over a large area. You would inform your friends that the rock type being formed would be most likely to be
   A. granite.
   B. andesite.
   C. basalt.
   D. rhyolite.

15. You have been informed that an explosive volcanic eruption has taken place at an undisclosed location and that a huge nuée ardente (pyroclastic flow) flowed off the steep-sided volcano. You could respond that the magma type is likely to be
   A. basaltic.
   B. rhyolitic.
   C. ultramafic.
   D. gabbroic.

16. Where are andesitic volcanoes located?
   A. where diverging plate boundaries occur
   B. at transform boundaries
   C. along the mid-oceanic ridge crest
   D. along converging plate boundaries

17. A large resort located on a beautiful lake and known for its hot springs is experiencing a drop in business due to publicity about the recent swarm of small earthquakes in the area. The lake is actually located within a caldera, and beautiful rock towers and spires of weathered volcanic tuff are found all along the edge of the lake. As the director of the resort, you're concerned about the change in business and the potential risk to your guests. What should you do?
    A. You cannot be worried because you know a volcano can't blow up on you.
    B. You know that earthquake swarms can be a precursor to volcanic eruptions and that very explosive eruptions have happened at the place in the recent geologic past, so you decide that the resort should close until the situation is safe.
    C. Advertise the resort as the best place to see beautiful basalt lava fountains.
    D. Earthquakes have occurred occasionally along a nearby known fault, and there have been no historic volcanic eruptions, so you're not concerned.

18. Which type of lava is most likely to erupt at the mid-ocean ridge? Refer to Figure 12.23.
    A. basalt
    B. andesite
    C. rhyolite
    D. diorite

19. Which type of lava is most likely to erupt at a hot spot? Refer to Figure 12.23.
    A. basalt
    B. andesite
    C. rhyolite
    D. diorite.

20. Which type of lava is most likely to erupt at a convergent boundary along the edge of a continental plate, as shown in Figure 12.23?
    A. basalt
    B. andesite
    C. rhyolite
    D. diorite

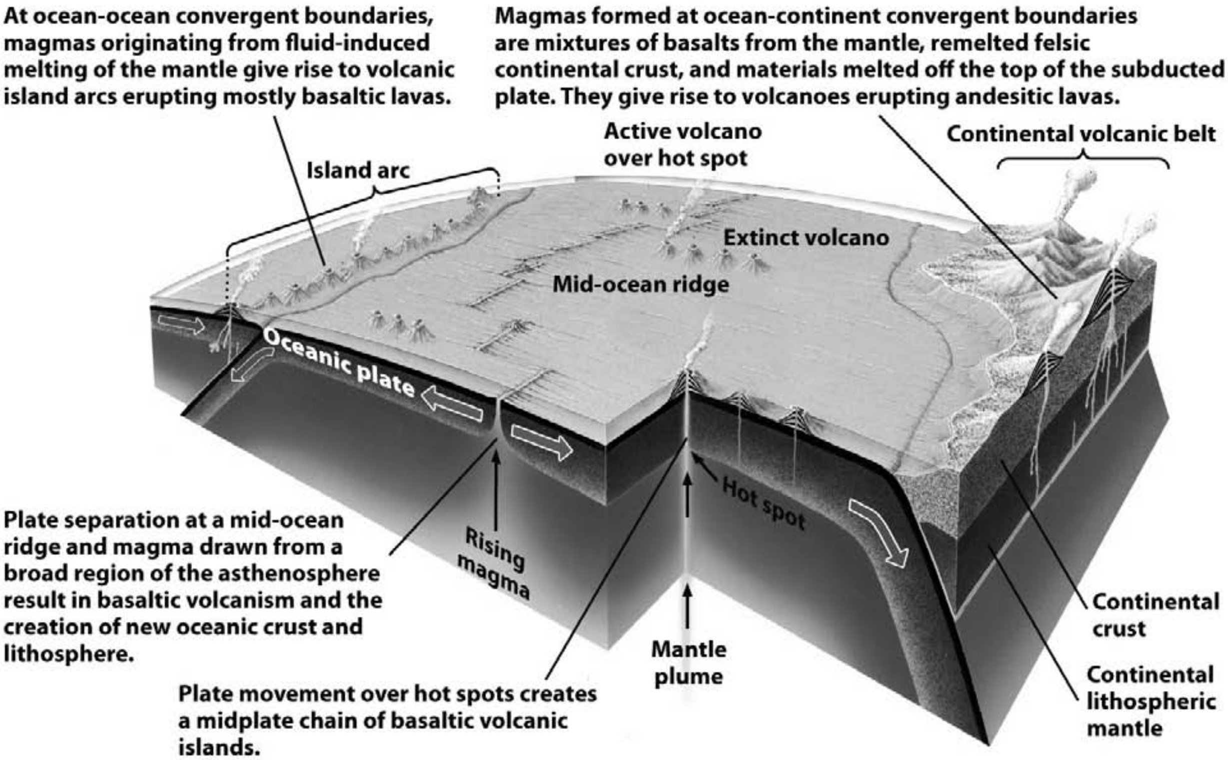


Figure 12.23. Plate tectonic processes explain the global pattern of volcanism.

21. Which of the following volcanic deposits can be formed from felsic lava?
    A. pahoehoe
    B. flood basalt
    C. volcanic dome
    D. shield volcano

22. If lava flows of progressively younger ages all erupted from a single large magma chamber, how would you expect their composition to have progressively changed?
    A. enriched in iron as they get younger
    B. enriched in silica as they get younger
    C. more mafic as they get younger
    D. more fluid as they get younger

23. Which of the following statements about mafic rocks is true?
    A. Mafic rocks are richer in silica than felsic rocks.
    B. Mafic rocks crystallize at higher temperatures than felsic rocks.
    C. Mafic rocks are more viscous than felsic rocks.
    D. Mafic rocks tend to be lighter in color than felsic rocks.

24. Large volcanoes can potentially affect global climate when they erupt because they release
    A. geothermal heat.
    B. volcanic dust, sulfur, and carbon dioxide gas.
    C. lahars and lava flows.
    D. nitrogen and argon gases.

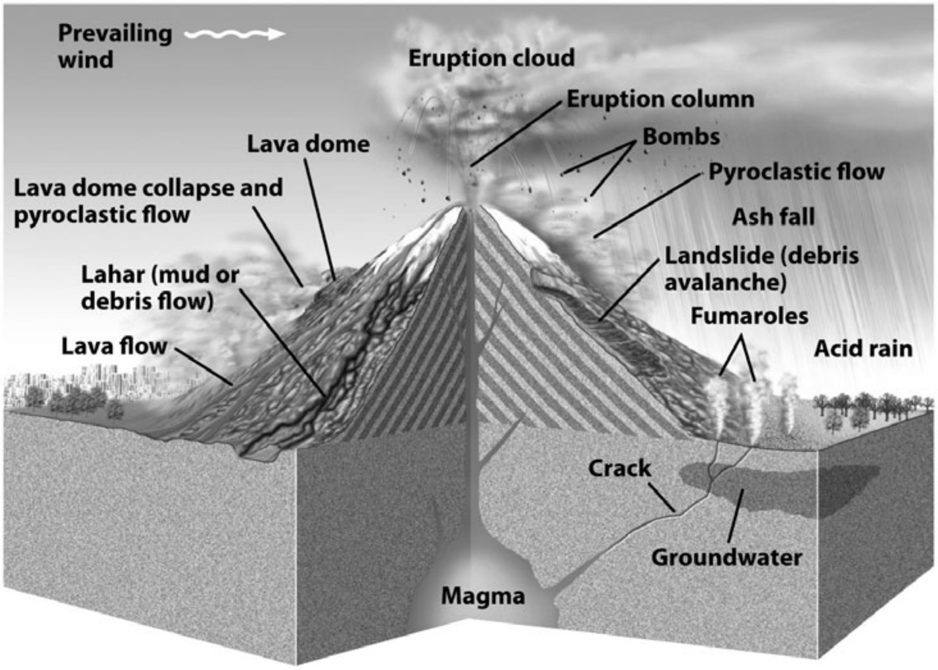


Figure 12.29. Some of the volcanic hazards that can kill people and destroy property [B. Meyers et al./USGS].

CHAPTER 13

Earthquakes

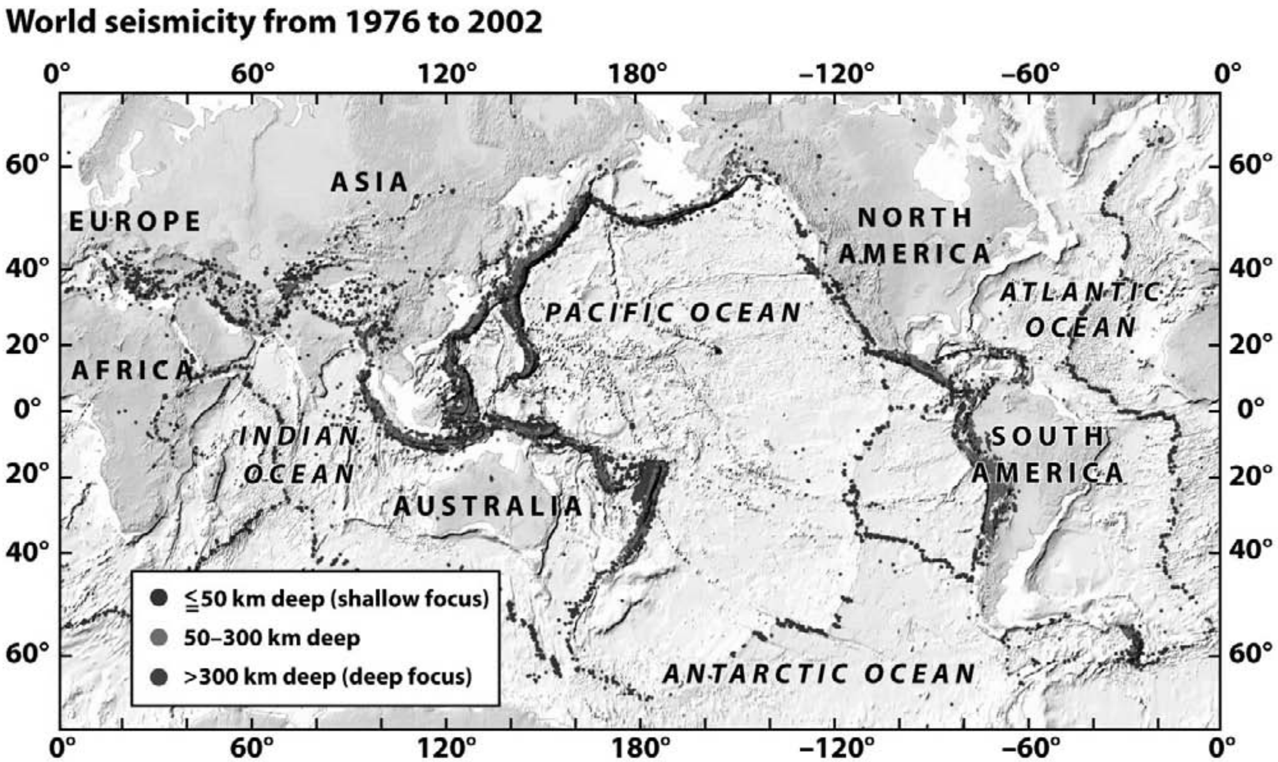


Figure 13.15. Earthquakes indicate how tectonic plates interact at their boundaries.

Before Lecture

Before you attend lecture, be sure to spend some time previewing the chapter with the following questions.

Chapter Preview

- **What is an earthquake?**
  Brief answer: an earthquake is a shaking of the ground caused by seismic waves that radiate out from a fault that moves suddenly. Elastic rebound explains why earthquakes occur. Refer to Figure 13.3.
- **What are the three types of seismic waves?**
  Brief answer: P (primary/compressional) waves, S (secondary/shear) waves, and surface waves. Refer to Figure 13.7.
- **What is earthquake magnitude and how is it measured?**
  Brief answer: Earthquake magnitude is a measure of the size of the earthquake. The Richter magnitude is determined from the amplitude of the ground motion. The moment magnitude is closely related to the amount of energy radiated by the earthquake. The Mercalli Intensity Scale is a more qualitative measure of the damage done by an earthquake.
- **Where do most earthquakes occur?**
  Brief answer: Most but not all earthquakes occur along active plate tectonic boundaries. Refer to Figure 13.15.

Vital Information from Other Chapters

A careful review of Chapter 7, Deformation: Modification of Rocks by Folding and Fracturing, will provide you with important prerequisite information. Chapter 7 emphasizes brittle and plastic styles of rock deformation. Earthquakes are thought to be the result of the elastic behavior of solid rocks, analogous to the snap-back from a rubber band when it breaks.

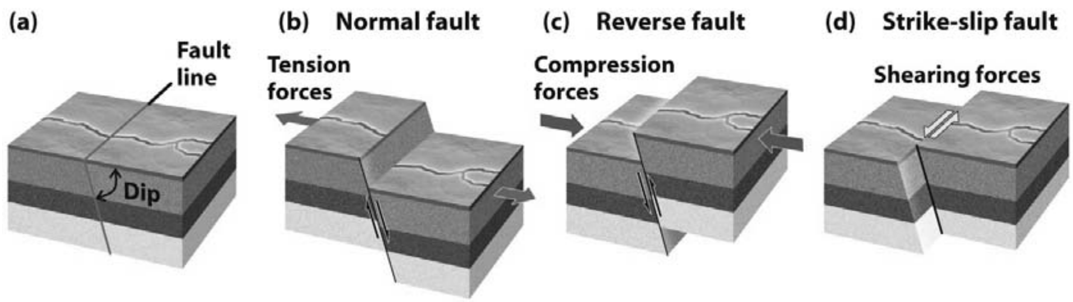


Figure 13.13. The three main types of fault mechanisms that initiate earthquakes and the stresses that cause them. (a) A fault before movement takes place; (b) Normal faulting due to tensional stress; (c) reverse faulting due to compressive stress; (d) strike-slip (lateral) faulting due to shearing stress (in this case, left-lateral).

Web Site Study Resources

http://www.whfreeman.com/understandingearth6e

During Lecture

One goal for lecture should be to leave the room with good answers to the preview questions.

- To avoid getting lost in details, keep the big picture in mind. Chapter 13 tells the story of earthquakes: how earthquake activity is measured, the seismic waves that are generated by earthquakes, and how earthquake activity is driven by plate tectonics—the location and characteristics of earthquakes is greatly influenced by the type of plate boundary.
- Focus on understanding the differences between the three kinds of seismic (P, S, surface) waves.

Note-Taking Tip: Mark possible test items

As the end of semester approaches, your instructor may mention that certain material will be covered in the end-of-semester exam. It will be helpful to have a systematic way of marking such material so that you won't miss it when you are studying your notes for the final. You could tag the material with a standard abbreviation like TQ (test question). It will obviously save time if your TQ mark is very visible. Mark it in dark, large print and put it out in the margin where your eye will easily spot it during review. Formatting tip: If you have adopted the strategy of leaving a column or the entire left page of your notebook blank for inserting visual material and special notes to yourself, put TQ tags in the blank column. See the following example.

Example of How to Mark Your Notes for Possible Test Items

Blank column or page for visual material, TQ, and other additions to your notes	Your notes
	What is an earthquake?
	ground shakes
	Seismic wave from a moving fault → Ground shakes
TQ	What are the three types of seismic waves?
(FS 13.5)	P (primary) wave
Final May 10!	S (secondary) wave
	surface waves

After Lecture

Review Notes

The perfect time to review your notes is right after lecture. The following checklist contains both general review tips and specific suggestions for this chapter.

Check Your Notes: Have you…

- ☐ identified the important points clearly? **Hint:** You should have headers in your notes for each of the questions in the **Chapter Preview.**
- ☐ filled in points that you didn't have time to record during lecture?
- ☐ marked possible test questions (TQ) in the margin?
- ☐ indicated important figures to study later?
- ☐ added visual material? Key visual material for Chapter 13 includes Figure 13.3, Elastic Rebound Theory of an Earthquake, Figure 13.7, Seismic Waves, and the figure you will develop in Practice Exercise 1 at the end of this Study Guide chapter. You can sketch simple versions of any aspect of these figures that will help you remember the ideas.
- ☐ made a comparison chart to help you review key ideas? Suggestion*:* Complete Practice Exercise 2, Characteristics of Seismic Waves. Add a copy of this exercise to your notes. It will be extremely useful for reviewing before an exam.

Intensive Study Session

Set priorities for studying this chapter. Give highest priority to activities that involve answering questions. We recommend the following strategy for learning this chapter.

- **What is an earthquake? What causes earthquakes to occur?** Be sure you have clear, accurate answers to these questions in mind before moving on to other material. It will be much more difficult to understand the discussions of seismic waves and other earthquake phenomena that are the major focus of Chapter 13 if you are at all fuzzy about earthquake basics.
- **Test yourself.** Complete Practice Exercise 1, Earthquake focus versus epicenter, and try to answer Review Questions 1, 2, 9, and 13 without looking at the answers. Then check your answers. Finally, and most important, explore the text material suggested for any questions you missed or any areas where you feel unclear about the concepts.
- **Text.** Preview the key figures in the text: Figure 13.3 (elastic rebound theory explains earthquake), Figure 13.7 (seismic waves), and Figure 13.9 (determining the epicenter of an earthquake). You have to understand these figures to complete the **Practice Exercises** and answer the **Review Questions.** Sometime before the exam, answer all seven of the exercise questions at the end of Chapter 13 in the text. These are short-answer questions and won't take long if you know the material.
- **Practice Exercises and Review Questions.** You will get the greatest return on your study time by working on Practice Exercises 1 and 2 because they will help you remember the most important ideas in the chapter. Then try

answering each of the review questions to check your understanding of the lecture. Check your answers as you go, but try to answer the question before you look at the answer.

- **Web Site Study Resources**

  http://www.whfreeman.com/understandingearth6e

  Complete the **Online Quiz**. Pay particular attention to the explanations for the answers. **Flashcards** will help you learn new terms. Complete the **Geology in Practice** exercises to learn more about earthquakes.

Exam Prep

Materials in this section are most useful during preparation for quizzes and exams. The Chapter Summary and the Practice Exercises and Review Questions should simplify your chapter review. Read the Chapter Summary to begin your session. It provides a helpful overview that should refresh your memory.

Next, work on the **Practice Exercises** and **Review Questions.** To determine how well you have mastered this chapter, complete the exercises and questions just as you would a midterm. After you answer the questions, score them. Finally, review any question you missed. Identify and correct the misconception(s) that resulted in your answering the question incorrectly.

In times of change, learners inherit the earth, while the learned find themselves beautifully equipped to deal with a world that no longer exists.

—Eric Hoffer

Chapter Summary

What is an earthquake?

- An earthquake is a shaking of the ground caused by seismic waves that emanate from a fault that moves suddenly. When the fault moves, the strain built up over years of slow deformation by tectonic forces is released in a few minutes as seismic waves.
- Elastic rebound theory explains why earthquakes occur. Over a period of time, the application of stress causes rock to slowly deform (bend) elastically until it breaks, and the rock snaps back as the fault moves. This stretching and breaking is analogous to stretching a rubber band until it breaks and snaps back to sting your hand.

What determines the depth of an earthquake?

- The focus is a point along the fault at which the earthquake initiates.
- Earthquakes occur only in brittle rock, which can break and snap back elastically. At high temperatures and confining pressures found at greater depths, rocks are ductile and do not break to generate earthquakes.
- Earthquakes occur within cold, brittle subducting oceanic lithosphere to a depth of about 700 km. Below this depth, the rock is too hot and soft to break.

Where do most earthquakes occur?

- Most but not all earthquakes occur along crust plate boundaries. Earthquakes at divergent plate boundaries are usually shallow, have lower magnitude, and are a consequence of tensional stress. Convergent plate boundaries produce shallow and deep earthquakes of low to high magnitudes and are commonly caused by compressive stress. Transform faults produce shallow to moderately deep earthquakes of low to high magnitude, usually in response to shear stress. Refer to Figure 13.15.

What governs the type of faulting that occurs in an earthquake?

- The stress applied to the lithosphere is largely determined by the type of plate boundary. Tensional, compressional, and shear stresses determine the type of fault. Refer to Figure 13.13.

What is earthquake magnitude and how is it measured?

- Earthquake magnitude is a measure of the size of the earthquake. The Richter magnitude is determined from the amplitude of the ground motion. The movement magnitude is closely related to the amount of energy radiated by the earthquake. The modified Mercalli intensity scale is a qualitative measure of the damage done by an earthquake.

What are the three types of seismic waves?

- There are three major types of seismic waves (Figure 13.7). Two types of waves travel through the Earth's interior: P (primary/compressional) waves, which move through all forms of matter and move the fastest, and S (secondary/shear waves) waves, which move through solids only and at about half the speed of P waves. The third type, surface waves, need a free surface like the Earth's surface to ripple across, like waves on the ocean. They move more slowly than the interior waves but cause most of the destruction associated with earthquakes.

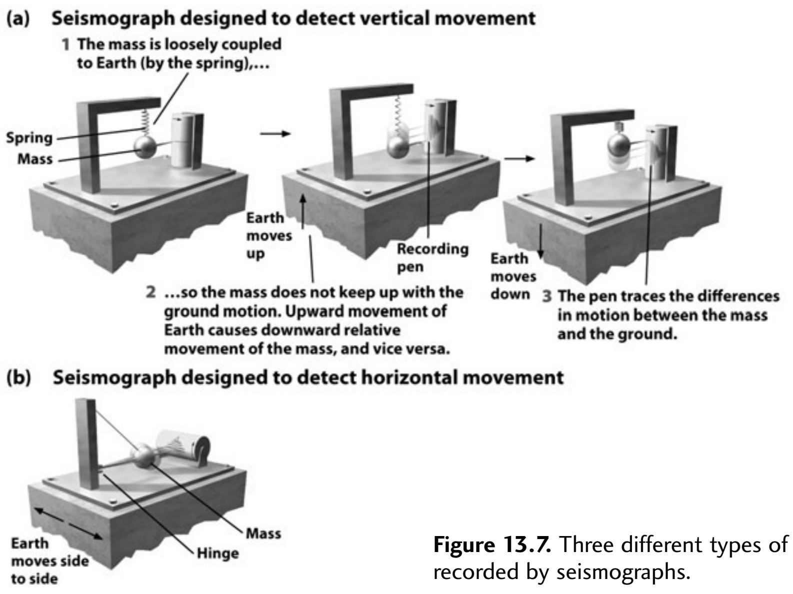


Figure 13.7. Three different types of seismic waves are recorded by seismographs.

What causes the destructiveness of earthquakes?

- The destructiveness of an earthquake does not depend on its magnitude alone. In addition to ground motion, the duration of the earthquake, avalanches, fires, liquefaction, tsunamis, proximity to population centers, and the construction design of buildings can all amplify the destructiveness of an earthquake. Refer to Earth Issues 13.3.

What can be done to mitigate the damage of earthquakes?

- The damage caused by earthquakes can be mitigated by regulating the construction design of buildings in earthquake zones; bolting houses to their foundation; securing appliances and tall furniture to walls and keeping heavy items at low levels; and having a community plan for dealing with emergencies generated by earthquakes. Geologists generate seismic risk maps to aid public authorities with their evaluations. Refer to Earth Issues 13.2.

Can scientists predict earthquakes?

- Scientists can characterize the degree of risk in a region, but they cannot consistently predict earthquakes.

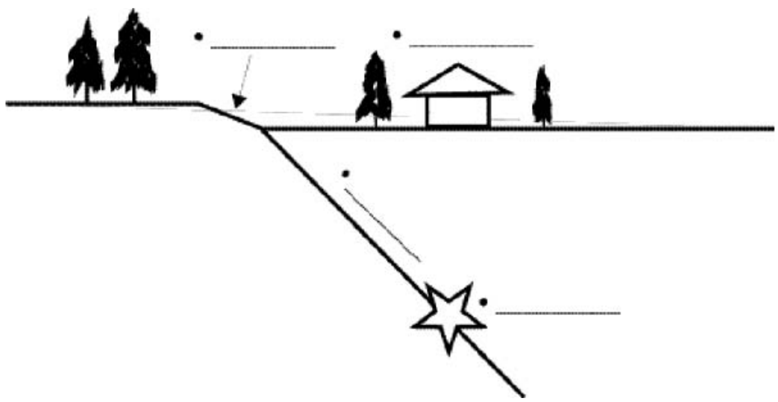
Practice Exercises

Answers and explanations are provided at the end of this Study Guide.

Exercise 1: Earthquake focus versus epicenter

Label the diagram by filling in the blanks with the following terms: *fault scarp, earthquake focus, fault zone, earthquake epicenter.* Use arrows to show the relative motion along the fault zone. The star marks the location from which fault movement propagated.

What type of fault is this? ___________________________



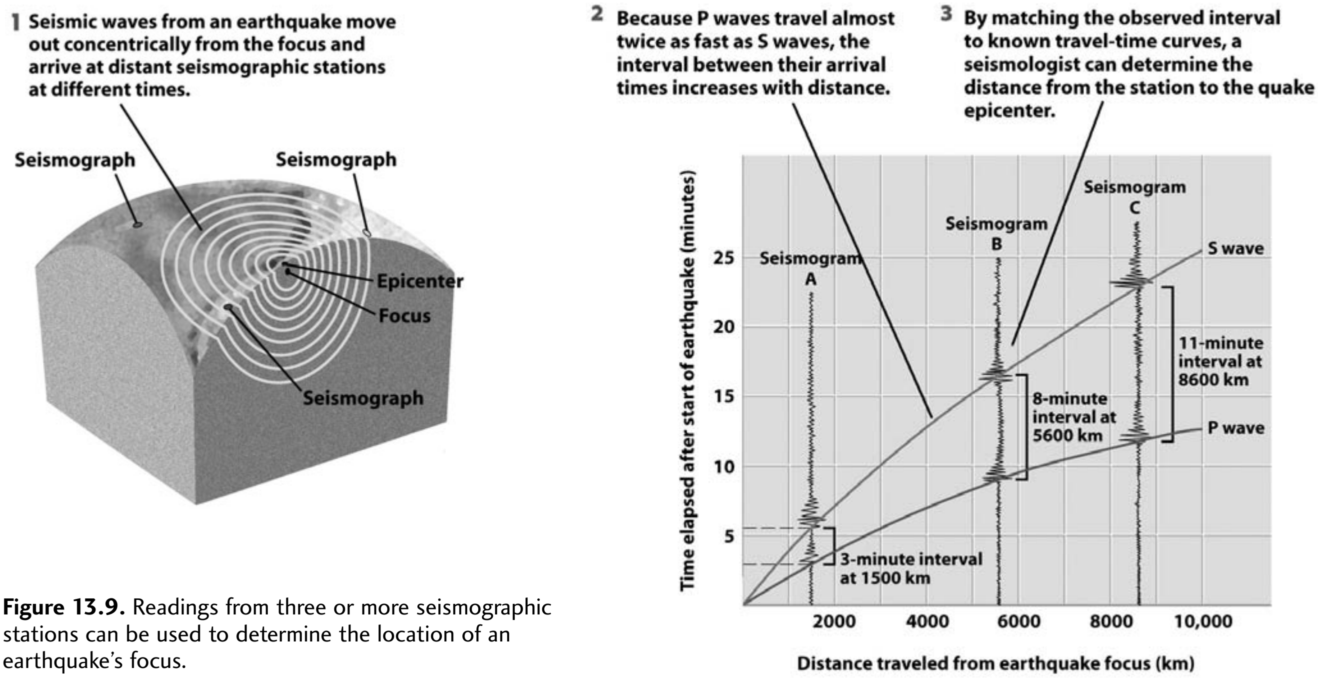


Figure 13.9. Readings from three or more seismographic stations can be used to determine the location of an earthquake's focus.

Exercise 2: Characteristics of seismic waves

Complete the table below by filling in the blank boxes. Figure 13.7 and the Seismic Waves section of the textbook will be helpful.

Characteristic	P (primary) waves	S (secondary) waves	Surface waves
Relative speed		*second fastest*	
Motion of material through which wave propagates			*rolling/elliptical and sideways motions*
Medium through which wave will propagate			*confined to the Earth's surface*
Analogy with common wave forms		*S wave propagation is difficult to visualize. It is somewhat analogous to the way cards in a deck of playing cards slide over each other as you shuffle the deck.*	

It often happens that the wave flees the place of its creation, while the water does not; like the waves made in a field of grain by the wind, where we see the waves running across the field, while the grain remains in place.

—Leonardo De Vinci

Exercise 3: Factors that amplify the damage caused by an earthquake

1. ____

   ____

2. ____

   ____

3. ____

   ____

4. ____

   ____

5. ____

   ____

Review Questions

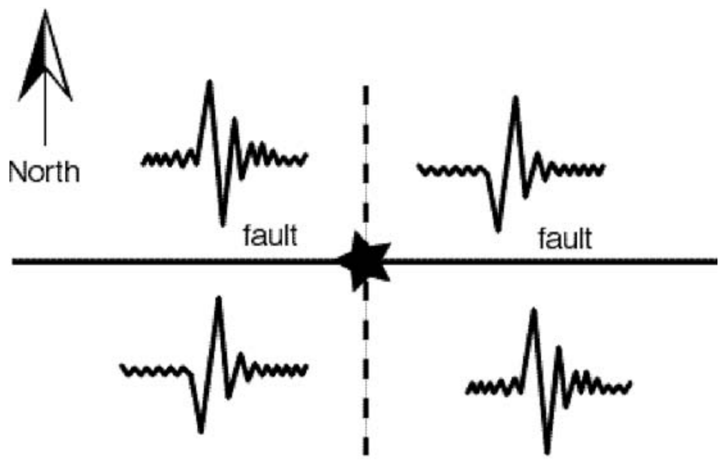
1. Elastic rebound theory says that earthquakes are produced when
   A. rocks deform plastically along a fault to produce anticlines and synclines.
   B. rocks abruptly slip past each other after an extended period during which elastic deformation is built up in the rocks.
   C. magma within the Earth abruptly begins to flow and elastically deforms the surrounding rocks.
   D. abrupt movement along faults are caused by tidal forces.
2. The actual rupture point within the crust that results in an earthquake is called the
   A. tsunami.
   B. focus.
   C. epicenter.
   D. static release.
3. The order of arrival of seismic waves at a recording station is
   A. P waves, S waves, surface waves.
   B. S waves, surface waves, P waves.
   C. P waves, surface waves, S waves.
   D. simultaneous.
4. To locate an earthquake epicenter, a minimum of _____ seismic stations is required.
   A. one
   B. two
   C. three
   D. between five and twelve, depending on the location of the earthquake
   Hint: Refer to Figure 13.9.

5. The Richter scale for earthquake magnitude measures the
   A. damage caused by the earthquake.
   B. amount of energy released by the earthquake.
   C. amount of ground motion.
   D. duration of the earthquake.
6. The ground motion generated by a Richter magnitude 8 earthquake is a factor of __________ times greater than a Richter 4 earthquake.
   A. 2
   B. 100
   C. 1000
   D. 10,000
7. Primary seismic waves (P waves), like sound waves,
   A. travel only through solid material.
   B. travel only through liquids and gas.
   C. travel through solid, liquid, and gas.
   D. are the slowest seismic waves.
8. Secondary seismic waves (S waves)
   A. travel parallel to P waves (parallel waves).
   B. travel only through solid material.
   C. travel through solid, liquid, and gas.
   D. are the fastest seismic waves.
9. A significant finding that supports the theory of plate tectonics is that most earthquakes occur
   A. randomly in the middle of tectonic plates.
   B. at all active tectonic plate boundaries.
   C. only at tectonic plate boundaries that move toward each other.
   D. only at tectonic plate boundaries that slide past each other.
10. You just started a job as a county planner in Colorado when the Board of Supervisors mandates earthquake risk assessment. Your first task is to assess the potential for a major seismic event in an area that has experienced only a few minor earthquakes. You decide to
   A. install a state-of-the-art seismic recording station to monitor earthquake activity.
   B. develop a seismic risk map showing the likelihood of an earthquake based on the number that have occurred in the past.
   C. develop an earthquake protection plan with local and state officials.
   D. investigate the records for tsunamis.
11. Given four structures all built identically, the one built on ___________ would sustain the MOST damage during an earthquake when all four are located the same distance from its epicenter.
   A. a hillside composed of unfractured granite
   B. a quartz-cemented sandstone formation
   C. solid unfractured granite bedrock
   D. a water-saturated stream delta

   Hint: Refer to the section How Earthquakes Cause Their Damage in your textbook.
12. Your seismograph has just recorded an earthquake. You are curious whether the earthquake occurred in North America or somewhere else in the world. Given the arrival time of 5 minutes for the first P waves and 10 minutes for the first S waves, you determine that the approximate distance between you and the earthquake is ___________ kilometers.
   A. 100
   B. 1000
   C. 3000
   D. 7000

   Hint: Use the graph in Figure 13.9 to make the estimate.

13. Which of the following features does NOT characterize a divergent plate boundary?
    A. shallow-focus earthquakes
    B. basalt eruptions
    C. deep-focus earthquakes
    D. a rift valley
    Hint: Refer to Figure 13.15.
14. Which of the following states has the lowest potential for seismic hazard?
    A. Washington
    B. Utah
    C. Texas
    D. New York
    Hint: Refer to Figure 13.21.
15. The first motions of an earthquake as recorded at four different stations are displayed on the strike-slip fault shown below. Using this first motion data and Figure 13.14, determine the direction of relative motion along the fault at the time of the earthquake.



Bird's-eye view of a fault zone with the first motion data for P waves arriving at four seismograph stations during an earthquake. The star marks the epicenter. The dashed line is a north–south reference line plotted perpendicular to the fault (solid line).

    A. The north side moved east (right) and south side moved west (left).
    B. The north side moved west (left) and south side moved east (right).
    C. The north side moved down and south side moved up.
    D. The north side moved up and south side moved down.
16. What type of fault produced the first motion shown in question 15? __________
    Hint: Match the illustrations in Figure 13.13 and 13.14 to determine the type of fault.

CHAPTER 14

Exploring Earth's Interior

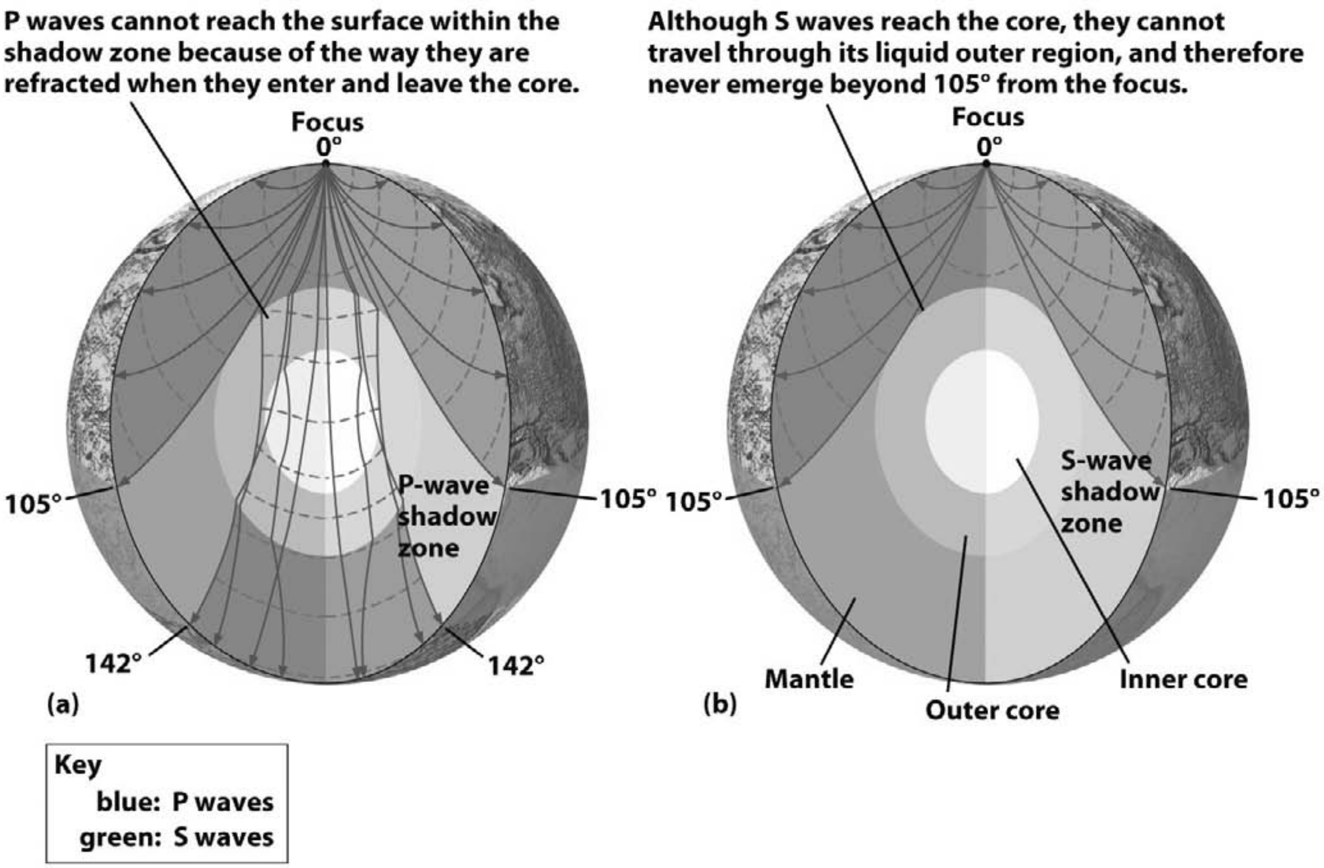


Figure 14.2. Earth's core creates P-wave and S-wave shadow zones.

Before Lecture

Previewing will greatly increase your understanding of the lecture. For an efficient preview use the following questions.

Chapter Preview

- **What do seismic waves reveal about the Earth's interior?**
  Brief answer: Seismic waves reveal that the Earth has a concentrically zoned internal structure. The felsic crust lies on a denser ultramafic mantle composed mostly of peridotite. The crust and upper mantle make up the rigid lithosphere. Beneath the lithosphere lies the asthenosphere, the weak layer of the mantle across which the lithosphere slides in plate tectonics. The liquid outer core and solid inner core are mostly iron. Refer to Figures 1.11 and 14.8.
- **What has seismic tomography revealed about structures in the mantle?**
  Tomographic images show how tectonic plates vary from very thin under the mid-ocean ridges to very thick under continental cratons. Many features of mantle convection are also revealed. Refer to Figure 14.11.
- **How hot does it get in Earth's Interior?**
  Refer to Figure 14.10.
- **What does Earth's gravity field and isostatic rebound tell us about the interior?**
  Brief answer: The observed gravity field is in agreement with the pattern of mantle convection inferred from seismic tomography. Measuring the rate of post-glacial isostatic rebound provides information on the viscosity of the mantle and how it affects rates of uplift and subsidence of the buoyant lithosphere. Refer to Earth Issues 14.1.
- **What does Earth's magnetic field tell us about the fluid outer core?**
  Brief answer: The Earth's magnetic field is produced by convective motions of electrically conducting iron-rich fluid in the outer core.
- **What is paleomagnetism and what is its importance?**
  Brief answer: The Earth's magnetic field flips back and forth over geologic time. Preserved in some rocks is a record of past changes in the orientation of Earth's magnetic field. Refer to Figure 14.17.

Vital Information from Other Chapters

It is very important to review the information on seismic waves presented in the text section Studying Earthquakes at the beginning of Chapter 13. Pay particular attention to the section Seismic Waves and Figure 13.7, and be sure you understand the distinctions between P waves and S waves. A quick review of models for mantle convection will also be helpful. The key information is covered in Figures 1.15, 2.18, and 12.27. Finally, take another look at Figure 2.12, which was your first exposure to paleomagnetism in the text.

During Lecture

One goal for lecture should be to leave the room with good answers to the preview questions.

- To avoid getting lost in details, keep the big picture in mind: Chapter 14 tells the story of the interior of the Earth, its structure and composition, and how Earth's interior supplies heat energy to drive geological processes. Key points:
  - Earth's interior is a concentrically zoned structure.
  - Continents float on the mantle.
  - Mantle behaves like a viscous fluid.
  - P and S waves reveal a liquid outer core and a solid inner core.
  - Heat transfer occurs via convection.
  - Earth's magnetic field is best understood as a geodynamo: Convective movement (driven by Earth's internal heat) generates an electromagnetic field.

- Focus on understanding Figures 14.2, 14.7, 14.8, and 14.10. If you have looked at them before coming to lecture, it will be easy to follow the lecture: You can simply annotate the figures with important new material provided by your instructor and underline material in the captions.

Note-Taking Tip

We all have moments when we don't understand a point being made in lecture. When momentarily confused, continue taking notes. Hopefully, the necessary insight will come to you. If it does not, the notes you take will provide a clue to what you need to investigate further in your text or in a conversation with your instructor.

After Lecture

Review Notes

Check Your Notes: Have you…

☐ annotated figures in the text with important material discussed by your instructor? Figures 14.2, 14.7, 14.8, and 14.10 are the important figures in Chapter 14.

☐ added visual material? Since this chapter depends heavily on material from Chapters 1, 2, and 13, it may be useful to quickly sketch key ideas about P and S waves and mantle convection in your notes.

☐ added a brief big picture overview of this lecture in your own words?

Intensive Study Session

Set priorities for studying this chapter. Give highest priority to activities that involve answering questions. We recommend the following strategy for learning this chapter.

- **Text.** Study figures 14.2, 14.7, 14.8, 14.10, 14.11, 14.14, and 14.17, and Earth Issues 14.2. You have to understand these figures to answer the **Review Questions.**

  Some time before your next exam complete the text exercises at the end of the chapter. These are short-answer questions and won't take long if you know the material. Notice that helpful animations are provided on the Web site for some of the chapter exercises.

- **Practice Exercises.** Complete Exercises 1 and 2. Working on these exercises will help you remember the most important ideas in the chapter.

- **Review Questions.** Answer each of the review questions to check your understanding of the lecture. Check your answers as you go, but do try to answer the question before you look at the answer. Notice the test taking-tips that are interspersed with these questions. They are designed to help you do better on your next exam.

- **Web Site Study Resources**
  http://www.whfreeman.com/understandingearth6e

  Complete the **Online Quiz.** Pay particular attention to the explanations for the answers. Did you know that Cleopatra adored peridot, a gemstone from the upper mantle? Check out **Geology in Practice** to find out more about "Cleopatra's emeralds" (peridot) and the composition of the upper ultramafic mantle. **Flashcards** will help you review the new terminology in this chapter.

Exam Prep

Materials in this section are most useful during preparation for exams. The **Chapter Summary** and the **Practice Exercises** and **Review Questions** should simplify your chapter review. Read the **Chapter Summary** to begin your session. It provides a helpful overview that should refresh your memory.

Next, work on the **Practice Exercises** and **Review Questions.** Complete the exercises and questions just as you would for an exam, to see how well you have mastered this chapter. After you answer the questions, score them. Finally, and most important, review each question you missed. Identify and correct the misconception(s) that resulted in your answering the question incorrectly.

Chapter Summary

What do seismic waves reveal about the layering of Earth's crust and mantle?

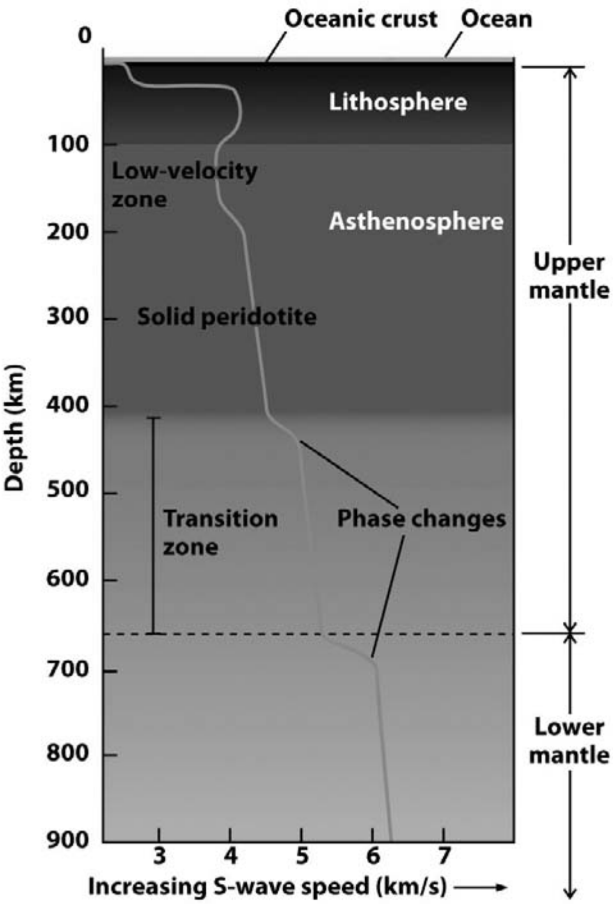


Figure 14.8. The structure of the mantle showing the S-wave velocity to a depth of 900 km. Changes in velocity mark the strong lithosphere, the weak asthenosphere, and two zones in which changes occur because increasing pressure forces a rearrangement of the atoms into denser and more compact crystalline structures.

- Seismic waves reveal that the Earth has a concentrically zoned internal structure. Felsic continental and mafic ocean crusts lie on a denser ultramafic mantle consisting of iron-rich silicates, like peridotite. Refer to Figure 14.8.
- The Moho or Mohorovičić discontinuity in seismic wave velocities marks the boundary between the crust and the mantle. Refer to Figures 1.11 and 14.7.
- Earth's tectonic plates are large fragments of the lithosphere, which includes the crust and the uppermost, rigid mantle. Below the lithosphere in the upper mantle is a weak (soft) zone called the asthenosphere. Refer to Figure 14.8.
- Abrupt increases in seismic wave velocities coupled with laboratory studies on high-pressure minerals suggest that there are zones at progressively greater depths within the mantle where the crystal structures of minerals collapse (change phase) under the intense pressure to form more compact atomic structures and therefore different minerals.

What do seismic waves reveal about the layering of Earth's core?

- P-wave and S-wave shadow zones reveal a liquid outer core and a solid inner core. Refer to Figure 14.2.
- P-wave velocities in the core, the natural abundance of iron in nature, the existence of iron–nickel meteorites, the Earth's strong magnetic field, and the need for a very dense core to account for the overall mass of the Earth all support an iron–nickel composition for the Earth's core.

What has seismic tomography revealed about structures in the mantle?

- These CAT scan–like images of the Earth's interior reveal how tectonic plates vary from very thin under the mid-ocean ridges to very thick under continental cratons. Also revealed are features associated with mantle convection, such as sinking slabs of lithosphere and superplumes. Refer to Figure 14.11.

How hot does it get in Earth's Interior?

- Within normal continental crust, temperature increases at a rate of 20º to 30º C per kilometer. The rate of temperature increase slows way down in the mantle and core. The most rapid change in temperature (steepest geothermal gradient) occurs in the outermost layer of our planet. This is not surprising, if you consider how rapidly temperature changes from the outside to the inside of a kitchen oven door. Refer to Figure 14.10.
- Seismic and laboratory studies suggest that the temperature in the outer liquid core is higher than 3000ºC, and at the Earth's center the temperature may reach 6000º to 8000ºC. Refer to Figure 14.10.

What does Earth's gravity and isostatic rebound tell us about the interior?

- Measuring the rate of postglacial isostatic rebound provides information on the viscosity of the mantle and how it affects rates of uplift and subsidence of the buoyant lithosphere. Refer to Earth Issues 14.1.
- The observed gravity field is in agreement with the pattern of mantle convection inferred from seismic tomography. Earth Issues 14.1.

What does Earth's magnetic field tell us about the fluid outer core?

- Earth's magnetic field basically looks like a dipolar bar magnet. Refer to Figure 1.16.
- A geodynamo explains how Earth's magnetic field is generated. Rapid convection in the molten outer core is thought to stir up electrical currents in the conducting iron to create the major component of the magnetic field.
- The magnetic field changes strength, position, and polarity over time. There is a nondipole component. Both the dipole and nondipole components exhibit secular variations over time spans of decades. Reversals in polarity also occur over time spans of thousands of years. Refer to Figure 14.17.

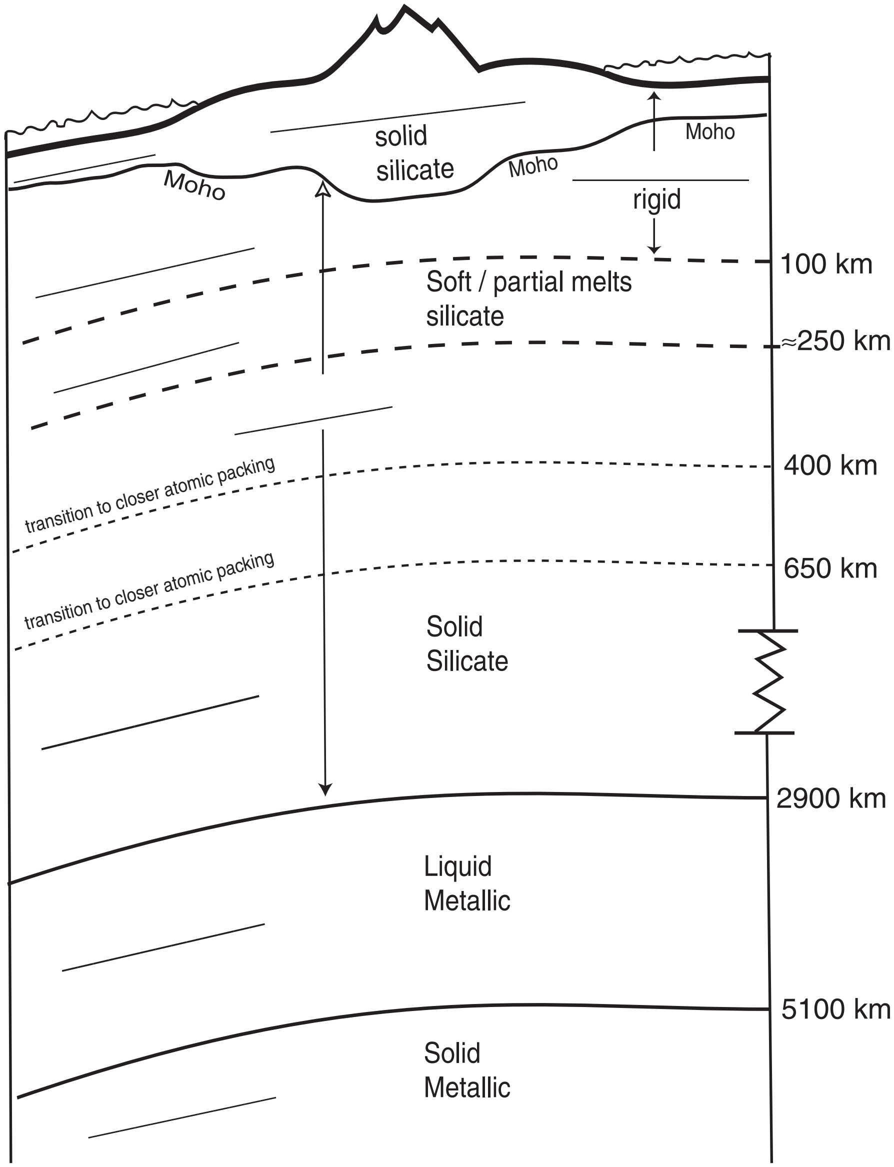
What is paleomagnetism and what is its importance?

- Preserved in some rocks is a clear record of past changes in the orientation of Earth's magnetic field. The chronology of magnetic field reversals has been worked out so that the direction of remnant magnetization of a rock formation is often an indicator of its stratigraphic age. Refer to Figures 14.16 and 14.17. **Note:** The pattern of magnetic anomalies produced by paleomagnetic reversals recorded by ocean floor rock provided important evidence for seafloor spreading. Refer to Figure 2.12.

Practice Exercises

Exercise 1: The Earth's interior layers

It is important to understand Earth's layered composition. Label the Earth layers in the following figure, taking special note of the information about the composition of each. Refer to Figures 1.11, 14.7, and 14.8 and the accompanying text section The Layering and Composition of the Interior.



Exercise 2: Characteristics of Earth's internal layers

Complete the table by filling in the blanks and completing the sentences. Shaded boxes remain blank. Refer to text and figures in Chapters 1, 4, and 14. Key figures include 1.9, 1.11, 1.12, 4.2, 4.13, 14.8, and 14.10.

Characteristics of Earth's Internal Layers

Layer	Volume (% of total)	Mass (% of total)	Density (g/cm^3)	Physical state	Composition	Observations and evidence that support the characteristics of the layer
Crust	0.60	0.42				
Continental crust	0.44	0.25	≈ 2.7	Solid		Very heterogeneous. 40–65 km thick. Formed at convergent boundaries by orogenic processes.
Ocean crust	0.16	0.17	≈ 3.0			Very homogeneous. About 10 km thick. Formed at ________________________ from __________________ mantle rocks.
Mantle	83.02	67.77	3.3–5.7			
Mantle lithosphere						Crust and mantle lithosphere make up Earth's _____________. Thickness ranges from 0 km at spreading centers to 200 km beneath continents. S-wave velocities __________ through it.
Asthenosphere						Weak zone. A ______________ melting. Reaches close to the surface at spreading centers and deepens under older seafloor. S-waves ________________ and are partially absorbed.
Lower mantle						Abrupt __________ in S-wave velocities at 400- and ___ -km mark changes in mantle structure—collapse of the ________________ of minerals.
Core		31.79				
Outer core	15.68		9.9–12.2			P waves slow down; S waves are ____________ ____________. Iron–nickel composition is consistent with bulk density of the _________.
Inner core	0.70		12.6–13.0			P waves suddenly _____________ at 5100 km. S waves are _____________through inner core. Composition also consistent with the natural abundance of iron and meteorites.

Exercise 3: Evidence for the asthenosphere and its significance

A. Briefly discuss one line of evidence supporting the presence of an asthenosphere in the upper mantle.
B. What is the significance of the asthenosphere to plate tectonic theory?
Hint: Information in both Chapters 2 and 14 will help you complete this assignment.

Review Questions

1. Earth's core has a radius that is about __________ of the Earth's radius.
   A. 1/8
   B. 1/4
   C. 1/2
   D. 3/4
   Hint: Refer to Figure 14.7.
2. The thickness of Earth's tectonic plates is
   A. the same on the continents as under the oceans.
   B. at its thinnest under the oceans.
   C. at its thinnest in the continents.
   D. completely unknown.
   Hint: Refer to Figure 1.11 and 14.8.
3. The likely composition of the upper mantle is
   A. felsic.
   B. mafic.
   C. ultramafic.
   D. carbon (diamonds).
4. Which of the following constitutes the rigid, outer layer of Earth's tectonic plates?
   A. asthenosphere
   B. lithosphere
   C. crust
   D. mantle
5. Continental crust has an overall composition corresponding closely to that of
   A. ultramafic.
   B. mafic.
   C. felsic to intermediate.
   D. peridotite.
6. The lithosphere is a __________ layer, as opposed to the asthenosphere.
   A. plastic
   B. fluid
   C. weak
   D. rigid
7. The inference that Earth's outer core is liquid is supported by the observation that
   A. P waves do not pass through it.
   B. S waves do not pass through it.
   C. P waves travel more rapidly through it.
   D. S waves travel more slowly through it.
8. The highest density component of the Earth is
   A. the mantle.
   B. continental crust.
   C. the core.
   D. the whole Earth.
9. Earth's north magnetic pole is located
   A. at the north geographic pole.
   B. in Alaska.
   C. between Greenland and Baffin Island.
   D. in China.
   Hint: Refer to Figure 14.12 and an atlas.
10. The Earth's magnetic field is thought to be generated by
    A. permanent magnetism of minerals within the mantle.
    B. permanent magnetism of the solid iron-rich inner core.
    C. electrical currents generated by movement of the liquid outer core.
    D. electrical currents generated by convection in the asthenosphere

11. As opposed to the lithosphere, the asthenosphere is a ________ layer.
    A. brittle
    B. weak
    C. molten
    D. rigid
12. Mineral grains in sediments become magnetized by the Earth's magnetic field when
    A. they are struck a sharp blow by a meteorite.
    B. iron-rich minerals align parallel to the Earth's magnetic field.
    C. the Earth's magnetic field reverses itself.
    D. electricity from lightning strikes passes through the lava beds.

    Hint: Refer to Figure 14.16.
13. Which layer of the Earth experiences the most rapid increase in temperature with increasing depth?
    A. lithosphere
    B. asthenosphere
    C. mantle
    D. liquid outer core

    Hint: Refer to Figure 14.10.
14. On which boundary in the Earth's interior does the greatest change in composition occur?
    A. lithosphere–asthenosphere boundary
    B. crust–mantle boundary
    C. mantle–core boundary
    D. boundary between the outer and inner core

Test-Taking Tips: Test taking and learning style

Knowing your learning style can help during exams. Consider the following.

Visual Learners

- ☐ If you are a visual learner you probably pay better attention to directions that are written out (visual) than to spoken directions. Rely on written directions when they are available. If your exam proctor gives the directions verbally without a visual you must compensate. Make yourself listen and don't hesitate to ask as many questions as you need to to get the directions straight.
- ☐ When you get stuck on an item, activate your visual memory. Close your eyes and picture flow charts, pictures, field experiences or even lines of text.

Auditory Learners

- ☐ You probably pay better attention to directions that are spoken than to directions that are written out. Rely on spoken directions when they are available. If the directions are on a slide, compensate! Make yourself read them.
- ☐ Repeat written directions quietly to yourself (moving your lips is often enough).
- ☐ When you get stuck, remember your lecturer's voice covering this section.

Kinesthetic Learners

- ☐ You probably do best with directions that allow you to work an example. Unfortunately, it is a rare classroom exam that provides examples or samples as part of the directions. So you will need to make up you own. Take a minute to translate the directions into something you can do, or ask the instructor for a sample or example. Be sure to interact. Remember that you learn by doing.

There are a variety of things kinesthetic learners find helpful when they get stuck on a test item.

- ☐ When you get stuck, move in your chair or tap your foot, to trigger memory.
- ☐ Feel yourself doing a lab procedure.
- ☐ Sketch a flowchart to unlock memory of a process.
- ☐ Stuck on a geology problem? Sketching what is being described (what is "given" in the problem) may unlock your memory and get you started.

15. The crust is typically thickest beneath
    A. high mountain ranges and plateaus on the continents.
    B. ocean-spreading centers.
    C. continental interiors like the Great Plains in North America.
    D. passive margins of continents where topography is very flat.
    Hint: Refer to Figure 1.11.
16. Significant increases in S-wave velocity at about 400 and 650 kilometers depth are explained by
    A. changes in the chemical composition of the mantle.
    B. a collapse of the crystal structures to more close by packed forms.
    C. changes in the degree of partial melting within the mantle.
    D. rapid increases in temperature.
    Hint: Refer to Figure 14.8.
17. The Earth's core is inferred to be composed of mostly iron because
    A. iron is naturally very abundant.
    B. most meteorites representing the interstellar matter from which the planets formed are rich in iron.
    C. iron is very dense, so its presence in the core would account for the Earth's average density.
    D. all of the above.
18. Without any knowledge of what seismic waves tell us about the Earth's interior, why is it unreasonable to assume that a large portion of the lower mantle is molten?
    A. Actually, it could be molten. We just don't see evidence for it because silicate magmas are trapped within the Earth due to the confining pressures.
    B. Direct measurements show that the temperature at the core/mantle boundary is not high enough to melt the lower mantle.
    C. The magnetic field strength would be greatly reduced if more of the Earth's interior was molten.
    D. Silicate magmas are less dense and would rise to the surface, so we should observe widespread volcanic activity across the Earth's surface. The molten iron-rich outer core is too dense to rise.
19. As rocks experience increased pressure with depth, P waves in general will _______ as they migrate through them.
    A. travel faster
    B. travel slower
    C. travel at the same velocity
    D. rapidly die out
20. When a reversal of the Earth's magnetic field occurs,
    A. the sense of rotation of the Earth is also reversed.
    B. the Earth flips over in its orbit.
    C. the magnetic polarity of the Earth reverses so that the north end of a magnetic compass needle points toward the south geographic pole.
    D. almost all the igneous sedimentary rocks of the ocean floor reverses in magnetization to match the new orientation of the magnetic field.
21. The Moho, or Mohorovičić discontinuity between the crust and the mantle, was first detected from
    A. the abrupt decrease in seismic velocities as they cross the discontinuity.
    B. the abrupt increase in seismic velocities as they cross the discontinuity.
    C. the S-wave shadow zone through which S waves do not pass.
    D. the observation that no earthquakes occur below the Moho.

22. Supporting evidence for heat transfer by convection within the mantle comes from
    A. tomography and Earth's gravity field.
    B. the bulk density of the Earth.
    C. postglacial isostatic rebound.
    D. Earth's magnet field.

23. The "Cretaceous quiet zone" is a name for a(n)
    A. period when dinosaurs were very sedate.
    B. time when plate motions slowed way down.
    C. break in volcanic activity on Earth due to a lack of mantle superplume activity.
    D. especially long period of normal polarity of Earth's magnetic field.
    Hint: Refer to Figure 14.17.

24. The P-wave shadow zone is caused by the way the Earth's core
    A. refracts the seismic waves.
    B. reflects the seismic waves.
    C. absorbs the P waves.
    D. blocks the P waves.

25. As the lithosphere cools slowly by the conduction of heat, it becomes
    A. less dense and rises.
    B. soft and weak.
    C. denser and rises.
    D. denser and subsides.
    Hint: Refer to Figure 14.9.

26. Earth's tectonic plates are located in the
    A. core, where their movement is driven by intense heat and pressure.
    B. mantle, where their movement is driven by convection.
    C. lithosphere, where their movement is driven by gravity.
    D. atmosphere, where their movement is driven by the prevailing westerlies.

CHAPTER 15

The Climate System

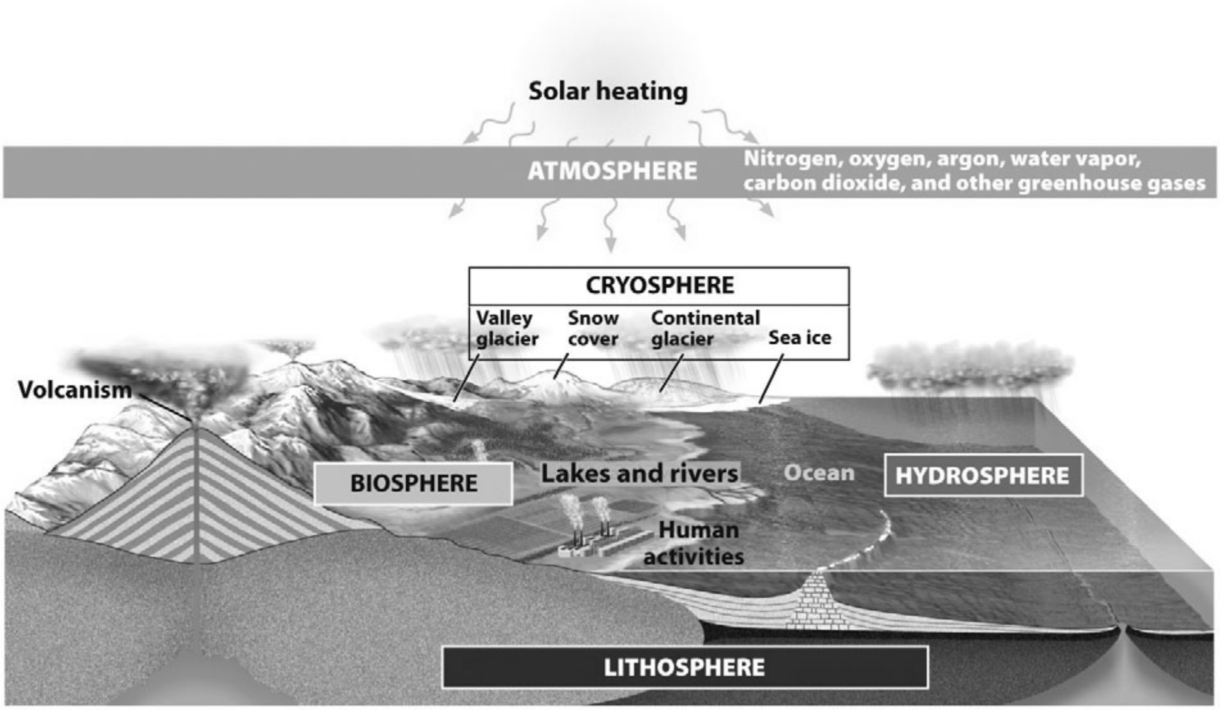


Figure 15.1. Earth's climate system involves complex interactions among many components.

Before Lecture

Before you attend lecture, spend some time previewing the chapter. For an efficient preview, use the **Chapter Preview** questions.

Chapter Preview

- **What is the climate system?**
  Brief answer: The major components of the climate system are the atmosphere, hydrosphere, lithosphere, and biosphere. It is important to understand how these systems interact with each other via feedback mechanisms. Refer to Figure 15.1.
- **What is the greenhouse effect?**
  Brief answer: Carbon dioxide and other trace atmospheric gases are transparent to sunlight but absorb heat (infrared radiation), which warms Earth's surface environments. Refer to Figure 15.7.
- **How has Earth's climate changed over time?**
  Brief answer: The largest changes are the 100,000-year glacial cycles. But there are also significant short-term climate cycles that average 1,000 and 10,000 years. Refer to Figures 15.10 and 15.11. There are also random climate events, like El Niño. Note that we are currently living in an exceptional time, the most prolonged stable warm period in the last 400,000 years.
- **What is the carbon cycle?**
  Brief answer: Geochemical cycles trace the flux of Earth's elements like carbon from one reservoir to another. The carbon cycle describes the movement of carbon between four main reservoirs: (1) the atmosphere; (2) the global ocean, including marine organisms; (3) the land surface, including terrestrial animals, plants, and soils; and (4) the deeper lithosphere. The carbon cycle is particularly important because of its strong link to life processes and climate change. Refer to Figure 15.16.
- **How can internal geologic processes cause climate change?**
  Brief answer: Over the short term of a few years, sulfuric acid aerosols and volcanic ash ejected from large volcanic eruptions can absorb solar radiation before it reaches the lower atmosphere and thus decrease global temperatures. Over the long term of millions of years, plate tectonic movements can shift continents over the poles, stabilizing polar ice caps; block or open gateways to ocean currents; and cause uplift, which alters weathering systems and rates of chemical weathering that draw down atmospheric carbon dioxide.
- **Was the twentieth-century warming caused by human activities?**
  Brief answer: Global warming of about 0.6°C during the twentieth century correlates with the significant rise in atmospheric CO_2 and other greenhouse gases caused by fossil-fuel burning, deforestation, and other human activities.

Vital Information from Other Chapters

Review the section Classification of Chemical and Biological Sediments and Sedimentary Rocks in Chapter 5. Also preview the section in Chapter 21 that discusses climate change during the last series of ice ages.

The geobiological processes you learned in Chapter 11 play a significant role in the climate system. Carbon is removed from the atmosphere via the biochemical process of photosynthesis (Figure 11.3) and returned to the atmosphere via another biochemical process, animal respiration. Oxygen makes up 21 percent of Earth's atmosphere. Oxygen is supplied and maintained homeostatically by living organisms via the metabolic process of photosynthesis (see Figure 11.3 and the section Metabolism in Chapter 11). Microbes, such as cyanobacteria, produced Earth's original oxygenated atmosphere (see the section Origin of Earth's Oxygenated Atmosphere in Chapter 11). Finally, methane-producing microbes contributed the methane supplies that "burped" out of sediments, triggering global warming and an extinction event that marks the Paleocene–Eocene boundary.

As you read Chapter 15, keep in mind that the climate system is composed of many subsystems. Climate is a tapestry of complex and fascinating interactions.

During Lecture

- Keep the big picture in mind as you take notes. Chapter 15 tells the story of Earth's climate system and how global climate results from interactions between four Earth system components: atmosphere, hydrosphere, biosphere, and lithosphere. Human activities are becoming an increasingly important factor influencing how Earth systems function. Focus on understanding the components, fluxes, and feedbacks in each system.
- Because of the social importance of global climate, there may be opportunities for discussion/debate activities. Previewing the chapter will prepare you to take part in these activities.

After Lecture

Review Notes

The perfect time to review your notes is right after lecture. The following checklist contains both general review tips and specific suggestions for this chapter.

Check Your Notes: Have you…

☐ written a summary of what is covered in this lecture? Your summary should say something significant about how human activities change the global environment and the potential for global warming during your lifetime. Suggestion: Write a brief position paper on a Chapter 15 issue that concerns you. Ask yourself what Earth system information in Chapter 15 is relevant to the issue. Try to develop a position that is reasonable and consistant with existing science.

☐ added important visual material to your notes? Suggestions: Draw overview sketches of the climate system (Figure 15.1) and the carbon cycle (Figures 15.16 and 15.17). To understand how climate changes over time, pay particular attention to the different time scales (years, decades, centuries, thousands of years) used in Figures 15.11 and 15.19.

Intensive Study Session

Set priorities for studying this chapter. Give highest priority to activities that involve answering questions. We recommend the following strategy for learning this chapter.

- **Text.** Preview the key figures in Chapter 15, Figure 15.7 (the greenhouse effect) and Figure 15.16 (the carbon cycle). You have to understand these figures to answer the **Review Questions**. Figures 15.2, 15.3, 15.12, 15.15, and 15.19 also contain important information, relevant to Chapters 15, 21, and 23.

Sometime before your exam, answer the exercises at the end of the chapter. These are short-answer questions and won't take long if you know the material. Focus on Exercises 1 and 5 and Thought Questions 3, 5, and 7.

- **Practice Exercises.** Complete Practice Exercises 1 and 2. They will help you remember the most important ideas in the chapter.
- **Review Questions.** Try answering each of the review questions to check your understanding of the lecture. Check your answers as you go, but do try to answer the question before you look at the answer.
- **Web Site Study Resources**
  http://www.whfreeman.com/understandingearth6e

  Complete the **Online Quiz.** Pay particular attention to the explanations for the answers.

  Did you know that it takes about 2 pounds of coal to produce the energy for you to copy a megabyte of music off the Internet and that this releases 4 pounds of carbon dioxide into the atmosphere? The **Geology in Practice** exercises for Chapter 15 explore how this is possible.

Exam Prep

Materials in this section are most useful during your preparation for exams. The **Chapter Summary** and the **Practice Exercises** and **Review Questions** should simplify your chapter review. Read the **Chapter Summary** to begin your session. It provides a helpful overview that should refresh your memory.

Next, work on the **Practice Exercises** and **Review Questions**. Complete the exercises and questions just as you would for an exam, to see how well you have mastered this chapter. After you answer the questions, score them. Finally, and most important, review each question you missed. Identify and correct the misconception(s) that resulted in your answering the question incorrectly.

Chapter Summary

What is the climate system?

- Major components of the Earth's climate system are the atmosphere, hydrosphere, lithosphere, and biosphere. Refer to Figure 15.1.
- Earth's surface would be much colder without the presence of greenhouse gases like water and carbon dioxide in the atmosphere.
- Ocean currents play a major role in distributing heat across the Earth because water has a very high capacity for storing heat.
- Topography affects climate by influencing the flow of our atmosphere.
- Volcanic eruptions affect climate by changing the composition of the atmospheric gases and by adding dust and haze that increase the albedo of the atmosphere.
- Various factors may exert a positive or negative feedback on the climate system. In some cases, feedback mechanisms can act to stabilize Earth's climate, and in other cases they may destabilize it by amplifying climate change.

What is the greenhouse effect?

- Carbon dioxide and other trace atmospheric gases act like the glass windows in a greenhouse. They are transparent to sunlight but absorb heat (infrared radiation), which warms Earth's surface environments. Refer to Figure 15.7.

How has Earth's climate changed over time?

- The largest changes are the 100,000-year glacial cycles.

- The alternation between glacial and interglacial ages observed during the Pleistocene epoch is explained best by the Milankovitch cycles. Refer to Figure 15.12.
- There are also significant short-term climate cycles that average 1,000 and 10,000 years. Refer to Figures 15.11 and 15.19, and note the regularity of these cycles. Note also that we are currently living in the most prolonged stable warm period in the last 400,000 years.
- Short-term variations of climate are associated with El Niño events and large volcanic eruptions.

What are geochemical cycles and how can they impact climate?

- Geochemical cycles trace the flux of Earth's elements, like carbon, from one reservoir to another.
- Understanding the carbon and calcium cycles is important because of their strong link to life processes, climate, and the greenhouse effect. Refer to Figures 15.15 and 15.16.
- The release of carbon dioxide by the burning of fossil fuels is having a significant impact on the flux of carbon from the lithosphere into the atmosphere. Refer to Figure 15.17.

What caused the twentieth-century warming?

- Between the end of the nineteenth century and the beginning of the twenty-first, the mean surface temperature rose by about 0.6°C. Refer to Figure 15.19.
- From a variety of climate indicators, scientists have concluded that climate during the thousand years that preceded the twentieth century experienced an irregular but steady global cooling of about 0.2°C and the maximum fluctuation in mean temperatures during any one of the nine previous centuries was probably less than 0.3°C.
- Climate models that include changes in atmospheric greenhouse gases as a factor match the global temperature rise and also reproduce the pattern of temperature change both geographically and with altitude in the atmosphere.

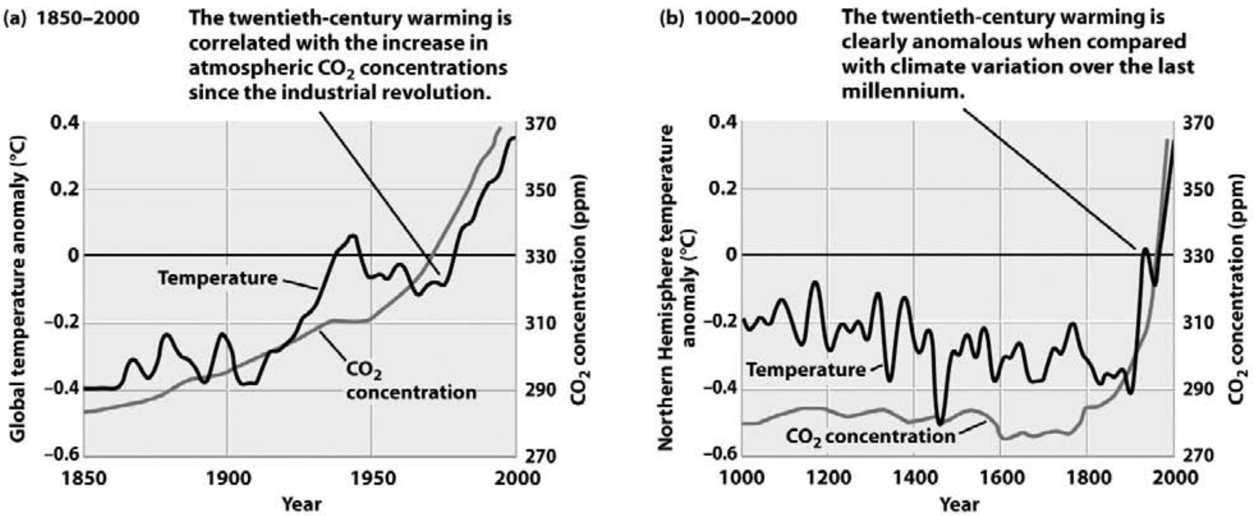


Figure 15.19. A comparison of Earth's average annual surface temperature with atmospheric CO_2 concentrations shows recent warming trend correlates with the increase in CO_2.

It is virtually impossible to change one thing in a complex system without affecting other parts of the system, often in as yet unpredictable ways.

—ANONYMOUS

How hard to realize that every camp of men or beast has this glorious starry firmament for a roof! In such places standing alone on the mountain top it is easy to realize that . . . we all dwell in a house of one room—the world with the firmament for its roof—and are sailing the celestial spaces without leaving any track.

—JOHN MUIR, 1890

Practice Exercises

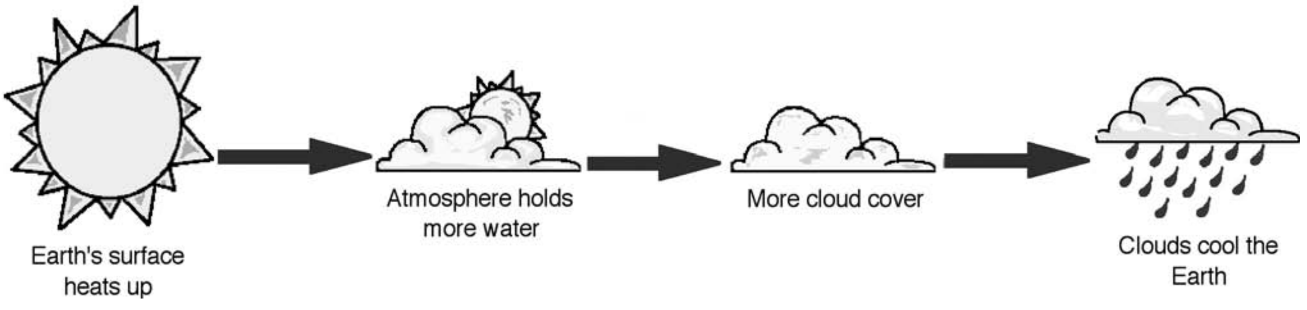
Exercise 1: Conceptual map/Flowchart of a climate factor

Construct a conceptual map/flowchart characterizing one other factor besides clouds that can affect Earth's climate. Also provide a brief written explanation, as in the clouds example illustrated. Follow these guidelines.

- Be sure you understand and clearly explain how the factor causes climate to change.
- Include in your flowchart possible positive and negative feedback systems. For example, the cooling effect of low clouds, like storm clouds, will reduce evaporation rate and may have a short-term negative feedback on additional cloud formation.

Example: The following conceptual map/flowchart shows how clouds impact climate.

Climate Change Factor: Clouds



Explanation of flow chart

In a simple model, as air temperature increases, more moisture is evaporated and held in the atmosphere. This usually leads to more cloud cover. Clouds increase the albedo of the atmosphere and may cool the Earth's surface by reducing the amount of sunlight reaching the surface. Increasing cloud cover potentially would have a negative effect on global warming. Clouds may also have a warming effect on the Earth's surface by reducing the loss of heat to space during the night.

Note: How clouds affect climate is still debated. High clouds have been shown to cause warming and low clouds cooling at the Earth's surface. There is growing evidence that clouds have an overall but not very great net cooling effect.

Conceptual Map/Flowchart showing how ______________ impacts climate

Explanation

Exercise 2: Release of carbon dioxide from the burning of fossil fuels

A. Explain why the release of carbon dioxide from the burning of fossil fuels might lead to an increase in cloud cover

B. Would an increase in cloud cover have a positive or negative affect on climate? Explain. For example, would an increase in cloud cover enhance or reduce the effect of increasing carbon dioxide in the atmosphere? See the section titled "Balancing the System Through Feedbacks" in the textbook for examples of feedback mechanisms that can help to balance or stabilize the climate system.

The balance of evidence suggests a discernible human influence on global climate.

—UN CLIMATE COMMITTEE, IPCC, 1995, p. 4

Exercise 3: Flow of carbon through Earth's systems and reservoirs

Carbon dioxide is an important greenhouse gas that can greatly impact Earth's surface temperatures. Because the Earth is a closed system, the carbon cycle and distribution of carbon in the various reservoirs is a very important component of any model for how climate changes.

Complete the table to summarize the flow of carbon through Earth's systems and reservoirs. Flux is the amount of energy or matter flowing through a given area or reservoir in a given time. Refer to Figures 15.7, 15.15, 15.16, and 15.17, and the accompanying text in Chapter 15.

Carbon fluxes	Brief description of flux	Direction of flux	Climatic impact/ implications
Photosynthesis and precipitation of carbonates	*Carbon is fixed in living organisms, which ultimately contribute to organic matter in sediments, coal, and oil.*	*Carbon flows from the atmosphere and oceans into rock—the lithosphere.*	
Sedimentation	*Calcium and carbonate ions combine to produce calcium carbonate, which can precipitate and collect to form limestone or help cement other rock particles.*		*Climate cools. Carbon dioxide is drawn out of the oceans and atmosphere. The loss of CO_2 from the oceans results in a reduction of CO_2 in the atmosphere.*
Volcanism			
Chemical weathering	*CO_2 in rainwater combines with minerals in rock to form calcium carbonate.*	*Carbon flows from the atmosphere and oceans into the crust.*	*Climate cools. Carbon is being drawn out of surface environments and stored in the crust. Uplift of high plateaus and mountains may enhance this flux.*
Metamorphism	*Heating, recystallization, and decomposition of rocks during metamorphism can release large amounts of CO_2.*	*Carbon flows from the rocks (the crust) into the atmosphere and oceans.*	*Climate warms. Increased levels of CO_2 in the atmosphere enhance the greenhouse effect, which acts to trap heat energy and slow down the loss of heat to space.*
Human activities: Combustion of fossil fuels	*The burning of fossil fuels releases large amounts of CO_2 into the atmosphere.*	*Carbon flows from the lithosphere (coal, oil, and gas) into the oceans and atmosphere.*	

Refer to this Web site for the latest information on global warming:
http://www.ngdc.noaa.gov/paleo/globalwarming/home.html

Review Questions

1. Which of the following gases is most abundant in the Earth's present atmosphere?
   A. nitrogen
   B. carbon dioxide
   C. water
   D. oxygen
2. Why is carbon dioxide considered a greenhouse gas?
   A. It absorbs heat.
   B. It reflects radioactivity.
   C. It absorbs UV light.
   D. It reflects sunlight.
3. Earth's global temperature trend is clearly
   A. upward over the last century.
   B. downward over the last century.
   C. unchanged over the last few decades.
   D. variable, but there has been no overall change.
   Hint: Refer to Figure 15.19.
4. It has been suggested that the uplift of the Himalayan mountains and the Tibetan plateau could have contributed to or even caused a global cooling. The link between the Himalayan mountains and climatic cooling is probably related to
   A. the collision of India with Asia, triggering volcanism and increasing the CO_2 concentration in the atmosphere.
   B. the uplift intensifying the monsoon and associated physical and chemical weathering, which resulted in a draw-down of carbon dioxide from the atmosphere.
   C. the fact that high mountains generate more clouds, and their albedo (reflectivity) cools the Earth's surface.
   D. El Niño and the North Atlantic deep-water current.
5. Which of the following is NOT associated with El Niño events?
   A. trade winds slackening or reversing direction
   B. volcanic activity
   C. change in ocean circulation patterns
   D. worldwide anomalous weather patterns
6. As the oceans become warmer, __________ CO_2 is released from the oceans into the atmosphere, resulting in a __________ effect.
   A. more/positive
   B. less/negative
   C. more/negative
   D. less/positive
   Hint: Is CO_2 more or less soluble in warmer water?
7. The increase of the average temperature on Earth is linked to burning fossil fuels because the
   A. burning process consumes oxygen.
   B. burning process consumes CO_2.
   C. burning process generates CO_2.
   D. smoke given off by burning insulates the Earth.

8. The surface temperatures on Venus, Earth, and to a lesser extent Mars are all well above what can be explained by their distance from the Sun. What other factor significantly contributes to elevated surface temperatures for these inner planets?
   A. the presence of greenhouse gases, like carbon dioxide
   B. interior heat
   C. dust from windstorms and volcanoes, which acts to trap heat
   D. presence of argon and nitrogen in the atmosphere

9. At present the greatest flux of carbon dioxide occurs between our atmosphere and
   A. oceans.
   B. volcanoes.
   C. living organisms.
   D. humans.
   Hint: Refer to Figures 15.16 and 15.17.

10. Which of the following contributes the most carbon to the atmosphere?
    A. human deforestation and agriculture
    B. plant uptake of carbon
    C. ocean air gas exchange
    D. burning of fossil fuel by humans
    Hint: Refer to Figure 15.17.

11. Most of the mass of the atmosphere, where weather forms and what commercial jets fly in, is the
    A. troposphere.
    B. stratosphere.
    C. mesosphere.
    D. thermosphere.
    Hint: Refer to Figure 15.2.

12. 75% of the world's fresh water is stored in
    A. lakes.
    B. rivers and streams.
    C. caves.
    D. continental glaciers and ice sheets.

13. Thermohaline circulation refers to
    A. convection in the lower atmosphere.
    B. global oceanic circulation driven by differences in temperature and salinity (salt content).
    C. changes in the trade winds that are thought to cause El Niño events.
    D. a global oceanic current driven by wind.
    Hint: Refer to Figure 15.3.

14. The geochemical cycle of calcium is linked to long-term climate change by the fact that
    A. weathering of carbonate rocks removes carbon dioxide from the atmosphere and lithosphere.
    B. calcium is precipitated as gypsum in evaporite deposits.
    C. photosynthesis precipitates calcium.
    D. heat released by the reaction of calcium with bicarbonate ion warms the surface water of the oceans.

15. Global warming of about ______ during the twentieth century correlates with the significant rise in atmospheric CO_2 and other greenhouse gases caused by fossil-fuel burning, deforestation, and other human activities.
    A. 0.6°C
    B. 1.6°C
    C. 2.0°C
    D. 2.6°C

16. Earth's albedo is not affected by a change in the amount of
    A. sea ice.
    B. CO_2 in the atmosphere.
    C. trees covering land masses.
    D. cloud cover.

17. Milankovitch cycles correlate strongly with Pleistocene glacial cycles (ice ages) because
    A. eccentricity, wobble, and precession can all influence Earth's albedo.
    B. solar output changes during these cycles.
    C. ice cores show that the amount of CO_2 in the atmosphere is higher during the ice ages.
    D. a high orbital eccentricity reduces the solar radiation reaching the Earth.
    Hint: Refer to Figure 15.12 and the textbook section Milankovitch Cycles.

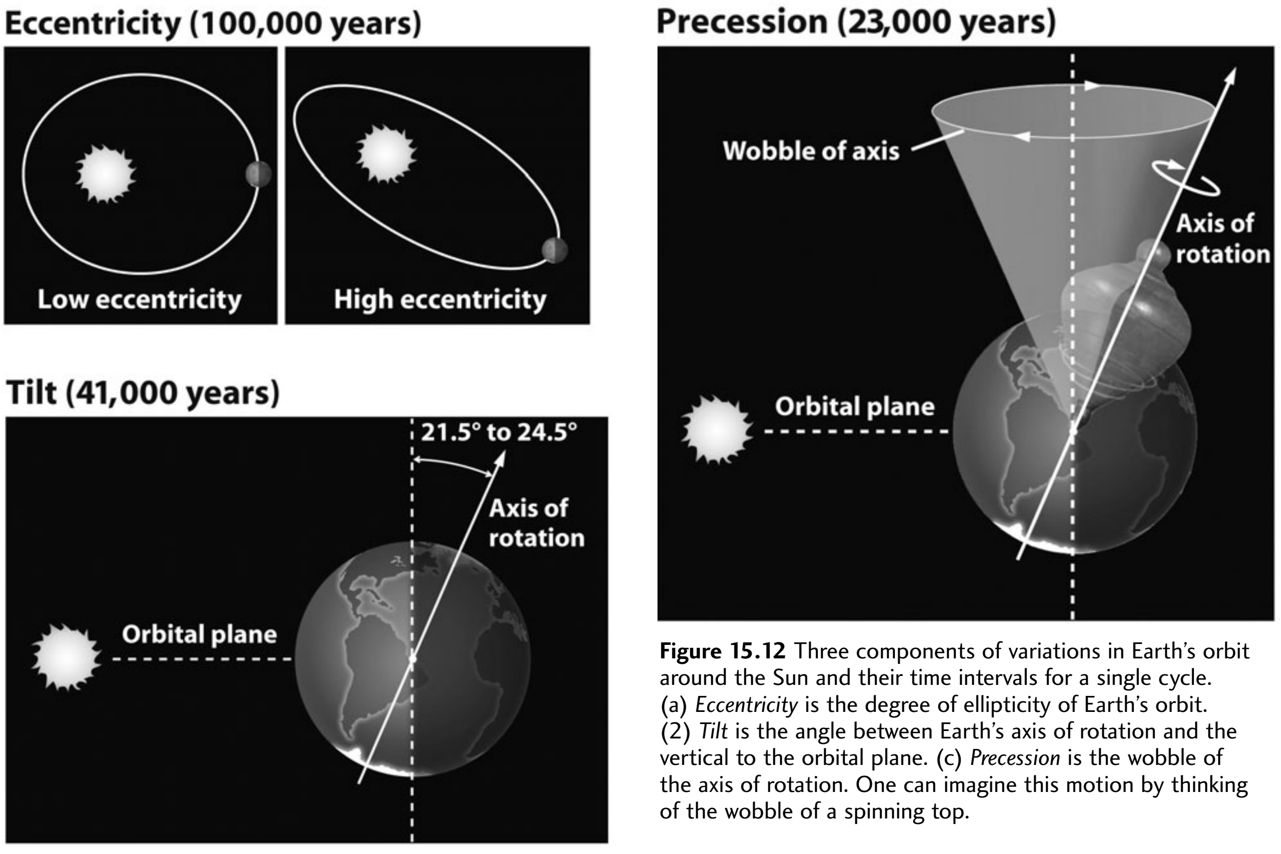


Figure 15.12 Three components of variations in Earth's orbit around the Sun and their time intervals for a single cycle. (a) *Eccentricity* is the degree of ellipticity of Earth's orbit. (2) *Tilt* is the angle between Earth's axis of rotation and the vertical to the orbital plane. (c) *Precession* is the wobble of the axis of rotation. One can imagine this motion by thinking of the wobble of a spinning top.

CHAPTER 16

Weathering, Erosion, and Mass Wasting: Interactions Between the Climate and Plate Tectonic Systems

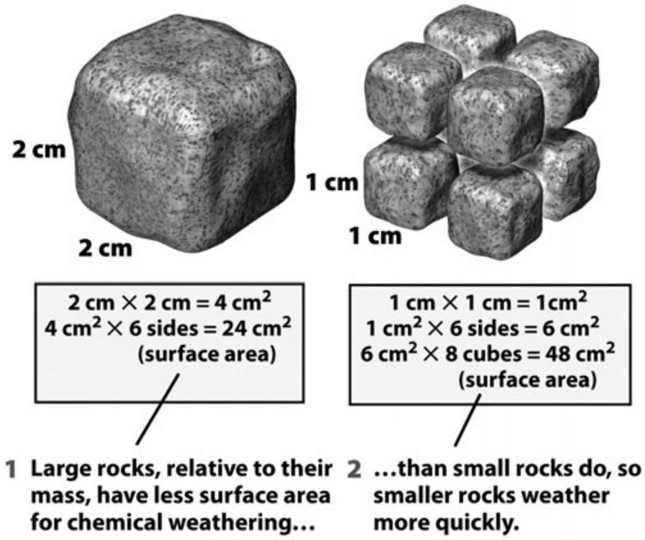


Figure 16.3. As a rock mass breaks into smaller pieces, more surface area becomes exposed to the chemical reactions of weathering.

Before Lecture

Chapter Preview

- **What is weathering?**
  Brief answer: Weathering is the breakdown of rocks by chemical and physical processes.

- **How does chemical weathering work?**
  Brief answer: Water, oxygen, acids, and physical weathering facilitate chemical weathering reactions that alter and break down minerals to form new minerals, oxides, and salts and release silica.
- **How does physical weathering work?**
  Brief answer: Physical weathering breaks rocks into fragments. Processes that aid physical weathering include chemical weathering, frost wedging, and the growth of plant roots.
- **How do soils form as products of weathering?**
  Brief answer: Soils form in rock materials by chemical weathering. Soil formation is influenced by the composition of the rock, stability of the weathering surface (topography), time, and most important, climate. Life processes and their by-products are also important factors in soil formation and soil type.
- **What is mass wasting?**
  Brief answer: Mass wasting, also called mass movement, is the down-slope movement of rock material.
- **Why do mass movements occur?**
  Brief answer: The three most important factors enhancing the potential for mass movements are the steepness of the slope, the nature of the rock making up the slope, and the water content of the slope material.
- **How can damage from mass movements be minimized?**
  Brief answer: Careful engineering and the restriction of land use can minimize the hazards associated with mass movements.

When we try to pick up anything by itself,
we find it entwined with everything else in the universe.

—John Muir

Learning Warm-Up

Science and art are synergistic; that is, each enhances the other. For example, many aspects of nature that we consider beautiful are the product of a weathering process. Before lecture spend five minutes scanning the text photos for beautiful features and effects created by weathering. As you enjoy the photos, you might ask yourself, "How did weathering processes create the colors and shapes in this photo?"

Vital Information from Other Chapters

Review the Rock-Forming Minerals section and Table 3.1 and the Sedimentary Rocks section and Figure 3.26 in Chapter 3.

The composition and internal fabric of rocks significantly influence the rock's strength and the potential for mass movement. Therefore, a review of the composition and especially of the different kinds of fabrics (textures) of igneous, sedimentary, and metamorphic rocks will provide you with vital information for understanding the different circumstances that cause mass movements. While reviewing the basic rock textures described in Chapters 4, 5, 6, and 7, ask yourself what textures and deformation fabrics might contribute to a weaker rock and an enhanced potential for mass movement.

Previewing Tip

It will be very helpful to work on the Practice Exercise 2 before going to lecture. Complete the exercise and take it to class with you. Your lecturer will probably show slides to help you understand the different kinds of mass wasting. You will understand these differences better if you have worked on them before lecture.

During Lecture

As you take notes during this lecture, be sure to get details on how weathering works. One goal for lecture should be to leave class with good answers to the Chapter Preview questions.

- Focus on understanding specific chemical weathering processes such as oxidation and dissolution. Be sure to distinguish clearly between the chemical processes (for example, dissolution, oxidation) and the physical processes (for example, frost wedging, exfoliation, etc).
- Focus on understanding Figure 16.11, which shows the two basic soil-forming processes, translocation and transformation.
- To avoid getting lost in details, keep the big picture in mind. Chapter 16 tells the story of what causes mass wasting. Mass wasting is about classification, and your job is to understand the differences between the types of wasting. Be sure to pay close attention to comments the lecturer may make about how each kind of mass wasting *differs* from the others. **Hint:** In general these differences will be about the *steepness* of the slope, the *kind of rock* in the slope being moved, and the *water content* of the slope material.
- You may not be familiar with the kinds of mass wasting (rock avalanche, creep, earthflows, and so on). To help you visualize this process, the lecturer may show slides of various kinds of mass wasting. Some of the slides may be very dramatic (for example, pictures of landslides). Enjoy the drama and excitement!
- If you completed Practice Exercise 2 before class, you can refer to it as the lecturer talks about the different kinds of mass wasting.

After Lecture

Review Notes

The perfect time to review your notes is right after lecture. If you wait even one day most (80 percent) of what you heard will have disappeared from memory.

Check Your Notes: Have you…

- ☐ clearly identified the important points? Example: You should have clear descriptions of each type of chemical and physical weathering.
- ☐ added visual material? Chunking material is a good learning strategy. There are a lot of chemical and physical weathering processes in Chapter 16. It may be useful to make a list of processes that you can look at as a group all in one place in your notebook. Use a two-column format for this list, in which both chemical and physical weather processes are listed in one column and details you need to remember about each process are briefly described in a second column to the right.
- ☐ added simple sketches? Chapter 16 includes lots of material that is best learned by visualization. Sketches will help you remember the key aspect of each kind of mass wasting. **Hint:** Your sketch need not be artistic to be useful. Sketch only the features you need to remember. Example: For a rock avalanche you could draw a steep slope (one line at 45° angle) with a pile of large blocks at the bottom to designate large masses of broken rock (see Figure 16.18).

☐ added a comparison chart that will help you master the classification of different kinds of mass wasting? **Hint:** See Exercise 2.

☐ created a brief big picture overview of this lecture (using a sketch or written outline) showing how weathering works? Suggestion for Chapter 16: Write a brief summary of the most important points you have learned from this chapter that might influence your choice of future home sites.

Intensive Study Session

Set priorities for studying this chapter. We recommend giving the highest priority to activities that involve answering questions. Pay particular attention to any exercises recommended by the instructor during lecture and answer those first. The instructor is also your best resource if you are wondering which material is most important.

Answering questions while using your text and lecture notes as reference material is far more efficient than rereading chapters or glancing over notes. As always, you have three sources from which to choose questions.

- **Practice Exercises and Review Questions.** Be sure to do the exercises, as they will focus on the key information you need to learn in this chapter—namely, how weathering works, how soils form, factors that enhance the potential for mass wasting, and the classification of mass movements.
- **Text.** Answer Exercises 2, 4, 5, and 8. Also complete Thought Questions 1, 2, 4, 6, 9, and 10.
- **Web Site Study Resources**
  http://www.whfreeman.com/understandingearth6e
  The **Geology in Practice** exercises will allow you to apply what you learned about weathering to understanding the beautiful formations of Bryce Canyon National Park. There is also a **Geology in Practice** exercise on assessing potential hazards from mass wasting. Complete the **Graded Online Quiz**. Pay particular attention to the explanations of the answers.

Note that the susceptibility of common silicate minerals to chemical weathering is closely related to their silicate crystal structure. Quartz, a framework silicate, is very stable on the Earth's surface, whereas olivine, with an isolated silica tetrahedral crystal structure, is very susceptible to chemical weathering. Refer to Figure 3.11.

As you study the many different types of mass movement illustrated in the figures, assess what factors are most important in causing slope instability. Remember that the three most important factors enhancing the potential for mass movements are the steepness of the slope, the nature of the rock material in the slope, and the water content of the slope material.

Man can live without gold, but not without salt.

—Falvius Magnus Cassiodorus
A Roman Politician of the Fifth Century A.D.

Exam Prep

Organization is key to successful exam preparation. It begins with note taking and time management. Start thinking now about how to organize your time for your next exam. Here are a few tips that should make your exam prep more efficient.

Tips for Preparing for Exams

- Use the clues the instructor provides in lecture about what is important. Even when a department agrees on a common core of material (rare), each instructor carves out a course that is unique and has a particular character or flavor and distinct areas of emphasis. The instructor is the ultimate guide to the question "What is important?"
- Be sure you know the format of the exam. Multiple choice? True–false? Essay? Thought problems? All of the above?
- Review the notes marked TQ (test question).
- Ask the instructor if exams are available from the previous semester. Review them to check the format of questions, to see what areas of content are stressed, and to see what types of problem solving are included. Don't make the mistake of assuming that the same questions will be asked this semester.
- Be sure to attend review sessions if they are offered. Attending a review session will raise your exam score.
- If your class has tutors, preceptors, supplemental instruction leaders, or other peer helpers who have taken the class, ask for their suggestions about preparing for the exam.
- Once you are clear about the nature of the exam, begin your review. Conduct the review in an orderly, systematic manner that ensures focused review of all the important material. Be sure to take a look at the Eight-Day Study Plan in Appendix A. This plan is a great model for productive review.

Materials in this section are particularly useful during your preparation for quizzes and examinations. The **Chapter Summary** and the **Practice Exercises** and **Review Questions** will simplify your chapter review. Read the **Chapter Summary** to begin your session. It provides a helpful overview that will refresh your memory.

Next, work on the **Practice Exercises** and **Review Questions**. Complete the exercises and questions just as you would on an exam, to see how well you have mastered this chapter. After you answer the questions, score them. Finally, and most important, review each question that you missed. Identify and correct the misconception(s) that resulted in your answering the question incorrectly.

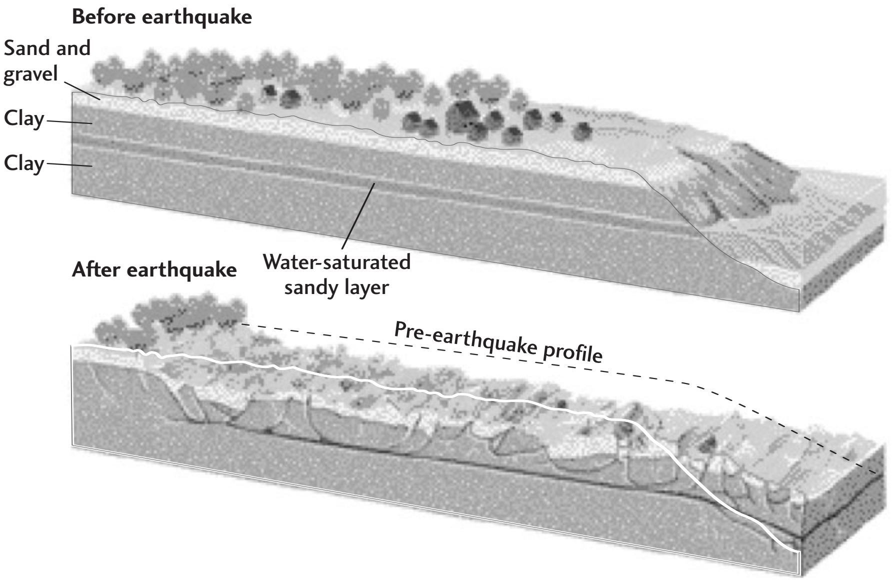


Figure 16.16(b). Landslide at Turnagain Heights, Anchorage, Alaska, triggered by the earthquake of 1964. This is a classic example of the role of liquefaction in enhancing the potential for mass wasting.

Chapter Summary

What is weathering?

- Physical weathering breaks rock into smaller pieces, and chemical weathering alters and dissolves the minerals in the rock. The principal factors that influence weathering are the composition of the parent rock, topography (stability of the land surface), and climate. There is a positive feedback between physical and chemical weathering, where one enhances the other if conditions are favorable. A good example of this positive feedback is soil formation. As physical and chemical weathering proceed to alter a stable surface of rock material, a soil forms. The formation of soil promotes weathering by increasing the availability of moisture and producing acidic chemical conditions. Soils also promote the growth of plants, which aid both physical and chemical weathering.

How does chemical weathering work?

- How chemical weathering works is well illustrated by three examples. First, the chemical weathering of feldspars, which are the most abundant silicate mineral in the Earth's crust, illustrates how water with the help of carbonic acid can transform feldspars into clay minerals and dissolve silica and salts (cations). Refer to Figure 16.4. Second, the reaction of oxygen with the iron in ferromagnesium minerals like pyroxene illustrates oxidation. Refer to Figure 16.5. Third, the reaction of calcite and other carbonate minerals that make up limestone exemplifies the role naturally acidic water plays in dissolving rock.

How does physical weathering work?

- Physical weathering involves a variety of processes that break rock into fragments. Physical weathering is promoted by chemical weathering, which weakens grain boundaries within the rock. Physical weathering also promotes chemical weathering by increasing the surface area of the broken rock fragments. Frost wedging, mineral crystallization, and life processes play a major role in breaking rock apart.

How do soils form as products of weathering?

- Soils are a product of chemical weathering of rock that has remained in place for a period of time. Soil formation is most affected by climate. The composition of the parent rock, climate, topography, life processes, and time are also important factors in soil formation. Soil formation involves the transformation and translocation of materials. Refer to Figure 16.11. Soils, water, and the air we breathe are the three most basic natural resources.

What is mass wasting?

- Mass movements (also called mass wasting) are slides, flows, or falls of large masses of rock material down slopes when the pull of gravity exceeds the strength of the slope materials. Mass movements can be triggered by earthquakes, absorption of large quantities of water from torrential rainfall, undercutting by flooding rivers, human activities, or other geologic processes.

Why do mass movements occur?

- The three most important factors influencing the potential for mass movements are the steepness of the slope, the nature of the rock making up the slope, and the water content of the slope material. See Table 16.4. Although steep slopes are prone to mass movements, slopes of only a few degrees can also fail catastrophically because of these other factors.

- Slopes become unstable when they become steeper than the angle of repose (the maximum slope angle that unconsolidated material will assume). Slopes in consolidated material may also become unstable when they are oversteepened or denuded of vegetation. Erosion by rivers and glaciers and human activities can oversteepen slopes and thereby increase the potential for mass movement.
- The composition, texture, and geologic structure of the slope material is another important factor influencing the potential for slope failure. For example, rocks with high clay content tend to be weak and may liquefy. Tilted layers of sedimentary or volcanic rocks are more likely to fail along bedding planes when the bedding parallels the slope. Failure of foliated metamorphic rocks is more likely to occur parallel to the direction of foliation.
- Water absorbed by the slope material contributes to instability in two ways: (1) by lowering internal friction (and thus resistance to flow) and (2) by lubricating planes of weakness in the slope.

How are mass movements classified?

- Material that makes up the slope, the way it moves, and the rate of movement are used to classified mass movements. Refer to Figure 16.17 and the many other figures that illustrate types of mass movement.

How can damage from mass movements be minimized?

- The hazards and damage associated with mass movements can be minimized by careful geological assessment, engineering, and land use policies that restrict development on unstable slopes. Of particular importance is the avoidance of steepening or undercutting slopes and minimizing the amount of water that can infiltrate the slope material. In some areas particularly prone to mass movements, development may have to be restricted.

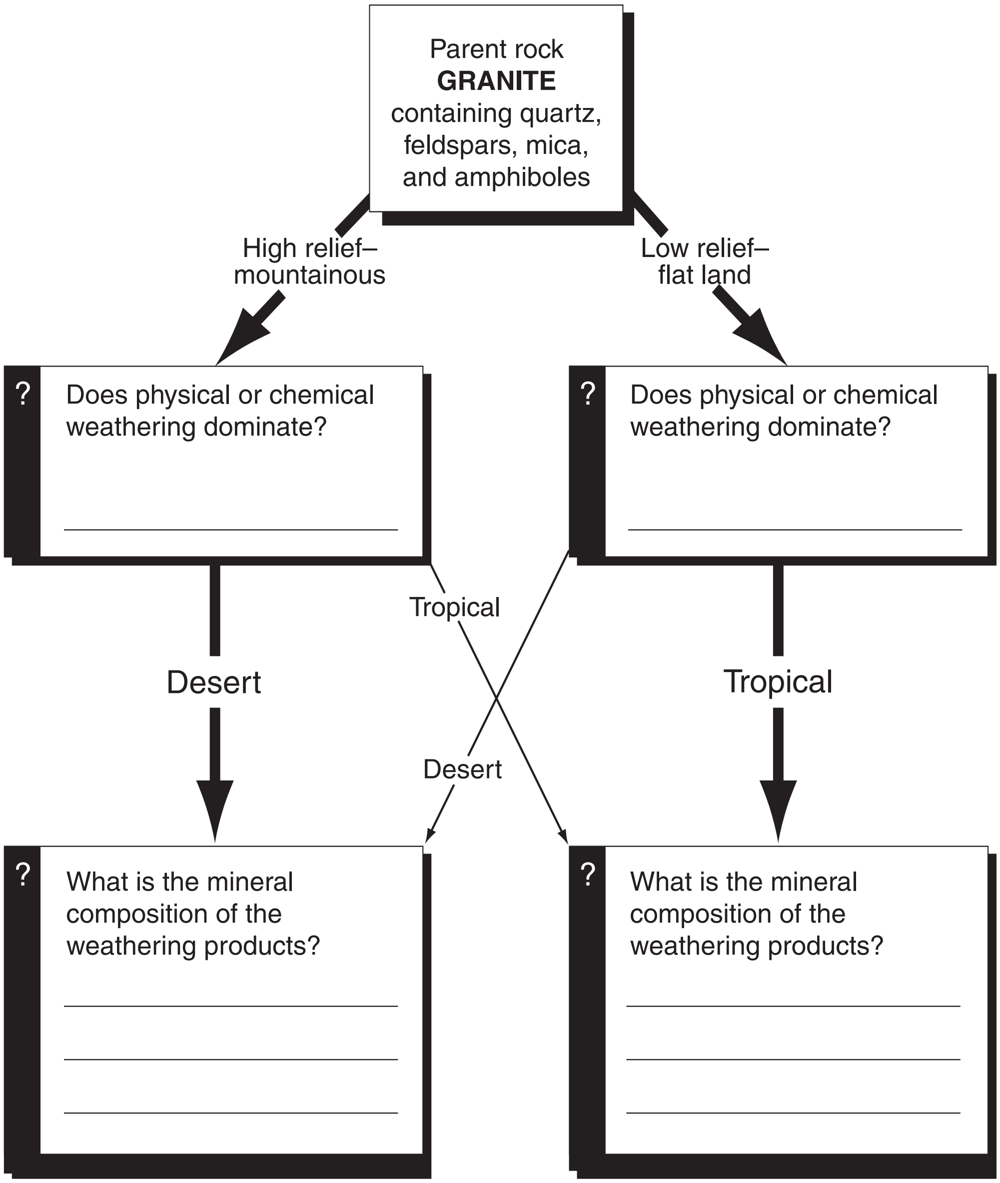
Table 16.4 Factors That Influence Mass Movements

Nature of slope material	Water content	Steepness of slope	Stability of slope
UNCONSOLIDATED	dry	angle of repose	high
Loose sand or sandy silt	wet		moderate
Unconsolidated mixture of sand,	dry	moderate	high
silt, soil, and rock fragments	wet		low
	dry		high
	wet	steep	low
CONSOLIDATED			
Rock, jointed and deformed	dry or wet	moderate to steep	moderate
Rock, massive	dry or wet	moderate	high
	dry or wet	steep	moderate

Practice Exercises

Exercise 1: Physical and chemical weathering

Answer the questions in the flowchart.



Exercise 2: Inventory of the different kinds of mass wasting

The authors discuss eight different kinds of mass wasting. As an aid to learning the circumstances that favor each one, use your textbook to complete the table. Textbook figures and figure captions will help you.

Hint: You probably haven't seen many of these features before, so be sure to examine the photos and figures of each type of mass wasting in your textbook. If you are a visual learner, this activity may be vital. Also, to get a kinesthetic feel for these movements, imagine yourself trying to outrun each movement. Indicate in the space labeled "Speed" whether you could escape the mass movement by walking, running, or moving as fast as a speeding auto.

Kind of mass wasting	Composition of slope (consolidated vs. unconsolidated and wet vs. dry)	Characteristics
Rock avalanche		Speed: *Running or a speeding auto* Slope angle: *Steep slopes* Triggering event(s): *Earthquakes* Notes: *Occur in mountainous regions where rock is weakened by weathering, structural deformation, weak bedding, or cleavage planes*
Creep		Speed: Slope angle: *Any angle* Triggering event(s): *None* Notes:
Earthflows		Speed: Slope angle: *Any angle* Triggering event(s): *Intense rainfall* Notes: *Fluidlike movement*
Debris flow		Speed: Slope angle: *Any angle* Triggering event(s): Notes:
	Mostly finer rock materials with some coarser rock debris with large amounts of water	Speed: Slope angle: Triggering event(s): *Intense rainfall or catastrophic melting of ice and snow by a volcanic eruption.* Notes: *Contains large amounts of water*
Debris avalanche	*Water-saturated soil and rock*	Speed: Slope angle: Triggering event(s): Notes:
Slump		Speed: *Walking* Slope angle: *Any angle* Triggering event(s): *Rainfall* Notes:
	Surface layers of soil	Speed: *Walking* Slope angle: *Any angle* Triggering event(s): Notes: *Occurs only in cold regions when water in the surface layers of the soil alternately freezes and thaws; water cannot seep into the ground because deeper layers are frozen.*

Exercise 3: Water's role in mass wasting

Water enhances the potential for mass wasting in many ways. Using your textbook as a guide, briefly describe five different ways water enhances the potential for mass movements.

1. ____
2. ____
3. ____
4. ____
5. ____

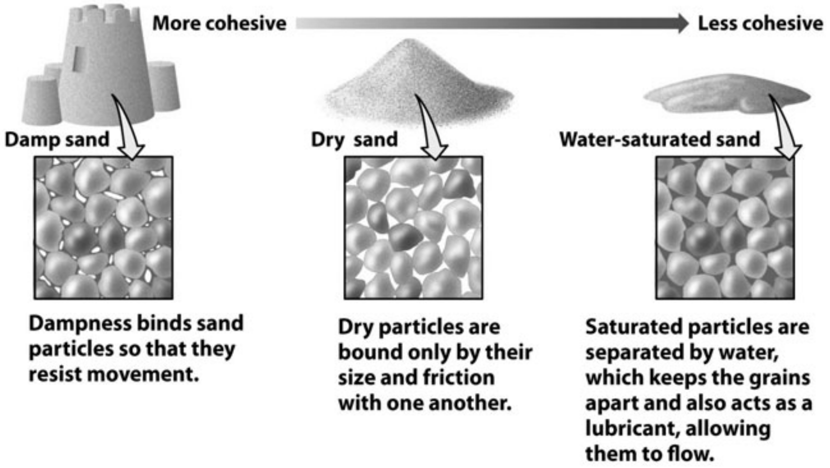
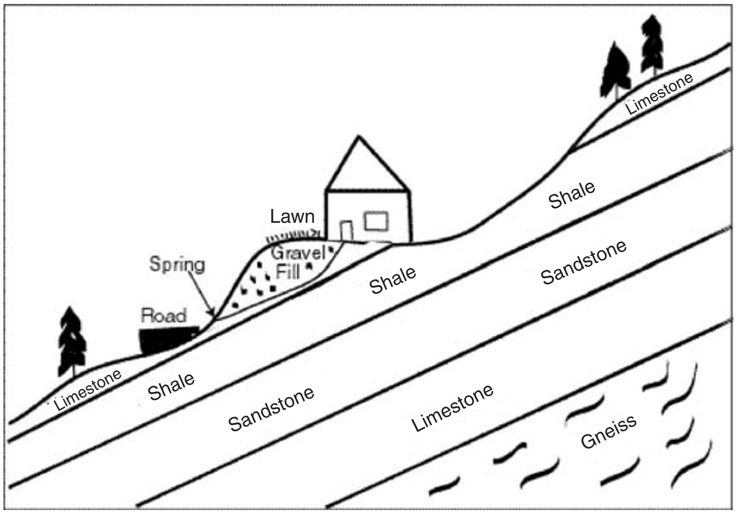


Figure 16.13 (c) Mass movement depends on the nature of the materials, their water content, and the slope steepness.

Exercise 4: Evaluation of slope stability



A. Discuss three factors that enhance the potential for mass movement at the home-site in the figure.

1. ______________________________

2. ______________________________

2. ______________________________

B. Given that the house is already built on this site, briefly discuss two possible ways of reducing the risk of damage to the house due to slope failure.

1. ______________________________

2. ______________________________

Review Questions

1. Of the following agents, which is NOT involved in the process of chemical weathering?
   A. water
   B. oxygen
   C. carbon dioxide
   D. nitrogen

2. The following products all result from chemical weathering EXCEPT
   A. feldspar.
   B. iron oxides.
   C. silica in solution.
   D. clay minerals.

3. Which of the following minerals does NOT chemically weather into a clay mineral?
   A. muscovite
   B. K-feldspar
   C. pyroxene
   D. quartz

4. Of the following materials, which one would make the longest lasting tombstone?
   A. limestone
   B. shale
   C. granite
   D. sandstone cemented with calcium carbonate.

5. An example of chemical weathering is
   A. rusty streaks on a rock wall.
   B. angular blocks of rock rubble in the mountains.
   C. potholes in pavement.
   D. rocks wedged apart by tree roots.

6. Although water is an important agent of chemical weathering in its own right, it becomes more effective if small amounts of carbonic acid are present. Carbonic acid is formed when
   A. carbon from coal beds or from graphite deposits is pulverized along a fault or fracture and then added to water.
   B. carbon dioxide from the atmosphere or from organic decomposition is added to water.
   C. sulfur from coal-fired power plants is added to water.
   D. water comes in contact with the calcite in a limestone layer.

7. The potential for chemical weathering can be greatly enhanced by physical weathering because physical weathering increases
   A. the surface area of the rock particles.
   B. the availability of chemical agents.
   C. drainage and thereby reduces contact with water.
   D. the size of the rock particles.

8. Limestone and other carbonate rocks weather relatively fast in a ______ climate due to ______.
   A. dry / oxidation
   B. dry / hydrolysis
   C. wet / physical weathering reaction
   D. wet / dissolution promoted by carbonic acid

9. Georgia soil, along with that of other warm, humid regions, is deep red in color. This color is due to
   A. iron oxides.
   B. quartz.
   C. feldspar.
   D. clay minerals.

10. Clay minerals, like kaolinite, are a product of ______ weathering of ______ minerals and are a raw material for ______.
    A. chemical / silicate / pottery
    B. physical / sulfate / cement
    C. chemical / sulfide / asphalt
    D. physical / carbonate / fertilizers
    Hint: Refer to Figure 16.4.

11. Which of the following climatic regions experiences the most rapid chemical weathering?
    A. hot, low precipitation
    B. extremely cold, low precipitation
    C. hot, high precipitation
    D. extremely cold, high precipitation

12. Soil production is often described as a "positive feedback" process. Why?
    A. Carbon dioxide in rainwater is used up by organisms, so weathering of underlying rock is impeded.
    B. Rainwater becomes more acidic as it percolates through the soil, so weathering of underlying rock is promoted.
    C. Once a layer of soil is formed, the underlying rock is protected from further weathering.
    D. Plant growth reduces the potential for weathering and therefore of soil development.

13. Of the following minerals, the one most rapidly altered by chemical weathering would be
    A. mica (sheet silicate), such as biotite.
    B. amphibole (double chain silicate), such as hornblende.
    C. pyroxene (single chain silicate), such as augite.
    D. isolated silica tetrahedra mineral, such as olivine.
    Hint: Refer to Table 16.2.

14. Acid rain _________ the potential for chemical weathering.
    A. neutralizes
    B. does not affect
    C. increases
    D. decreases
    Hint: Refer to the Global Change section in Chapter 23 of the textbook.

15. What happens chemically to the quartz sand grains in a calcite-cemented sandstone that is undergoing moderate chemical weathering?
    A. They combine with water.
    B. They dissolve.
    C. They oxidize.
    D. Virtually nothing—they become grains of quartz sand.

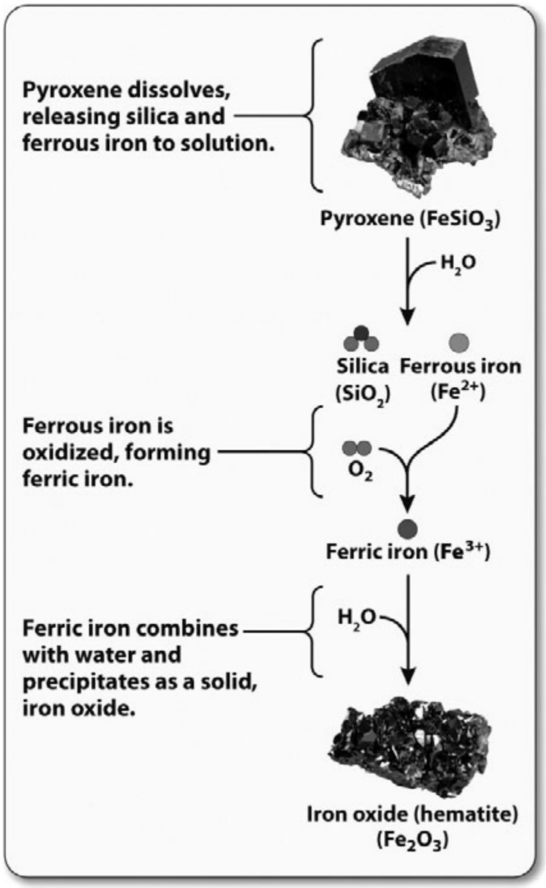


Figure 16.5. The general course of chemical reactions by which an iron-rich mineral, such as pyroxene, weathers in the presence of oxygen and water.

16. Rock material that tends to result in the most fertile soils is __________weathered.

A. not at all
B. very weakly
C. moderately
D. intensely

17. Physical and chemical weathering in the warm, wet climates of the Earth's surface alter exposed granite to

A. quartz and feldspar sand.
B. olivine sand.
C. iron-rich soil.
D. quartz sand and clay.

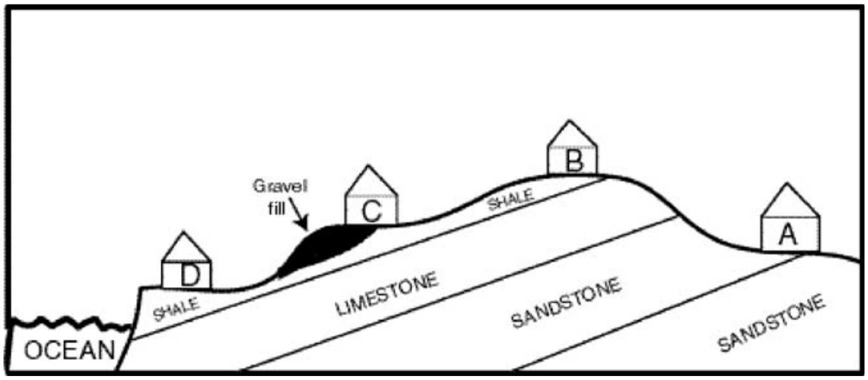
18. In the days of the pharaohs of Egypt, a cherished status symbol was the obelisk, a stone column decorated with hieroglyphs (designs carved into the stone—usually sandstone). In 1879 the obelisk of Thothmes III from the temple of Heliopolis was moved to Central Park in New York City. Within about sixty years the hieroglyphs were barely visible on the obelisk, while its counterpart still standing in Egypt remains in nearly perfect condition in the desert sun after almost 4,000 years. Why did the stone obelisk deteriorate so quickly when it was moved to New York City? **Hint:** Refer to Figures 16.1 and 16.10.

____

____

____

19. Which hillside homesite is the best long-term investment?



A. site A
B. site B
C. site C
D. site D

20. What force drives mass wasting?

A. heat
B. gravity
C. friction
D. convection

21. Mass wasting tends to occur when

A. a slope becomes steeper due to undercutting by a river or ocean waves.
B. the mass on a slope decreases by draining water from the ground.
C. friction is increased by draining water from the ground.
D. friction is decreased by taking water out of the ground.

22. Talus consists largely of

A. clay and other very fine rock particles.
B. a mixture of powdered rock and ice.
C. coarse, angular rock fragments.
D. alternate layers of sand, silt, and clay.

23. The angle of repose is the

A. angle at which rock material is most stable.
B. angle at which lava flows solidify without spreading out.
C. angle of a slope that will no longer support large boulders and rock pillars.
D. maximum slope at which loose material lies without cascading down.

24. An important factor in mass wasting is the orientation of rock layers, foliation, or jointing. For layered sedimentary and volcanic rocks, which condition is the least stable?
    A. Rock layers are at right angles to the slope.
    B. Rock layers are parallel to the slope.
    C. Rock layers are horizontal to the slope.
    D. Rock layers stand vertical.

Test-Taking Tip

Time permitting, it is sometimes helpful to sketch the alternatives to a test question. For example, if you aren't sure about the answer to Review Question 24, then you could sketch rock layers at right angles to the slope, rock layers parallel to the slope, and so on. Sketching can be particularly useful if you are a kinesthetic learner, as the action of drawing may jog or unlock your memory when you are stuck.

25. Which of the following would be most subject to mass movements (assuming slope and climate are the same in each case)?
    A. high-grade gneiss, with highly contorted foliation
    B. quartz-cemented sandstone, with layering perpendicular to the slope
    C. shale, with bedding parallel to the slope
    D. massive granite bedrock
26. Solifluction usually occurs in
    A. cold regions.
    B. very cold regions like Antarctica.
    C. any area where there is a lot of sunshine.
    D. tropical regions.
27. Which of the following options is the most effective way to stabilize an active landslide?
    A. piling additional rock and soil material on the landslide near its top
    B. saturating the landslide itself with water
    C. draining the water away from and out of the landslide area
    D. cutting away the toe (base) of the landslide
28. Roads through mountainous regions tend to be unstable and require more maintenance if they are built on
    A. bedrock such as granite.
    B. horizontal lava flows.
    C. rock layers that dip perpendicular to the hillslope.
    D. rock layers that dip parallel to the hillslope.
29. Your beautifully landscaped house, built on an idyllic Georgia hillside site of small, irregularly undulating knolls and depressions, with trees tilted at interesting angles, has developed a bad case of broken and shifting foundation. The probable cause for the foundation problem is
    A. melting permafrost.
    B. that the house is built on an active earthflow.
    C. mudflow from an active nearby volcano.
    D. root wedging from the trees.
30. Homeowners in California whose houses survived recent wildfires are not quite out of the woods yet. With the approaching rainy season their next problem will be
    A. increased potential for mudflows and debris flows.
    B. accelerated soil erosion.
    C. flash floods.
    D. all of the above.

CHAPTER 17

The Hydrologic Cycle and Groundwater

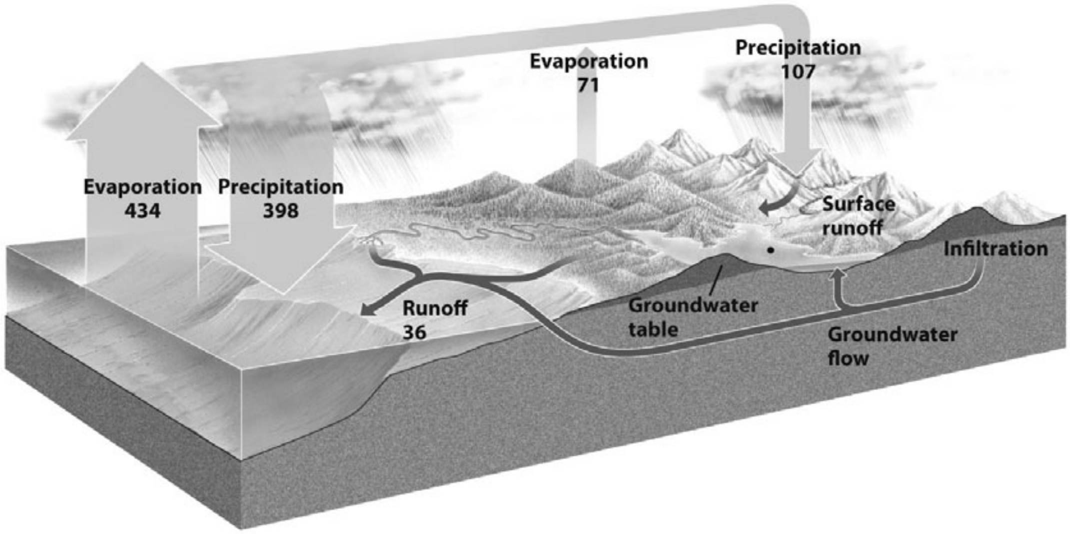


Figure 17.2. The hydrologic cycle is the movement of water through Earth's crust, atmosphere, oceans, lakes, and streams. The numbers indicate the amounts of water (in thousands of kilometers per year) that flow between these reservoirs annually.

Before Lecture

Before you attend lecture, be sure to spend some time previewing the chapter. For an efficient preview use the **Chapter Preview** questions, a framework for understanding the chapter. Previewing works best if you do it just before lecture. With the main points in mind, you will understand the lecture better and take better notes.

How much time should you devote to preview? Obviously, more time is better than less. But even a brief (five- or ten-minute) preview session just before lecture begins will produce a result you will notice. For a refresher on why previewing is important, see Part I, Chapter 3, How to Be Successful in Geology.

Chapter Preview

- **How does water move around and in the Earth?**
  Brief answer: The hydrologic cycle is a model for the movement of water on Earth. Refer to Figure 17.2.
- **How does water move below the ground surface?**
  Brief answer: Porosity and permeability are the principle factors that control the infiltration and flow of groundwater. (Skim the textbook section How Water Flows.)
- **What factors govern our use of groundwater resources?**
  Brief answer: Water, like soil and air, is a basic natural resource. Some of the most important factors governing our ability to use groundwater are the depth to the groundwater table, springs and artesian systems, the balance between recharge and discharge, Darcy's law, and water quality.
- **What geologic processes are affected by groundwater?**
  Brief answer: Groundwater is the geologic agent responsible for caves, karst topography, and the formations that decorate caves. Groundwater is a vital component of geothermal systems. See Figures 17.21, 17.23, and 17.25.

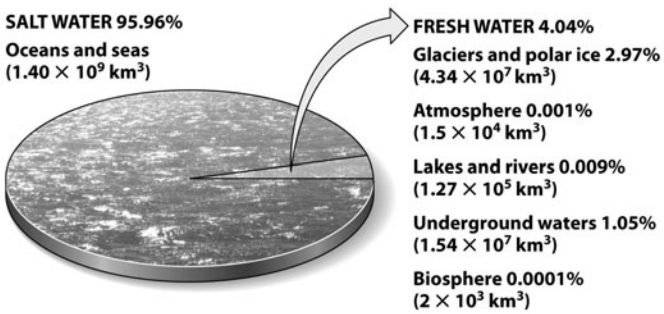


Figure 17.1. The distribution of water on Earth.

During Lecture

Warm-Up Activity

Spend 5 to 10 minutes just before lecture browsing Earth Issues 17.1, Water Is a Precious Resource: Who Should Get It? and 17.2, The Ogallala Aquifer: An Endangered Groundwater Resource. Which issue interests you the most? After browsing, ask yourself what you would most like to learn from this chapter and lecture.

One goal for lecture should be to leave the room with good answers to the preview questions.

- To avoid getting lost in details, keep the big picture in mind. Chapter 17 is a survey of water in and around the Earth. It tells the story of the hydrologic cycle: how water moves around and in the Earth and maintains a balanced waterflow budget.
- First focus on understanding Figure 17.2 (the hydrologic cycle).
- Then work on understanding the factors that govern the flow of groundwater, illustrated in Figures 17.9, 17.10, and 17.11.

After Lecture

Review Notes

The perfect time to review your notes is right after lecture. The following checklist contains both general review tips and specific suggestions for this chapter.

Check Your Notes: Have you…

- ☐ included a clear representation of the hydrologic cycle somewhere in your notes (see Figure 17.11)?
- ☐ clearly identified factors that govern our use of groundwater, for example, depth of the groundwater table, springs and artesian systems, the balance between recharge and discharge, Darcey's law?
- ☐ added visual material to help you understand the material? Suggestion: Sketch a simple version of Figure 17.9 (porosity of rock materials; make a copy of Practice Exercise 1 after you have completed the chart and insert it into your notes. (It will be great aid for exam review, it summarizes all you will need to know about porosity.)
- ☐ created a brief big picture overview of this lecture (using a sketch or written outline)? Figure 17.2 provides a good visual summary of the chapter. Activate kinesthetic learning by adding a simplified version to your notes.

Intensive Study Session

Set priorities for studying this chapter. Give the highest priority to activities that involve answering questions. We recommend the following strategy for learning this chapter.

- **Text.** Review the important figures in Chapter 17. They are Figures 17.2, 17.9, 17.11, 17.12, 17.14, 17.15, 17.17, and 17.23. Insert simple sketches of these figures into your lecture notes.

  Sometime before the next exam, complete the exercises at the end of the text chapter. The exercises require short answers and won't take long if you know the material.
- **Practice Exercises and Review Questions.** Complete Practice Exercises 1 and 2. These exercises will help you remember important ideas in the chapter. Then work on answering each of the Review Questions to check your understanding of the lecture. Check your answers as you go, but do try to answer the question before you look at the answer. Pay attention to the test-taking tips. They will help you do better on quizzes and exams.
- **Web Site Study Resources**
  http://www.whfreeman.com/understandingearth6e
  Complete the **Online Review Questions**. Pay particular attention to the explanations for the answers. The **Geology in Practice** exercises involve you in an ongoing case study involving ground contamination.

Exam Prep

Materials in this section are most useful during your preparation for quizzes and exams. The **Chapter Summary** and the **Practice Exercises** and **Review Questions** should simplify your chapter review. Read the **Chapter Summary** to begin your session. It provides a helpful overview that should refresh your memory.

Next, work on the **Practice Exercises** and **Review Questions**. Complete the exercises and questions just as you would an exam, to see how well you have mastered this chapter. After you answer the questions, score them. Finally, and most important, review each question that you missed. Identify and correct the misconception(s) that resulted in your answering the question incorrectly.

Chapter Summary

How does water move around and in the Earth?

- The hydrologic cycle is a flowchart or model for the distribution and movements of water on and below the surface of the Earth. The major reservoirs of the hydrologic cycle are oceans, glaciers, groundwater, lakes and rivers, the atmosphere, and the biosphere, in decreasing volumes. Water moves in and out of these reservoirs by various pathways and at varying rates. Over the short term a balance is maintained among the major reservoirs at and near the Earth's surface. However, climate change and longer-term tectonic processes such as mountain building and human activity can alter the rate of water movement between reservoirs and can affect the size of the reservoirs.

How does water move below the ground surface?

- The infiltration of water into the ground and groundwater flow are largely controlled by the porosity and permeability of the rock materials and topography. A groundwater aquifer is in dynamic balance between recharge (the amount of water that infiltrates into the aquifer) and discharge, which can occur from springs or wells.

What factors govern our use of groundwater resources

- Darcy's law describes the groundwater flow rate in relation to the slope of the water table and the permeability of the aquifer.
- Human demand for groundwater has increased to a level where pumping discharges from many aquifers exceeds the natural rates of recharge. As a result, aquifers are being depleted and groundwater tables are lowering to a point where dependably high-quality groundwater is becoming more and more of a challenge to supply.
- Water quality may be compromised by both natural and human sources of contamination. Various factors like recharge rate and aquifer size influence the amount of effort and effectiveness of attempts to clean up contamination.

What geologic processes and features are associated with groundwater?

- Caves, sinkholes, and associated karst topography are a result of the dissolution of carbonate rocks (limestone) by groundwater. Karst topography is well developed in regions of high rainfall, abundant vegetation, underlying fractured limestone, and an appreciable hydrologic gradient to enhance groundwater flow rates. Environmental problems associated with karst regions include surface subsidence from collapse of underground space and catastrophic cave-ins and sinkhole formation.
- All rocks below the groundwater table are saturated with water. With increasing depth, porosity and permeability typically decrease as confining pressure increases. Water temperature increases progressively with increasing depth and, as a result, the water dissolves more solids. Hot springs and geysers are surface expressions of the circulation of hydrothermal waters over a magma body or along a deep-seated fault.

Practice Exercises

Exercise 1: Evaluating rock materials as potential aquifers

You have recently purchased a rustic country cabin and need to drill a new well for a dependable water supply for the cabin. The geology around your cabin is complex because of ancient mountain-building events. Because the rocks are folded and faulted, it is difficult to predict what rock might be encountered as the water well is drilled. Which of the rock materials in the table has the potential of yielding groundwater to your well? Fill in the blank parts of the table. **Hint:** Keep in mind that permeability generally, but not always, increases as porosity increases. Permeability also depends on the sizes of the pores, how well they are connected, and how tortuous a path the water must travel to pass through the material. Refer to Figure 17.9 and Table 17.2.

Rock material	Porosity (high, medium, low)	Potential as an aquifer (good, moderate, poor)
Loose, well-sorted, coarse sand		
Silt and clay	*Low*	
Granite and gneiss		*Poor*
Highly fractured granite		
Sandstone	*Medium*	
Shale		
Highly jointed limestone		*Moderate to good*

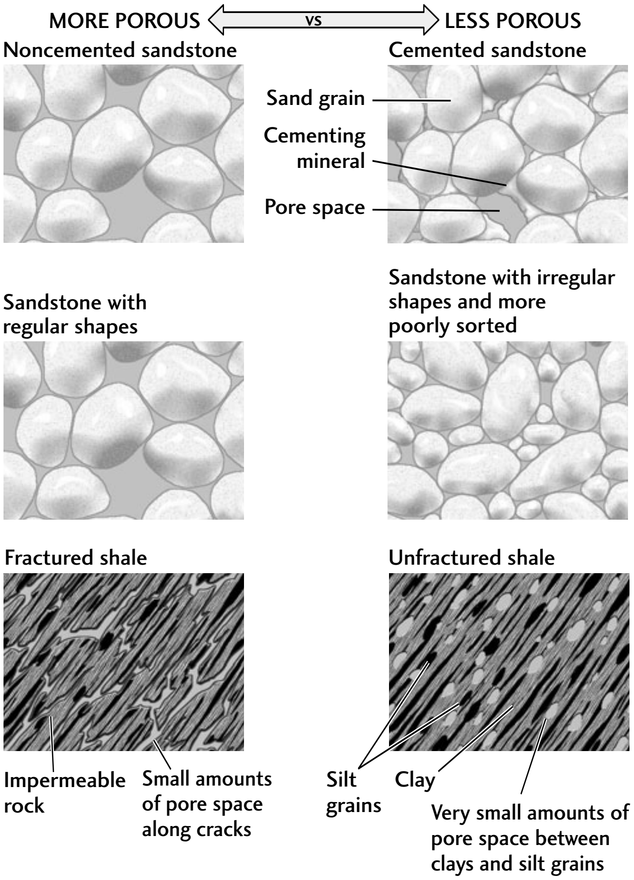
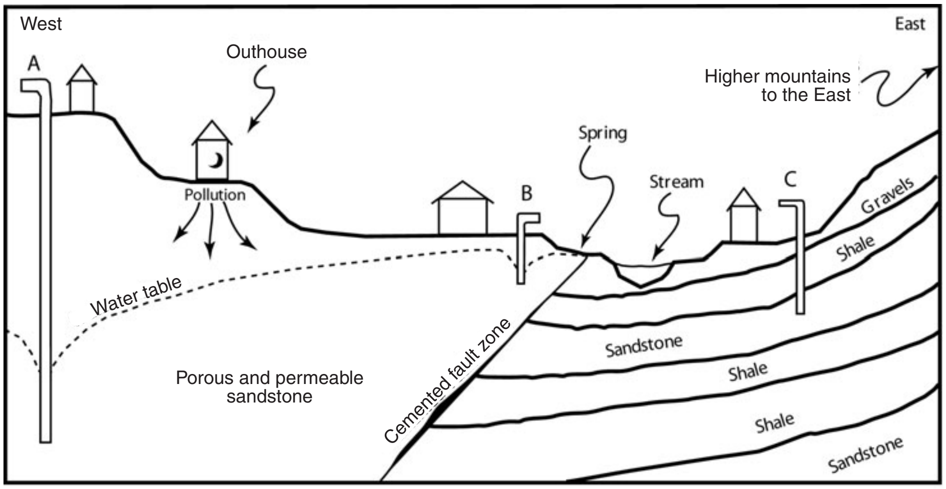


Figure 17.9. Porosity in rocks depends on several factors. In sandstones, the extent of cementation and the degree of grain sorting are both important. In shales, porosity is limited due to the small spaces between the tiny grains, but can be enhanced by fracturing.

Exercise 2: Evaluating groundwater wells



Evaluate the potential characteristics of each well as "high," "low," or "none."

Well A—potential for 1. pollution ______________________
2. artesian flow ______________________
3. discharge ______________________

Well B—potential for 4. pollution ______________________
5. artesian flow ______________________
6. discharge ______________________
7. long-term supply ______________________

Well C—potential for 8. pollution ______________________
9. artesian flow ______________________
10. discharge ______________________

Americans now drink more soda pop than water from the kitchen tap—47 gallons of soda pop to only 37 gallons of water per person each year.

—World Watch, 1990

Review Questions

Answers and explanations are provided at the end of the Study Guide.

1. In the hydrologic cycle, how does the evaporation rate from the land surface compare with the evaporation rate from the oceans?
   A. The evaporation rate is much greater from the land than from the oceans.
   B. The evaporation rate is much greater from the oceans than from the land.
   C. Evaporation rates from the land and oceans are equal.
   D. There is no reasonable comparison because it is too wet over the oceans for evaporation to occur.

   Hint: Refer to Figure 17.1.

2. The oceans contain by far the most amount of water on Earth. What is the second largest reservoir for water on Earth?
   A. lakes
   B. groundwater
   C. rivers
   D. polar ice and glaciers

3. The oceans contain about how much of the water in the hydrosphere?
   A. 96%
   B. 80%
   C. 50%
   D. 35%
4. What happens to the porosity as the grain size gets smaller?
   A. It increases.
   B. It remains unchanged.
   C. It decreases.
   D. none of the above
5. The water table is
   A. the top of the unsaturated zone.
   B. the top of the saturated zone.
   C. generally present only in moist climates.
   D. the contact between an aquifer and an underlying, impermeable layer of rock.
6. The ability of a solid, such as rock, to allow fluids to pass through it is
   A. discharge.
   B. capillary fringe
   C. permeability
   D. porosity.
7. An iciclelike deposit hanging from the ceiling of a cave is a
   A. stalactite.
   B. karst formation.
   C. stalagmite.
   D. quartzite.
8. Of the following rock types, which is the most susceptible to groundwater solution, therefore making it the formation most likely to have caves?
   A. granite
   B. sandstone
   C. limestone
   D. shale
9. A rock or soil layer that is water-bearing is a(n)
   A. perched water table.
   B. zone of aeration.
   C. stratum.
   D. aquifer.
10. The potential for geothermal energy is highest in a region that has numerous
    A. surface lakes.
    B. caves.
    C. hot springs.
    D. sinkholes.
11. An aquiclude is
    A. a confined aquifer.
    B. always located at the top of the water table.
    C. a rock layer that provides a good flow of water into a well.
    D. an impermeable rock layer that does not allow water to flow through it.
12. Which of the following would make the best aquifer?

	Porosity	Permeability
A. rock A	5%	high
B. rock B	10%	medium
C. rock C	30%	low
D. rock D	35%	medium

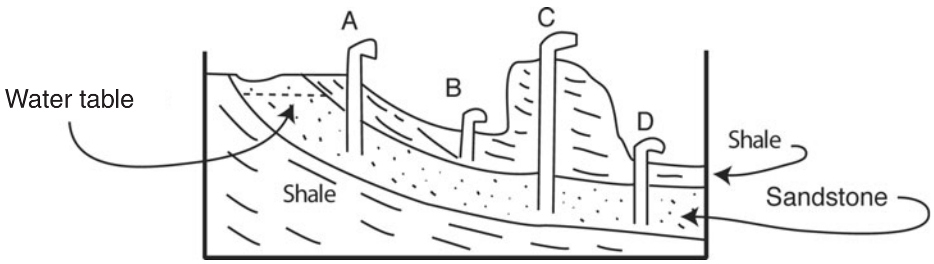
13. If all other conditions are equal, groundwater moves faster
    A. where sand grains are very well cemented.
    B. through loose sand than through clay.
    C. where permeability of the aquifer is lower.
    D. through clay than through sand.
    Hint: Refer to Figure 17.9.
14. A perched water table will most likely develop on top of
    A. shale.
    B. highly fractured granite.
    C. gravel.
    D. sandstone.
    Hint: Refer to Figure 17.14.
15. Rivers and streams that flow all year long, even during long periods without rain, are probably fed by
    A. sinkholes.
    B. springs.
    C. wells.
    D. karst conditions.
    Hint: Refer to Figure 17.14.

Test-Taking Tip

When you are unsure about an answer, you can sometimes make a correct guess just by looking at the responses. Long responses are more likely to be correct than short ones. This occurs because people who write test items have to be sure that the correct alternative is clear and accurate, and that may sometimes take more words. Obviously, this is a strategy to use only as a last resort, when you have no clue what the correct answer is. The safer strategy is to learn the material thoroughly.

16. An artesian well will flow if the
    A. top of the well is lower than the water table in the recharge area.
    B. top of the well is higher than the water table in the recharge area.
    C. bottom of the well is lower than the land surface in the recharge area.
    D. bottom of the well is lower than the water table in the recharge area.
    Hint: Refer to Figure 17.12.

17. Which well will exhibit artesian flow?



A. well A
B. well B
C. well C
D. well D
Hint: Refer to Figure 17.12.

Test-Taking Tip: Leveraging correct answers

Be alert for items that test the same idea or fact. Often an item you are sure about can clue a correct response for another item you are not so sure about. Example: Items 16 and 17 both test the same concept, namely, what makes an artesian well flow. Let's say the picture helped you figure out item 17 but you had left item 16 blank or weren't sure of your answer. Now, after working item 17, you should be able to go back and answer item 16 correctly. In essence, you are learning as you take the test. Learning by answering questions is one of the best ways to master material. Sound familiar?

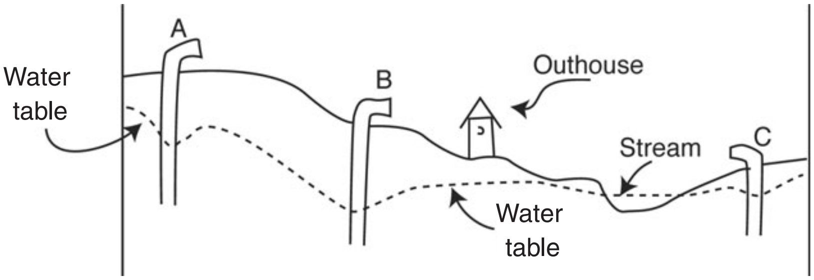
18. Which materials would make the best aquifer?
    A. clay and silt
    B. gravel and sand
    C. unfractured granite
    D. highly cemented sandstone

19. At a shallow depth, a well will most likely encounter a good water supply in which of the following locations?
    A. in granite on a ridge top
    B. in sandstone on a ridge top
    C. in shale in a valley bottom
    D. in sandstone in a valley bottom
    Hint: Make a sketch illustrating each situation.

Test-Taking Tip: Eliminating incorrect answers

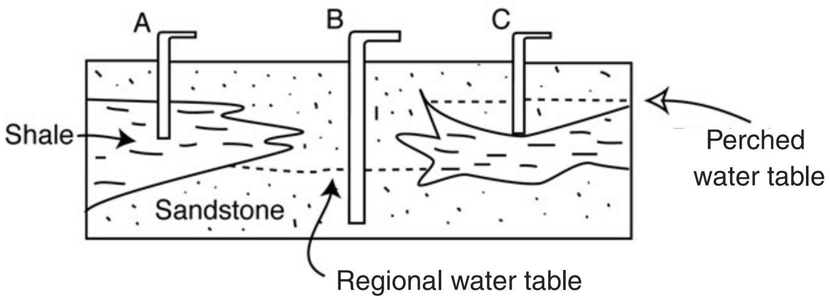
Unsure which is the right answer? Try going down the alternatives one at a time. Cross out each answer that you think is incorrect. Hopefully, only one alternative will remain. It will probably be the correct answer. Example: In 19, did you eliminate the two items that mentioned "ridge top"? If so, you narrowed your choice to shale and sandstone. If you completed the Practice Exercises, the choice between shale and sandstone was easy. If not and this were a real test, you would have to guess. But because you eliminated two of the incorrect items, your odds of guessing correctly would have doubled!

20. Which well is most likely to be pumping polluted water?



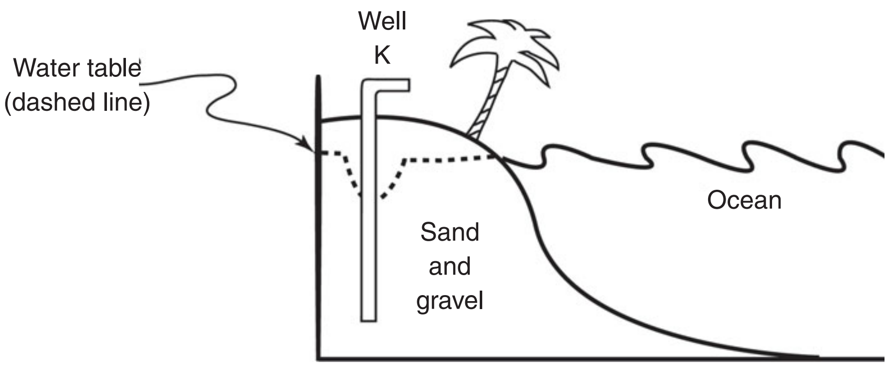
A. well A
B. well B
C. well C
D. none of the above

21. Which of the wells illustrated in the following diagram will produce the most water over the longest time?



A. well A
B. well B
C. well C
D. All of the wells will have high productivity.

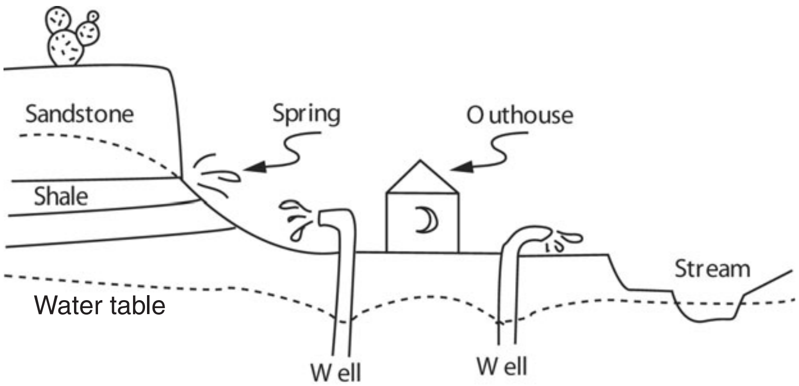
22. If water is pumped from well K faster than natural recharge replenishes it, the result is most likely to be



A. sinkholes.
B. ground subsidence.
C. salt-water intrusion.
D. a dry well.

Hint: Refer to Figure 17.17.

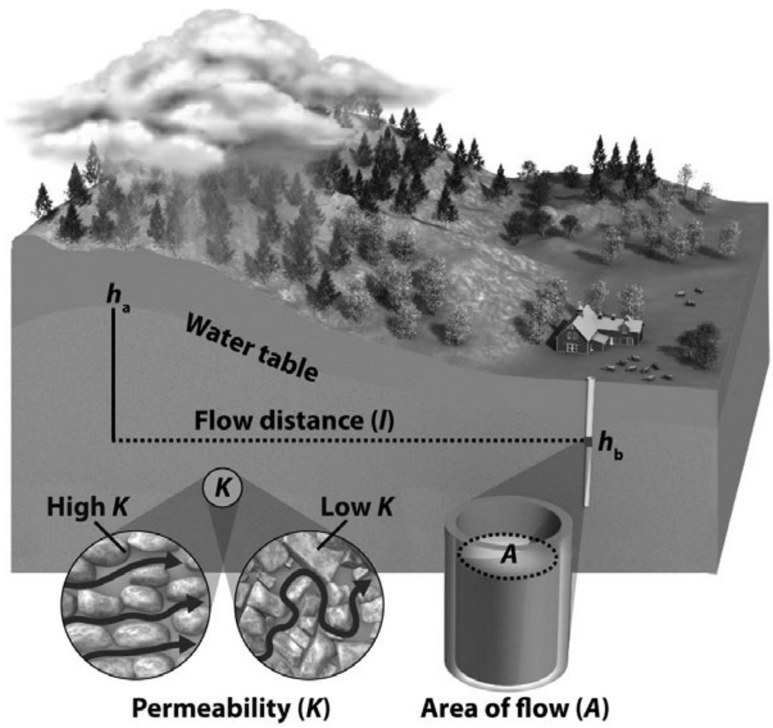
23. Which water source in the illustration is LEAST likely to be polluted?



A. the spring
B. well B
C. well C
D. the stream

24. Assume that you are dealing with the same aquifer at four different localities and that the cross-sectional area through which the water flows (A) and the hydraulic conductivity (K) are the same for each site. Given the following data on vertical drop (h) and flow distance (l), which well will produce water at the highest rate (Q)? Refer to Figure 17.15.

A. h = 20 meters and l = 500 meters
B. h = 30 meters and l = 1 kilometer
C. h = 300 meters and l = 6 kilometers
D. h = 600 meters and l = 100 kilometers



CHAPTER 18

Stream Transport from Mountains to Oceans

I do not know much about gods, but I think that the river is a strong brown god—sullen, untamed, and intractable.

—T. S. ELIOT, *THE DRY SALVAGES*

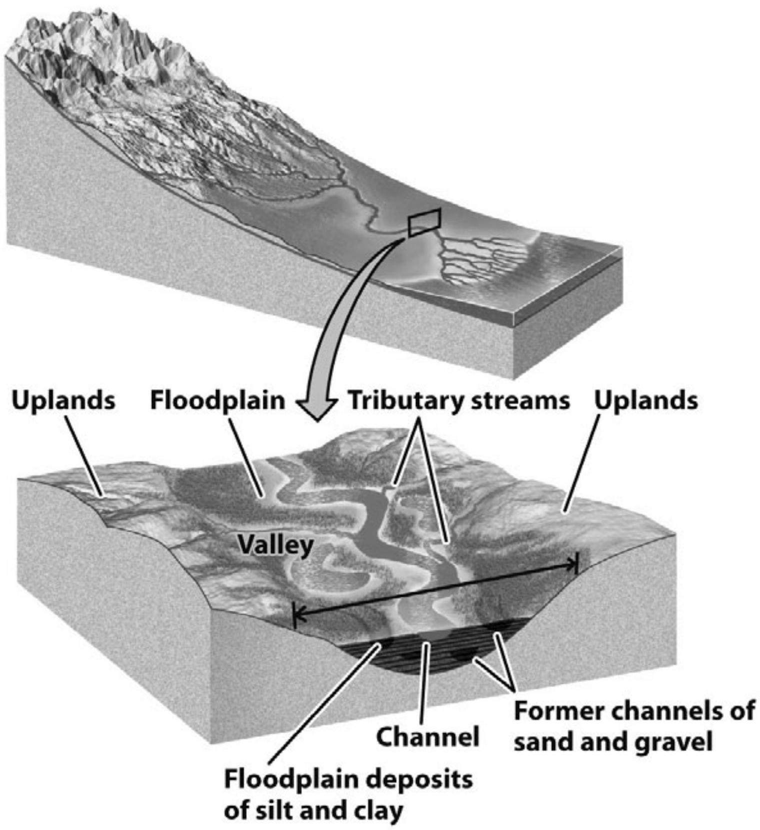


Figure 18.1. A stream flows in a channel that moves over a broad, flat floodplain in a wide valley. Floodplains may be narrow or absent in steep-walled valleys.

Before Lecture

As you preview this chapter, keep in mind the overarching question this chapter addresses: How do streams work?

Chapter Preview

- **How do stream valleys and their channels and floodplains evolve?**
  Brief answer: As a stream flows, it carves a valley. If the valley is wide enough, the channel will be surrounded by a floodplain into which the channel will overflow during times of high water, dropping its sediment load as the water spreads out and slows. Channels may be straight, meandering (winding), or braided (divided, interlacing channels).
- **How do drainage networks work as collection systems, and how do deltas work as distribution systems for water and sediment?**
  Brief answer: Rivers and tributaries constitute an upstream branching drainage network that collects the runoff for a particular drainage basin. Two notable examples are the Mississippi River basin and the Colorado River basin. The nature of a drainage pattern depends on the basin topography, rock type, and geologic structure. See Figure 18.8. Deltas form at the mouths of rivers as the river branches into numerous distributaries and drops (distributes) its load of sediment. See Figures 18.8, 18.18, and 18.19.
- **How does flowing water in streams erode solid rock and transport and deposit sediments?**
  Brief answer: Flowing water erodes rock by physical and chemical weathering processes. Turbulent flow is responsible for transporting sediments. When a stream flow slows, the stream loses its competence to carry sediment and deposits it. Refer to Figure 18.16.
- **How does a stream's longitudinal profile represent the equilibrium between erosion and sedimentation?**
  Brief answer: A stream's gradient (slope or longitudinal profile), base level, velocity (speed), discharge (amount of water), and the availability of sediment (load) determine whether a stream erodes, deposits, or reaches a balance between erosion and deposition—an equilibrium, called a graded stream. Changes in these stream characteristics can be used to predict the behavior of a stream when it is dammed or there is some other change in the drainage.

Vital Information from Other Chapters

Chapters 17 and 18 are a package. Be sure to review material in the first half of Chapter 17. Pay particular attention to the role that streams play in the hydrologic cycle (Figure 17.2) and how streams interact with the groundwater table (Figures 17.11, 17.14, and 17.23).

During Lecture

- Keep the big picture in mind. During this lecture you want to learn how streams work. You will learn how water flows in currents, how streams break up and erode solid rock, and how streams, channels, and entire drainage systems evolve over time.
- In this lecture it will be particularly helpful to keep the preview questions in front of you during the lecture. Notice which preview question is being addressed in each segment of the lecture.
- It may be helpful to bookmark some of the key figures so that you can refer to them and annotate your textbook as they are discussed during lecture. The

following are almost certain to be referred to: Figure 18.1 (components of a stream system), Figure 18.5 (formation of natural levees by river floods), Figure 18.8 (typical drainage networks), Figure 18.16 (velocity versus particle size), and Figure 18.20 (stream networks). Any figure from the text that is discussed in detail during lecture should be bookmarked and promptly sketched in your lecture notes. Be sure to leave space in your notes to add sketches of textbook figures. If you are not good at sketching or run out of time, cut and paste a copy of the figure into your notes.

Note-Taking Tip: Leave plenty of room for visual material

There is a lot of visual material in this lecture. It is important to take notes in a format that allows plenty of room to go back after lecture and make sketches that will help you understand what you wrote in your notes. If you take notes in a looseleaf notebook, leaving room is easy. Take notes on the right page, then you can go back after lecture and add simplified sketches on the blank left page. Use the text figures as models. If you take notes in a spiral notebook, you can divide the page into two columns by drawing a vertical line. Take notes in the right column and use the left column for sketches.

After Lecture

Review Notes

The perfect time to review your notes is right after lecture. The following checklist contains both general review tips and specific suggestions for this chapter.

Check Your Notes: Have you…

- ☐ explained how stream valleys and their flood plains evolve?
- ☐ explained how drainage systems work?
- ☐ explained how sediment loads are moved in water?
- ☐ explained the relationship between stream slope, velocity, discharge, and sediment transport?
- ☐ filled in from memory anything you didn't have time to write down during the lecture?
- ☐ added visual material to your notes? Suggestion: Be sure to include simple sketches of the types of drainage networks with an annotation about the factor(s) that influence the formation of each type.

Intensive Study Session

Set priorities for studying this chapter. Give highest priority to activities that involve answering questions. We recommend the following strategy for learning this chapter.

- **Text.** Review the key figures in Chapter 18. You have to understand these figures to answer the review questions. Focus on Figure 18.1 (components of a stream system), Figure 18.3 (channel patterns), Figure 18.5 (the formation of natural levees by river floods), Figure 18.8 (typical drainage networks), Figure 18.9 (antecedent stream), Figure 18.10 (superposed stream), Figure 18.23 (the longitudinal profile), and Figures 18.24 and 18.25 (base level changes). This is a long list of key figures, so feel free to go right to the questions and refer to the figures as you answer them. An excellent review strategy is to work through all ten exercises at the end of the chapter sometime before your next exam. These are short-answer exercises and won't take long if you know the material.

- **Practice Exercises and Review Questions.** Complete Practice Exercise 1. This is an easy way to master one of the most important ideas in the chapter (stream velocity). Then do the other Practice Exercises and the Review Questions. Check your answers as you go, but do try to answer each question before you look at the answer.
- **Web Site Study Resources**
  http://www.whfreeman.com/understandingearth6e

  Complete the **Online Quiz.** Pay particular attention to the explanations for the answers. The **Flashcards** will help you learn the terms in this chapter.

  Albert Einstein once addressed the question, Why do rivers meander? Figure 18.3 illustrates steps in the formation of river meanders. Why meanders form is still debated. The **Geology in Practice** exercises explore ideas for the formation of river meanders and their characteristics.

Exam Prep Tip

Study Chapters 17 and 18 as one integrated unit. Think of ways groundwater and stream flow are linked.

Exam Prep

Materials in this section are most useful during your preparation for quizzes and exams. The **Chapter Summary** and the **Practice Exercises** and **Review Questions** should simplify your chapter review. Read the **Chapter Summary** to begin your session. It provides a helpful overview that should refresh your memory.

Next, work on the **Practice Exercises** and **Review Questions**. Complete the exercises and questions just as you would an exam, to see how well have mastered this chapter. After you answer the questions, score them. Finally, and most important, review each question that you missed. Identify and correct the misconception(s) that resulted in your answering the question incorrectly.

Mark Twain, noting how muddy the Missouri was, proclaimed it "too thick to navigate, but too thin to cultivate."

Chapter Summary

How do stream valleys and their channels and floodplains evolve?

- The physical features (drainage pattern, stream channel, floodplain, meander bends in the channel, alluvial fans and deltas) of a stream system evolve over time.
- When sediment-laden water overflows the banks of a channel during flood stage, the water drops sediment, which builds up natural levees and floodplain deposits.

How do drainage networks work as collection systems and deltas as distribution systems for water and sediment?

- Drainage networks exhibit different patterns depending on topography, rock type, and geologic structure in the drainage area. Near its mouth, a river tends to branch downstream into distributary channels forming a delta.
- Deltas are major sites of sediment deposition. Where waves, tides, and shoreline currents are strong, deltas may be modified or even absent. Tectonics controls delta formation by uplift in the drainage basin and subsidence in the delta region.

How does flowing water in streams erode solid rock and transport and deposit sediments?

- Streams erode, transport, and deposit sediments. Turbulent stream flow allows water to erode and transport sediment by suspension, saltation, rolling, and sliding. The tendency for particles to be carried in suspension is countered by gravity, pulling them to the bottom and measured by the settling velocity. Refer to Figure 18.15.
- Deposition of sediments occurs when the velocity of the stream decreases. Refer to Figure 18.16.

How are the stream's gradient (slope), velocity (speed), discharge (amount of water), and sediment transport linked?

- Whether a stream is dominantly eroding or depositing its load (sediments) is determined by stream velocity. Stream velocity in turn depends on the stream's gradient (slope), discharge (amount of water in the stream), load (sediment in transport), and channel characteristics. A stream's drainage patterns, the stream channel, and the floodplain evolve in response to changes in stream velocity, gradient, sediment load, and discharge and the characteristics of the landscape over which the stream flows. Alluvial fans form at mountain fronts in response to an abrupt widening of the stream valley and a change in slope.
- The longitudinal profile represents the stream gradient. It is a plot of the elevation of the stream channel bottom at different distances along the stream's course. The longitudinal profile is controlled by local (the river into which the stream flows or a lake) and regional (the ocean) base levels. Refer to Figure 18.24. Streams cannot cut below base level, because base level is the bottom of the hill.

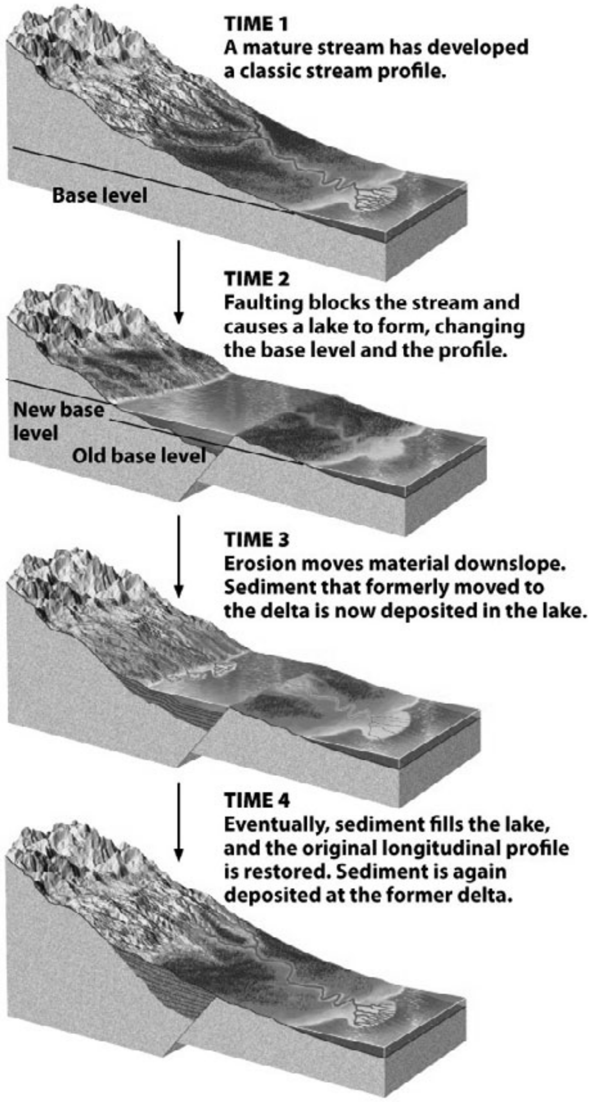


Figure 18.24. The base level of a stream controls the lower end of its logitudinal profile. The profiles illustrated here are for natural regional and local base levels of a river flowing into an ocean. In each river segment, the profile adjusts to the lowest level that the river can reach.

Practice Exercises

Exercise 1: Stream velocity

Stream velocity is a dependent variable that governs stream behavior—whether a stream is dominantly eroding and transporting or depositing sediments along a section of the channel. Various independent variables (factors) influence stream velocity and therefore can affect the behavior of a certain stretch of stream channel. The major independent variables affecting velocity are listed in the table. Complete the table by describing how changes in each factor affect stream velocity.

Variable affecting stream velocity	Relationship of variable to stream velocity	Analogy
Gradient—the slope of the stream channel		You tend to walk faster down a steeper slope.
Discharge—the amount of water in the stream channel		Will you move into a new house slower or faster if you have more people helping you?—faster.
Sediment load		Typically, will you travel faster or slower if you are carrying more in your backpack?—slower.
Channel characteristics		
• Channel roughness	*As channel roughness increases, velocity decreases.*	*Cross-country hiking without a trail tends to slow one down.*
• Channel shape	*The stream has more contact with the channel surface if the channel is very wide or very narrow. More contact with the channel increases drag and decreases velocity.*	*When you have more contact with the ground surfaces move slower. Crawling is slower than walking.*

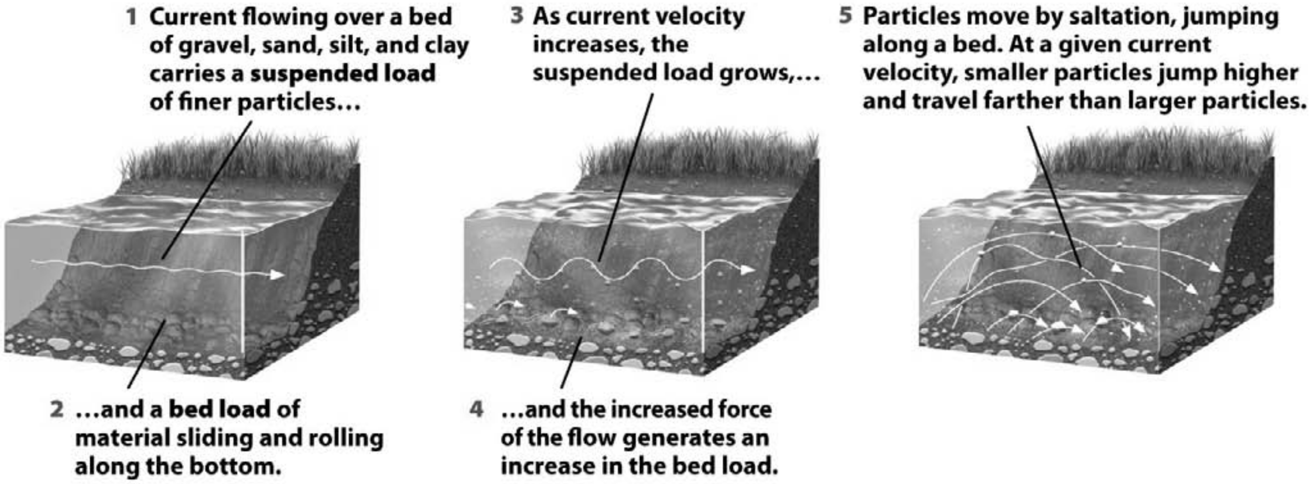


Figure 18.15. A current flowing over a bed of sand, silt, and clay transports particles in two ways: as bed load, the material sliding and rolling along the bottom; and as suspended load, the material temporarily or permanently suspended in the flow itself. Saltation is an intermittent jumping motion of grains. In general, the smaller the particle, the higher it jumps and the farther it travels.

Exercise 2: Relationship between stream flow and groundwater

Why do streams in desert regions typically flow intermittently and streams in more temperate regions, like New England, flow year-round? Drawing well-labeled diagrams illustrating each situation with a brief discussion is an excellent way to answer this question. Refer to Figure 17.11.

Desert (ephemeral) stream	Temperate (perennial) stream

Exercise 3: How do rivers cut through mountain ranges?

The Kali Gandaki River cuts one of the deepest gorges on Earth right through the Himalayan mountains. Briefly describe two ways that a river can cut through a mountain range. Refer to Figures 18.9 and 18.10.

A. ______________________________

____

____

B. ______________________________

____

____

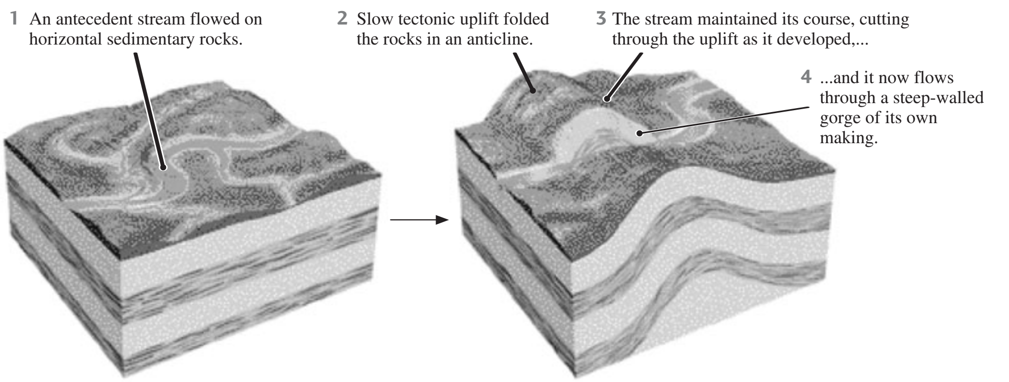


Figure 18.9. An antecedent stream.

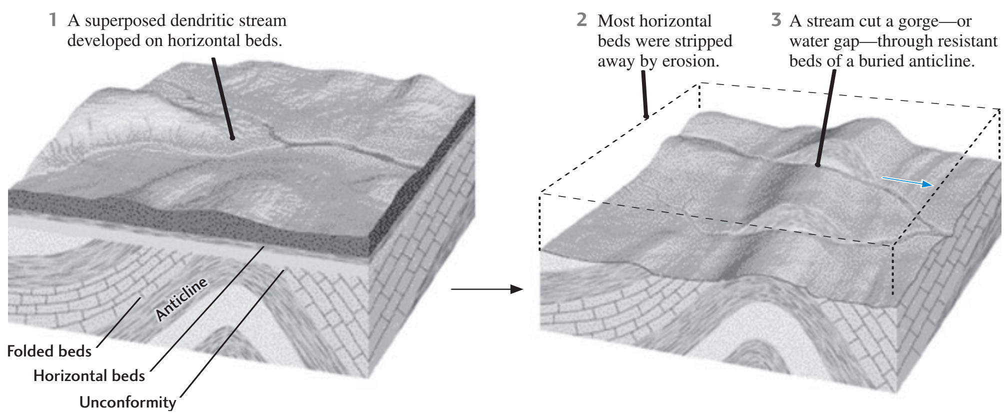


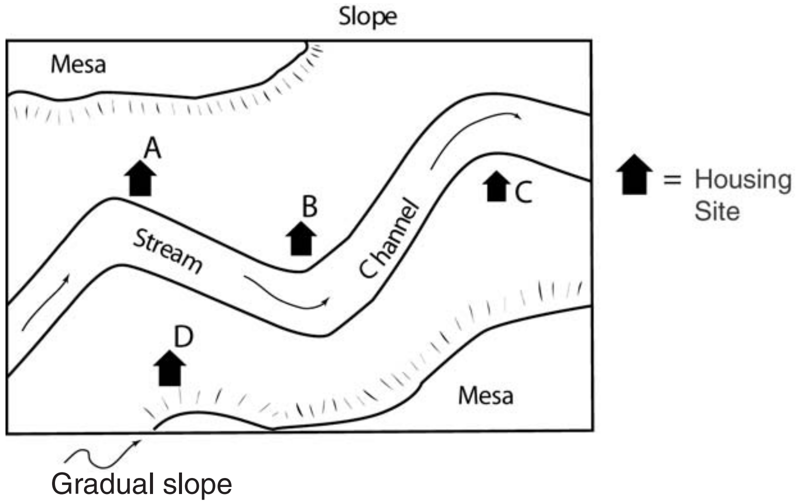
Figure 18.10. The development of a superposed stream by erosion of horizontal beds overlying folded beds of varying resistance to erosion.

Review Questions

1. Where do rivers obtain the power to erode and transport sediments?
   A. heat
   B. gravity
   C. electricity
   D. friction
2. The volume of water that flows past a given point along a stream channel in a given interval of time is the
   A. velocity.
   B. discharge.
   C. capacity.
   D. gradient.
3. If the gradient (slope) of a stream is increased, what happens to the velocity of the water?
   A. increases
   B. decreases
   C. remains unaffected
   D. may increase or decrease
4. Stream erosion and deposition are primarily controlled by a river's
   A. width.
   B. velocity.
   C. depth.
   D. channel shape.
   Hint: Refer to Figure 18.16.
5. You are canoeing a river in remote Alaska and your GPS shows an elevation of 2500 feet. After paddling for five days, you calculate that you have traveled 200 miles. Your GPS now shows an elevation of 2300 feet. What is the stream's gradient in feet/mile for the stretch you just canoed?
   A. 1 foot/mile
   B. 2 feet/mile
   C. 5 feet/mile
   D. 10 feet/mile
6. A trellis drainage pattern forms on
   A. horizontal lava flows.
   B. folded and tilted sedimentary rock layers of varying resistance.
   C. a dome.
   D. horizontal sedimentary rocks.
   Hint: Refer to Figure 18.8.
7. Stream competence is measured by the
   A. largest particle size the stream can transport.
   B. amount of material in the dissolved load.
   C. maximum width of the channel along the floodplain.
   D. total amount of suspended and bed load.
8. Particles tend to settle out of the suspended load in which order?
   A. clay, sand, pebbles
   B. pebbles, sand, silt
   C. sand, pebbles, cobbles
   D. clay, pebbles, sand
9. Active erosion in a meander bend takes place
   A. in the center of the stream.
   B. along the outer bank of a bend.
   C. along the inside bank of a bend.
   D. near a stream's headwaters.
10. Entrenched meanders like those shown for the San Juan River in Figure 18.2 are evidence of a
    A. decrease in stream gradient.
    B. decrease in discharge.
    C. change such that the river has renewed ability to erode.
    D. decrease in stream velocity.

11. If a dam is placed across a stream that has been carrying a large volume of sediment, the stream would probably
    A. deposit downstream and erode upstream from the dam.
    B. erode downstream and not change upstream from the dam.
    C. erode downstream and gradually deposit upstream from the dam.
    D. not change downstream but deposit upstream from the dam.
    Hint: Refer to Figure 18.25.
12. The regular dumping of crushed rock and coal waste into a stream leads to
    A. erosion upstream and deposition downstream from the dump.
    B. erosion both upstream and downstream from the dump.
    C. deposition both upstream and downstream from the dump.
    D. deposition upstream and erosion downstream from the dump.
13. If flood control engineers straighten out a meandering stream channel, the stream probably
    A. flows more slowly in the straightened stretch.
    B. deposits in the straightened stretch.
    C. downcuts in the straightened stretch.
    D. downcuts and flows more rapidly in the straightened stretch.
14. If a flood is classified as a fifty-year flood,
    A. it has been fifty years since the last flood that large occurred.
    B. a flood at least that large has occurred every year within the last fifty years.
    C. the flooded area is safe from a serious flood for at least fifty years.
    D. a flood that large occurs on the average of once every fifty years but also has a chance of occurring during any year.
    Hint: Refer to Figure 18.22.
15. Stream velocity generally increases downstream even though stream gradient decreases because
    A. the river channel typically becomes rougher downstream.
    B. channels typically meander less downstream.
    C. the amount of sediment decreases downstream.
    D. stream discharge typically increases downstream as tributaries contribute their water.
16. If the regional base level of a stream is lowered,
    A. the stream will deposit to raise the base level to its former position.
    B. the stream will begin to downcut at its headwaters.
    C. the stream will begin to downcut at its downstream end, and downcutting will progress upstream until the stream channel is graded with the new base level.
    D. it will have no effect on the stream.
17. Where streams emerge from a narrow mountain canyon onto a flat plain, alluvial fans form because
    A. the increase in the amount of water from tributary canyons results in deposition.
    B. stream velocity decreases due to a widening of the stream channel and a decrease in gradient.
    C. stream velocity increases due to a decrease in gradient.
    D. all of the above.
    Hint: Refer to Figure 18.26.
18. What stream feature(s) can develop as a result of regional uplift and erosion?
    A. accelerated downcutting in steams
    B. stream terraces
    C. incised meanders
    D. all of the above
    Hint: Refer to Figures 18.26 and 18.27.

19. Which house in the illustration will ultimately fall into the river channel due to channel bank erosion?



A. house A
B. house B
C. house C
D. house D

Hint: Refer to Figure 18.3.

CHAPTER 19

Winds and Deserts

The wind grew stronger, whisked under stones, carried up straws and old leaves, and even little clods, marking its course as it sailed across the fields. The air and sky darkened, and through them the sun shone redly, and there was a raw sting in the air.

—JOHN STEINBECK, *THE GRAPES OF WRATH,* 1939

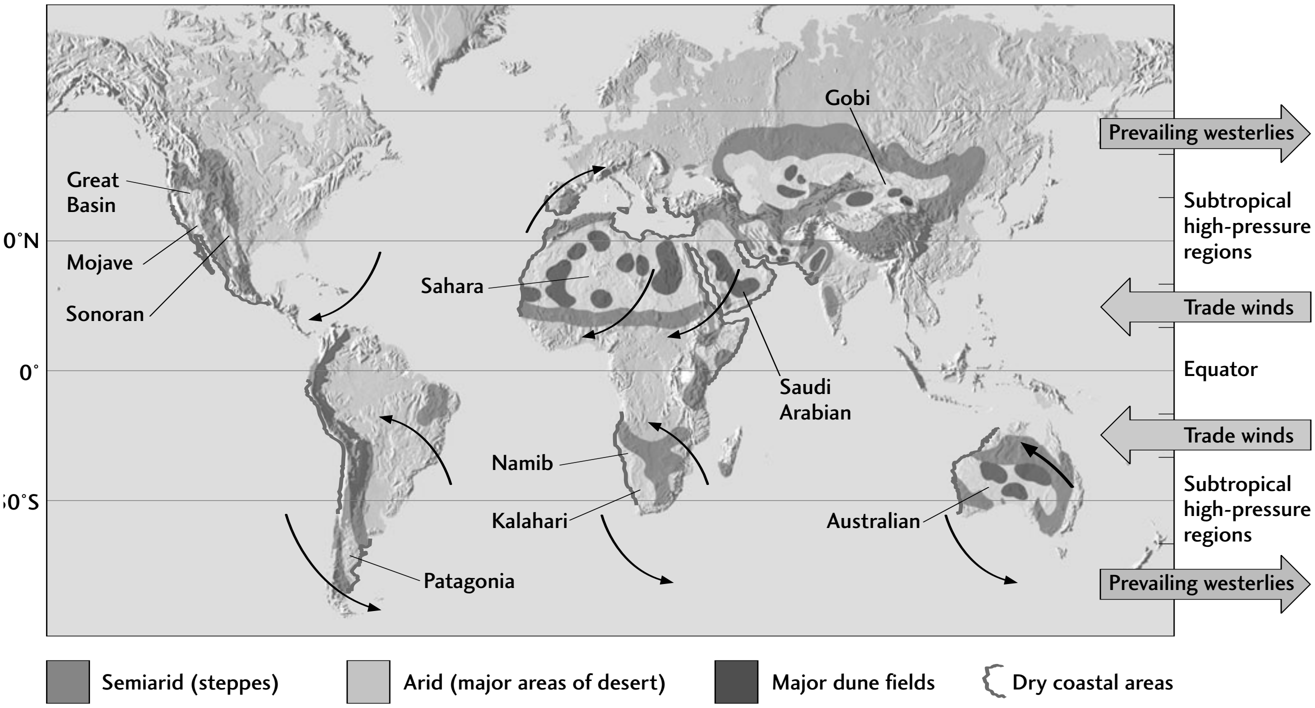


Figure 19.15. Major desert areas of the world (exclusive of polar deserts) in relation to prevailing wind directions and major mountain and plateau areas. Sand dunes make up only a small proportion of the total desert area.

Before Lecture

Before you attend lecture be sure to spend some time previewing the chapter. For an efficient preview, use the questions below. **Chapter Preview** questions constitute the basic framework for understanding the chapter. Preview works best if you do it just before lecture. With the main points in mind, you will understand the lecture better. This will in turn result in a better and more complete set of notes.

Chapter Preview

- **Where do winds form and how do they flow?**
  Brief answer: Warm air rises at the equator, causing cloudiness and abundant rain in the tropics. Air flows toward the poles and at about 30 degrees north and 30 degrees south the cooled air sinks, warms up, absorbs moisture, and often produces dominantly clear skies and deserts. Refer to Figures 19.1 and 19.15.
- **How do winds erode and transport sand and finer-grained sediments?**
  Brief answer: Turbulent airflow and forward motion combine to lift finer particles into the wind and carry them by suspension, sliding, rolling, and saltation.
- **How do winds deposit sand dunes and dust?**
  Brief answer: A decrease in wind velocity and gravity causes deposition of sediment being transported by wind. The formation and shape of sand dunes depends on the supply of sand and the strength and variability of wind direction.
- **What factors contribute to the existence of desert regions on Earth?**
  Brief answer: Global atmospheric circulation patterns, distance from water (oceans), topographic barriers like mountains, cold ocean currents, and polar climates contribute to the formation of desert conditions on Earth.
- **What features are characteristic of desert landscapes?**
  Suggestion: Many diagnostic features of deserts are described in this chapter. One question to ask yourself as you read about these features is, "What features might a geologist look for in the rock record that would serve as evidence for past desert conditions at localities that are no longer deserts?"

How much time do you have before lecture begins?	How to use it
30 minutes or more	With this much time you can dig deep into the chapter. Do as many of the following as your time allows. ✓ Read the **Chapter Preview** questions and brief answers. ✓ Read the **During Lecture** suggestions. ✓ Study the key figure(s) for this chapter (usually shown at the beginning of the Study Guide chapter). ✓ Study and annotate any additional figures, hints, or suggestions alluded to in the **Chapter Preview.** ✓ If time allows, do the **Practice Exercises** and **Review Questions.**
15–20 minutes	Do a brief but intense preview. ✓ Read the **Chapter Preview** questions and brief answers. ✓ Read the **During Lecture** suggestions. ✓ Study the key figure for this chapter (always shown at the beginning the Study Guide chapter).
5–10 minutes	Read the **Chapter Preview** questions and brief answers. Focus on getting the questions clearly in mind. Then listen for answers during lecture. Even five minutes of previewing helps!

Vital Information from Other Chapters

Review the section Hydrology and Climate in Chapter 17. Pay particular attention to Figure 17.3.

During Lecture

One goal for lecture should be to leave the room with good answers to the **Chapter Preview** questions.

- To avoid getting lost in details, keep the big picture in mind. Chapter 19 tells two related stories. First is the story of wind: Earth's atmospheric circulation pattern and how wind transports sediment and creates sand dunes. Second is the story of deserts: how Earth's circulation patterns produce deserts 15 to 30 degrees away from the equator and how unique features of a desert landscape (for example, desert pavement, sand dunes, and pediments) evolve.
- Focus on understanding Figure 19.1 (atmospheric circulation) and Figure 19.12 (dune types).

After Lecture

Review Notes

The perfect time to review your notes is right after lecture. The following checklist contains both general review tips and specific suggestions for this chapter.

Check Your Notes: Have you…

☐ added your own sketches of the four types of sand dunes?
☐ created a brief big picture overview of this lecture (using a sketch or written outline)? Suggestions: Sketch a simple figure that integrates the information in Figures 19.1 and 19.15. Your sketch should answer the question "Why do deserts tend to occur between 15 to 30 degrees on either side of the equator?"

Intensive Study Session

Set priorities for studying this chapter. Give highest priority to activities that involve answering questions. We recommend the following strategy for learning this chapter.

- **Text.** Review the key figures in the chapter. Focus your attention on understanding Earth's atmospheric circulation pattern (Figure 19.1) and how it is related to the formation of deserts, as shown in Figure 19.15. Then move on to understanding other features of deserts. Pay particular attention to the types of sand dunes (Figure 19.12) and to the formation of mountain pediments (Figure 19.20).
- **Practice Exercises and Review Questions.** Exercise 1 will help you remember the different types of sand dunes. Then answer the review questions to check your understanding of the lecture. Check your answers as you go, but do try to answer the question before you look at the answer.
- **Web Site Study Resources**
  http://www.whfreeman.com/understandingearth5e

  Complete the **Web Review Questions**. Pay particular attention to the explanations for the answers. Do the **Online Review Exercises** *Identify the World's Major Deserts* and *Understanding Global Air Circulation Patterns*. Explore the link between dust storms, rainforests, and coral reefs by doing the **Geology in Practice** exercises.

Exam Prep

Materials in this section are most useful during your preparation for exams. The **Chapter Summary** and the **Practice Exercises** and **Review Questions** should simplify your chapter review. Read the **Chapter Summary** to begin your session. It provides a helpful overview that should refresh your memory.

Next work on the **Practice Exercises** and **Review Questions.** Complete the exercises and questions just as you would for an exam, to see how well you have mastered this chapter. After you answer the questions, score them. Finally, and most important, review each question that you missed. Identify and correct the misconception(s) that resulted in your answering the question incorrectly.

Chapter Summary

Where do winds form and how do they flow?

- Prevailing winds on Earth are largely controlled by zones of rising and sinking air and the Coriolis effect. Hot (less dense) air rises and carries moisture up to where it condenses and falls as precipitation. As air radiates heat to space in the upper atmosphere, it cools, becomes denser, sinks to the surface, and flows back toward the equator. Sinking air is typically very dry because it comes from the cold and dry upper atmosphere. Because of the rotation of Earth, the Coriolis effect deflects air flow in both hemispheres.

What factors contribute to the existence of desert regions on Earth?

- Deserts are regions where evaporation exceeds precipitation.
- Desert regions on Earth are the result of (1) global air circulation patterns, which generate a relatively stationary zone of descending, warm, dry air at about 15° to 30° north and south of the equator; (2) distance from large bodies of water like the oceans; (3) the rain shadow generated by high mountains, which blocks the flow of moisture-rich air; (4) cold ocean currents, which reduce air temperatures and reduce the transport of moisture by the air; and (5) polar climates, where the air is so cold that it holds very little moisture at all.

How do winds erode and transport sand and finer-grain sediments?

- Wind is a major erosional and depositional agent, moving enormous quantities of sand, silt, and dust. Turbulent air flow within wind erodes and transports particles by suspension, sliding, rolling, and saltation. As velocity decreases, sediment is pulled out of air by gravity and is deposited as a blanket or as dunes of sand and dust.

How do winds deposit sand dunes and dust?

- Only about 20% of the area of desert regions is covered by sand. The distinctive types of sand dunes are governed by the amount of sand available, the strength of the wind, and the variability of wind direction. Loess, wind-blown dust, is another important wind deposit.

What features are characteristic of desert landscapes?

- Geologic and topographic features associated with desert regions include sand dunes, loess deposits, evaporite (salt) deposits, desert pavement, ventifacts (sandblasted rocks), alluvial fans and alluvial sands and gravels, pediments, mesas, distinctive soils (pedocals, rich in calcium carbonate), and rusty orange-brown colors of weathered rock surfaces. Some of these features are preserved in the rock record and provide geologists clues to ancient desert regions that no longer exist.

Practice Exercise

Exercise: Sand dune types

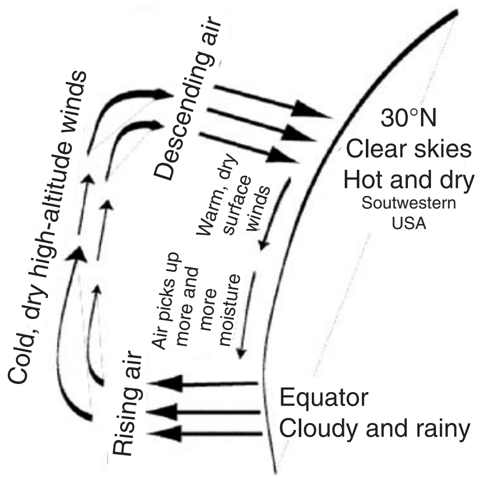
Complete the table. Figure 19.12 and the textbook section Dune Types will be helpful.

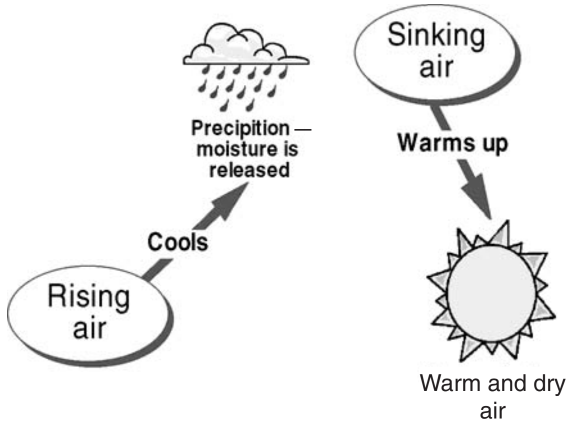
Dune type	Characteristics	Sand supply	Wind direction/strength
Barchan			
Transverse			
Blowout		*Limited to moderate*	*Unidirectional/gusty*
Linear (See Figure 19.8.)			

Review Questions

1. Wind belts on Earth are largely controlled by
   A. regions of sinking air.
   B. regions of rising air.
   C. the Coriolis effect.
   D. all of the above.
2. Deserts may be caused by all of the following EXCEPT
   A. rising air.
   B. proximity to cold ocean currents.
   C. great distance from the ocean.
   D. descending air.
3. As a dune advances,
   A. sand erodes from the windward slope.
   B. sand is deposited on the leeward slope.
   C. particles move over the crest by saltation.
   D. all of the above occur.
4. As a dune grows in height, wind streamlines over the dune become
   A. less compressed and their velocity decreases.
   B. less compressed and their velocity increases.
   C. more compressed and their velocity decreases.
   D. more compressed and their velocity increases.
5. A dried lake bed that has abundant salt deposits and that is flat enough for a space shuttle to land on is called a(n)
   A. pediment.
   B. desert pavement.
   C. playa.
   D. oxbow lake.
6. Loess is
   A. fine dust transported by wind in suspension and deposited on land.
   B. dust transported by wind, deposited, and then later eroded and redeposited by water.
   C. fine sand transported and deposited by wind.
   D. fine-grained salt particles eroded by wind off a playa surface.

Hadley cell
Atmospheric circulation pattern generated by the differential heating of the Earth's surface



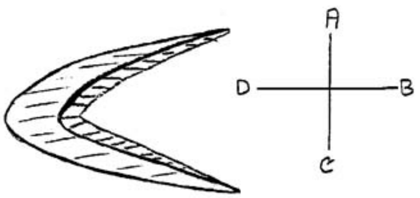


7. Desert pavement may be the product of
   A. deposition of gravel by flash floods.
   B. concentration of coarser particles as wind removes finer material.
   C. deposition of mud by flash floods.
   D. desert varnish.
   Hint: Refer to Figure 19.7.

8. Rock material carried in suspension by wind is mostly the size of
   A. sand.
   B. silt and clay.
   C. gravel.
   D. pebbles.

9. The Coriolis effect deflects winds in the northern hemisphere to the
   A. left (westward).
   B. right (eastward).
   C. north.
   D. south.
   Hint: Refer to Figure 19.1 and the section Wind Belts in the text.

10. You are lost in the Goblin Desert. The nearest town is due south. Winds blow from the south to the north but there is no wind blowing today. Furthermore, the sun is totally obscured by clouds. Without a compass, in which direction are you going to hike, given the orientation of the barchan dune shown in the illustration?



   A. direction A
   B. direction B
   C. direction C
   D. direction D
   Hint: Refer to Figure 19.12.

11. While hiking through a dune-filled coastal plain on a windless morning, you become surrounded by a dense fog and realize that you are lost. You know you are near a shoreline and that the beach will lead you back to camp, but you don't know which direction it is in. You recognize the crescent-shaped dunes that wrap moderate depressions as blow-out dunes. According to your compass, the tapered arms of the dunes point south. Then, remembering that in this region strong, gusty winds come onto the coastal plain off the ocean, you immediately remember which direction you should head to get to the beach:
    A. north
    B. south
    C. east
    D. west
    Hint: Refer to Figure 19.12.

12. Why are evaporites significant geological deposits?
    A. They are a good paleoenvironmental indicator of ancient desert conditions.
    B. They are a major source of chemicals like borax.
    C. They are a source of salt for the dinner table.
    D. all of the above

13. Petroglyphs, early Native American artwork, is scratched through ____________.

CHAPTER 20

Coastlines and Ocean Basins

. . . over all the face of Earth
Main ocean flowed, not idle; but, with warm
Prolifick humour softening all her globe . . .

—JOHN MILTON, *PARADISE LOST,* BOOK VII, LL. 278–280

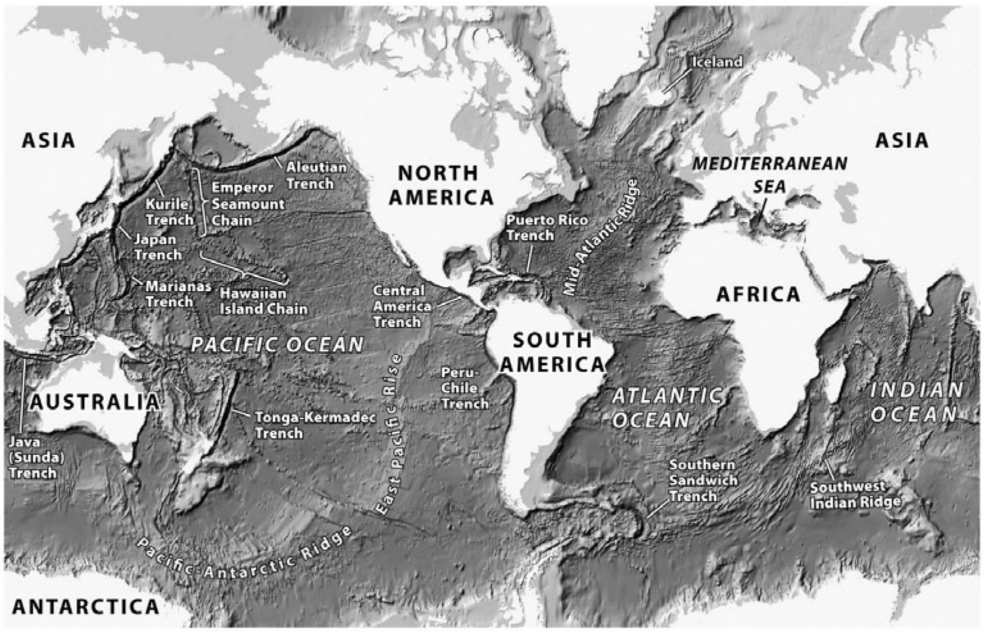


Figure 20.20. A topographic map of Earth's ocean basins, showing the major features of the deep seafloor.

Before Lecture

Chapter Preview

- **How does the geology of the oceans differ from that of the continents?**
  Brief answer: Ocean basins are created at ocean ridges (diverging margins) by volcanism and are destroyed in the brief period of several hundred million years by subduction at converging margins.
- **What processes shape the shoreline?**
  Brief answer: Waves and tides interact with tectonics to shape the shoreline. Winds blowing over the sea create waves. Waves approaching shallow water along the shoreline are transformed into breakers and refracted into longshore currents and longshore drift, which transports sand along the beach. Tides deposit sediment on longshore flats. Tectonic uplift creates cliffs and headlands, which are smashed by wave action, leaving behind cliff remnants called seastacks. Tectonic subsidence creates areas of long, wide beaches and low-lying coastal plains and sandbars, which may evolve into barrier islands.
- **How do hurricanes affect coastal areas?**
  Brief answer: Extremely high winds and a storm surge are characteristic of hurricanes. The storm surge can flood low-lying areas up to depths of 10 m and can be devastating over a very broad area of the coastline.
- **What are the major components of the continental margins and adjacent ocean floor?**
  Brief answer: Continental margins are flooded portions of the continent. The continental slope marks the edge of the continent and a transition to deeper water and the ocean floor. Turbidity currents transport fine sediments off the continental shelf and onto the adjacent abyssal ocean floor.
- **How is deep seafloor formed?**
  Brief answer: The deep seafloor is constructed by basaltic volcanism at ocean ridges and ocean hot spots and by deposition of fine-grained clastic and biochemically precipitated sediments. Prominent features of the deep seafloor landscape include seamounts, guyots, and abyssal plains and hills. Refer to Figures 20.23 and 20.25. Oceanic trenches (Figure 20.25) are formed where ocean plates converge.
- **What are the characteristics of a mid-ocean ridge?**
  Brief answer: A rift valley runs along the crest, basaltic volcanism and earthquake activity are common along the ridge crest, and smokers (hydrothermal springs) percolate through cracks on the flanks of the ridges. Refer to Figures 20.22 and 20.24.
- **What kinds of sedimentation occur in and near the oceans?**
  Terrigenous (note the similarity to the word *terrain*) *sediments* are muds and sands eroded from the continent and deposited by turbidity currents along the continental shelf. *Biochemical sediments* result from deposition of calcium carbonate from shells and coral reefs. *Open-ocean* (pelagic) *sediments* result from clays and oozes of calcium carbonate and silica shells of microorganisms (see Figure 20.26). *Evaporite sediments* result from intense evaporation in shallow tropical seas. Sediments derived from volcanic ash and lava flows are deposited near subduction zones. The carbonate compensation depth (CCD) is the level in the ocean below which calcium carbonate dissolves. Refer to Figure 20.27.

Vital Information from Other Chapters

Chapters 2, 4, and 5 contain key information on ocean basins and rock materials associated with marine environments. In Chapter 2, review Figures 2.4, 2.8, and 2.15. In Chapter 4, Igneous Rocks, review pages 103–108. In Chapter 5, review Figures 5.9 and 5.22, Tables 5.2 and 5.4, and Earth Issues 5.1. A quick reread of Chapter 5 would help immensely.

During Lecture

One goal for lecture should be to leave the room with good answers to the **Chapter Preview** questions. To avoid getting lost in details, keep the big picture in mind: Chapter 20 tells the story of the ocean depths. You will learn about various landform features of the deep ocean, continental margins, and shoreline and learn about the geological processes that create them.

Note-Taking Tip

There is a lot of new terminology in this chapter. Because the chapter is so terminology-rich, the lecturer may use terms you are not familiar with. Mark, circle, or underline them in your notes so that you can check them out later. Put the abbreviation *def.* (*define*) in the margin to remind yourself to do this.

. . . though we know the sea to be an everlasting terra incognita,
so that Columbus sailed over numberless unknown worlds. . . .

—Hermann Melville, *Moby-Dick* (1851)

After Lecture

Review Notes

The perfect time to review your notes is right after lecture. The following checklist contains both general review tips and specific suggestions for this chapter.

Check Your Notes: Have you…

☐ added visual material? Suggestions: Draw a profile sketch similar to Figures 20.23 and 20.25 that shows the major features of the deep ocean floor.
☐ reworked your notes into a form that is efficient for your learning style? Visual learners need to see illustrations and may want to copy key figures and insert them into their notes where the figures are explained. Kinesthetic learners may find it more beneficial to sketch the figures themselves, because the act of drawing helps them remember better.

Intensive Study Session

Set priorities for studying this chapter. Give highest priority to activities that involve answering questions. We recommend the following strategy for learning this chapter.

- **Text.** Review the key figures in Chapter 20. The sequence of figures tells the story of the ocean and its seafloor topography, continental margins, waves, tides, and beaches. You will need a general understanding of these figures to complete the **Practice Exercises** and **Review Questions.** Figures 20.2 and 20.3 explain how wave action (breaking and refraction) works along the shoreline of an ocean. Figure 20.4 explains how the moon and sun produce the tides. Figures 20.13 and 20.14 explain the structure and sand budget of an ocean beach. Figures 20.18 and 20.19 explain the geology of continental margins. Figures

20.23, 20.24, and 20.25 will help you learn about seafloor topography and landforms. Sometime before your exam, answer the exercises at the end of the textbook chapter. They are short-answer questions and won't take long if you know the material.

- **Practice Exercises and Review Questions.** Complete Study Guide Practice Exercises 1 and 2. These exercises will help you remember some of the most important ideas in the chapter. Then answer the **Review Questions** to check your understanding of the lecture. Check your answers as you go, but try to answer the question before you look at the answer.
- **Web Site Study Resources**
  http://www.whfreeman.com/understandingearth6e
  Complete the **Online Quiz.** Pay particular attention to the feedback. The **Geology in Practice** exercise *Why Are the Oceans Salty?* provides a good review of the links among weathering, erosion, and the composition of seawater.

Study Tip

Now is the time to look up the terms you didn't understand. Skim the margin of your notes. (You did mark unfamiliar terms *def*, didn't you?) The text provides two helpful aids for dealing with terms you don't know. Key Terms and Concepts at the end of each text chapter lists all new terms and handily provides the page number of a term so that you can look it up. Alternatively, use the Glossary at the end of the text.

Exam Prep

Materials in this section are most useful during your preparation for quizzes and exams. The **Chapter Summary** and the **Practice Exercises** and **Review Questions** should simplify your chapter review. Read the **Chapter Summary** to begin your session. It provides a helpful overview that should refresh your memory.

Next, work on the **Practice Exercises** and **Review Questions.** Complete the exercises and questions just as you would an exam, to see how well you have mastered this chapter. After you answer the questions, score them. Finally, and most important, review each question that you missed. Identify and correct the misconception(s) that resulted in your answering the question incorrectly.

Chapter Summary

How does the geology of the oceans differ from that of the continents?

- Volcanism and sedimentation shape the ocean floor. In contrast, folding, faulting, weathering, and erosion play important parts in shaping the continents.

What processes shape the shoreline?

- Waves and tides shape the shoreline. Waves are created by the wind blowing over the surface of the water. Ocean tides on Earth are a result of centrifugal force and gravitational forces acting among the Earth, Moon, and Sun.

- The beach is a result of the dynamic balance among waves, longshore currents that erode and transport rock material along the coast within the surf zone, and the supply of sand from rivers to the surf zone. Refer to Figure 20.14.
- Longshore currents result from the zigzag movement of water on and off the beach. Waves typically splash onto shore at an angle in part due to wave refraction. The backwash—off the beach—runs down the beach slope at a small but opposite angle to the swash. The net result of this swash and backwash of water on and off the beach slope is a longshore current that transports sand parallel to the beach within the surf zone.

How do hurricanes affect coastal areas?

- Extremely high winds and a storm surge are characteristic of hurricanes. The storm surge can flood low-lying areas up to depths of 10 m and can be devastating over a very broad area of the coastline.
- The hurricane intensity scale (Saffir-Simpson scale) is used to estimate the potential property damage and flooding expected along the coast from hurricane landfall. Refer to Table 20.1.

What are the major components of the continental margins?

- Continental margins are flooded portions of the continent. The continental slope and rise mark the edge of the continent and mark a transition to deeper water and the ocean floor.
- Passive continental margins form where rifting and seafloor spreading carry continental margins away from active plate boundaries. Active continental margins form where oceanic lithosphere is subducted beneath a continent, or where a transform fault coincides with the continental margin.
- Continental shelves are broad and relatively flat at passive continental margins and are narrow and uneven at active margins.
- Turbidity currents transport fine sediments from the continental shelf and to the adjacent abyssal ocean floor. Turbidity currents can both erode and transport sediments. Submarine canyons and fans are formed by turbidity currents.
- Coral reefs and atolls are constructed by coral and other marine organisms. The reef construct plays an important role in modulating wave energy and creating a favorable environment for shallow marine life. Refer to Figure 5.22 and Earth Issues 5.1.

How is the deep seafloor formed?

- Volcanism along ocean spreading centers (divergent plate boundaries) creates new seafloor, which eventually is recycled back into the mantle by subduction at the trenches (convergent plate boundaries).
- Basaltic volcanism, induced by pressure-release melting in the upper mantle beneath spreading centers, generates an ocean crust that is thin and iron-rich relative to continental crust. Review pages 103–108 in Chapter 4.

What are the characteristics of a mid-ocean ridge?

- A rift valley marks the crest of an ocean ridge.
- Hydrothermal springs form on the rift valley floor as seawater percolates through the new, hot oceanic crust.
- Transform faults offset ocean ridges at many places to accommodate different spreading rates along offset segments of the ridge. Refer to Figure 2.7.

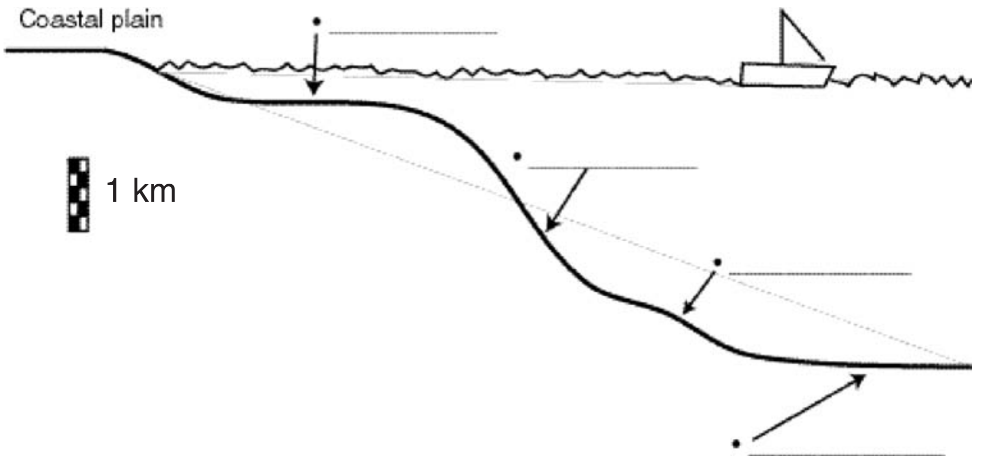
What kinds of sedimentation occur in and near the oceans?

- In the deep sea, fine-grained pelagic terrigenous and biochemically precipitated sediments settle to the seafloor. Foraminiferal oozes, composed of tiny foraminiferal shells, are the most abundant biochemical component of pelagic sediments. Foraminiferal and other carbonate oozes are abundant at depths less than about 4 km. Below a certain depth, called the carbonate compensation depth, carbonate sediments dissolve in deep seawater. Deep ocean water is colder, contains more carbon dioxide, and is under higher pressure. All these factors increase the solubility of carbonate sediments. Silica ooze is produced by sedimentation of the silica shells of diatoms and radiolaria.

Practice Exercises

Exercise 1: Profile from the Atlantic shoreline to the ocean floor

A. Fill in the blanks correctly to label this profile. **Hint:** Refer to Figure 20.18.



B. Does the profile illustrate an active or a passive continental margin? Explain.

____

____

____

Exercise 2: Passive versus active continental margins

Characterize each coastal locality either as a *passive* or as an *active (Andean type)* or *active (Marianas type)* continental margin. Figures 20.18, 20.20, 20.23, 20.25 are useful references.

A. coastline far from an active plate boundary __________

B. east coast of North America __________

C. west coast of South America __________

D. coastline with a very broad, featureless continental shelf __________

E. California coast along the San Andreas Fault __________

F. continental margin with no volcanic activity for millions of years __________

Review Questions

1. Ocean waves are generated mostly by
   A. tides.
   B. ships.
   C. the wind.
   D. earthquakes.
2. Geologically, the edge of a continent is considered to be
   A. on the ocean side of the seafloor trenches.
   B. the continental shelf.
   C. the continental rise and slope.
   D. the shoreline.
3. Which of the following processes is most important for building the ocean floor?
   A. volcanism
   B. metamorphism
   C. precipitation of carbonate rocks
   D. deposition of sediment derived from the land
4. The bending of waves as they approach shore is called
   A. wave reflection.
   B. wave erosion.
   C. longshore drift.
   D. wave refraction.
5. An erosional coast is characterized by
   A. sea cliffs, sea stacks, and wave-cut terraces.
   B. barrier islands.
   C. coral reefs.
   D. estuaries.
6. Ocean-floor rock is made up of
   A. basalt and pelagic sediments.
   B. granite and gneiss.
   C. obsidian and sand.
   D. rhyolite and carbonate sediments.
7. The rock that makes up a seamount is
   A. basalt.
   B. limestone.
   C. granite.
   D. marine sedimentary rock.
8. Sea stacks are
   A. piles of sedimentary rocks near the shore.
   B. the erosional remnants of sea cliffs.
   C. formed where a river drains onto the coastline.
   D. formed by rapidly growing corals on a reef.
   Hint: Refer to Figure 20.1.
9. The deep abyssal ocean plain lies at a water depth of
   A. between 100 and 500 meters.
   B. 600 to 1000 meters.
   C. 2000 to 3000meters.
   D. 4000 to 6000 meters.
   Hint: Refer to the text section Profiles Across Two Oceans.
10. Recent precise satellite measurements of the sea surface shows that the sea level
    A. rises a few millimeters per year.
    B. does not change.
    C. drops a few millimeters per year.
    D. rises and falls with the seasons.

11. What is sediment-charged water that flows rapidly down the continental slope called?
    A. turbidity current
    B. longshore current
    C. tidal current
    D. tsunami

12. The highest tides occur when
    A. the Sun, Moon, and Earth are all aligned.
    B. the Sun and Moon are at right angles to the Earth.
    C. the Earth is closest to the Sun.
    D. the Moon is in either its first or its last quarter.
    Hint: Refer to Figure 20.4.

13. You live on a beachfront. Your up-current neighbors are planning to build a groin to halt erosion and increase the width of their beach. What effect will this have on your beach?
    A. The groin will probably cause your beach to grow.
    B. It is likely that your beach will remain unchanged.
    C. The groin will probably cause your beach to erode.
    D. none of the above
    Hint: Refer to Practicing Geology: Does Beach Restoration Work?

14. Headlands and points experience greater erosion than bays and inlets because of
    A. longshore drift.
    B. wave refraction.
    C. wave reflection.
    D. the more resistant rock in the headland.
    Hint: Refer to Figure 20.3 (3).

15. If a river delivers sand to a shoreline faster than currents can transport the sediment, the result is
    A. erosion of the sand to form a rocky coastline.
    B. formation of a marine terrace.
    C. expansion of the sandy beach.
    D. formation of sea stacks and pillars.

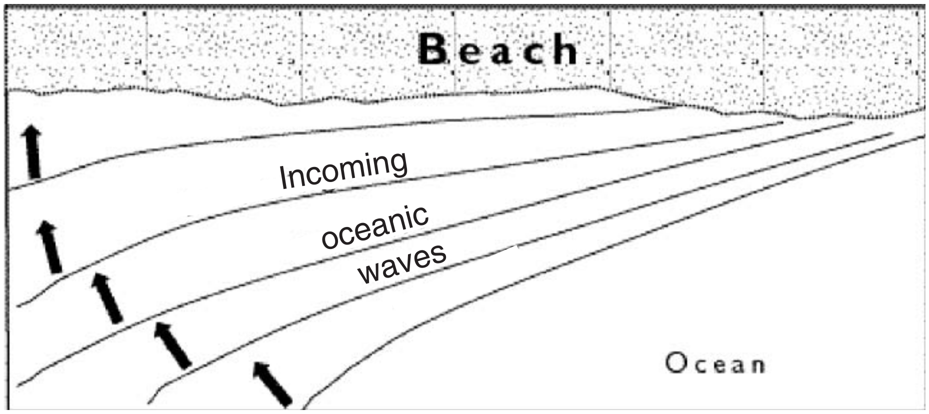
16. If you accidentally get caught in a rip current that is carrying you out to sea, what should you do?
    A. Swim parallel to the shore.
    B. Rest and float with the rip far out to sea and then swim back.
    C. Swim to shore, because this is the shortest distance.
    D. Scream for help.
    Hint: Refer to Figures 20.2 and 20.3. Rip currents are rapidly moving backflows.

17. Coral atolls form in tropical oceans by the upward growth of coral
    A. from deep, submarine mountains.
    B. on a continental shelf that is gradually subsiding.
    C. on subsiding volcanic islands.
    D. on exposed sections of the oceanic ridge system.
    Hint: Refer to Figure 5.22 and Earth Issues 5.1 in Chapter 5, Sedimentation: Rocks Formed by Surface Processes.

18. What is the motion of individual water molecules as a wave travels?
    A. The molecules travel along with the wave.
    B. The molecules follow a straight up-and-down path.
    C. The molecules follow a roughly circular path.
    D. The molecules travel laterally along longshore currents.

19. A result of wave refraction is that
    A. wave energy is concentrated on headlands and points.
    B. wave energy is concentrated in the bays.
    C. sediment is deposited in the vicinity of headlands, making them larger.
    D. wave energy is largely dissipated uniformly along the coastline.

20. Submarine canyons are formed by
    A. rifting of the lithosphere.
    B. erosion due to rivers.
    C. turbidity flows.
    D. glacial erosion.
21. On the diagram, draw an arrow indicting the direction of the longshore current that will be produced by the ocean waves hitting the beach.



22. Sediments deposited on the ocean floor at depths greater than about 4 km are
    A. fine-grained dust (terrigenous sediments) and silica oozes.
    B. foraminiferal oozes.
    C. a mixture of foraminiferal and silica oozes.
    D. gas hydrates and carbonate sediments.

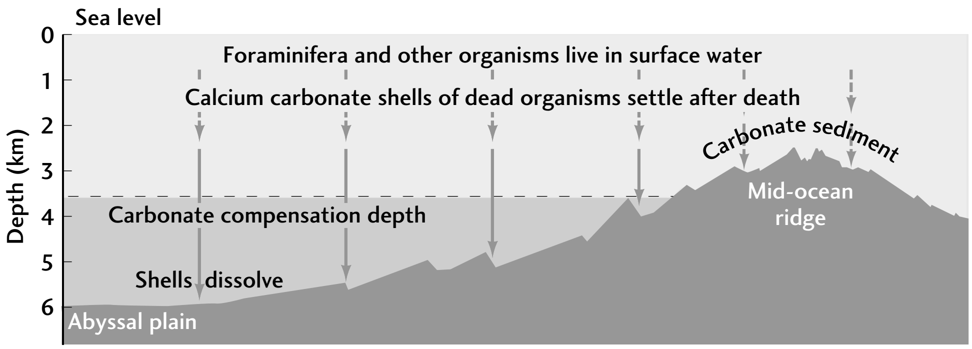


Figure 20.27. The carbonate compensation depth is the level below which calcium carbonate dissolves. As the carbonate shells of dead foraminifers and other organisms settle into deep ocean waters, they enter an environment undersaturated in calcium carbonate and therefore dissolve.

CHAPTER 21

Glaciers: The Work of Ice

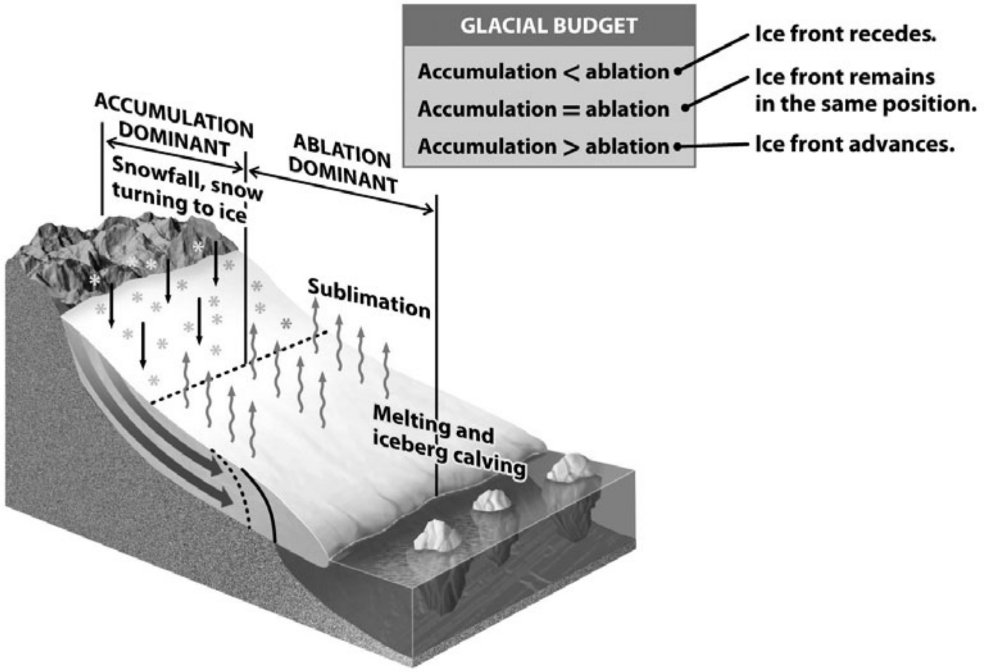


Figure 21.8. Accumulation of a glacier takes place mainly by snowfall over the colder upper regions. Ablation takes place mainly in the warmer lower regions by sublimation, melting, or iceberg calving. The difference between accumulation and ablation is the glacial budget.

Before Lecture

Before you attend lecture, be sure to spend some time previewing the chapter. For an efficient preview, use the **Chapter Preview** questions.

Chapter Preview

- **How do glaciers form and how do they move?**
  Brief answer: Glaciers form where snow accumulation exceeds snow melting. Refer to Figure 21.8. Glaciers move by a combination of plastic flow and slip at the base of the ice. See Figure 21.10.
- **Why do ice shelves float?**
  Brief answer: Ice floats on the ocean in exactly the same way that ice cubes float in a glass of water. Ice is less dense than water. See Earth Issues 21.1.
- **How do glaciers erode bedrock, transport and deposit sediments, and shape the landscape?**
  Brief answer: Glaciers erode by scraping, plucking, and grinding rock. Refer to Figure 21.15. The rock debris deposited by a glacier is called till. Till may contain debris from the size of rock flour to giant boulders. Glaciers sculpt a distinctive landscape with U-shaped and hanging valleys, arêtes, cirques, moraines, drumlins, kames, and other features. Refer to Figures 21.14, 21.16, 21.17, and 21.18.
- **What are the ice ages and what caused them?**
  Brief answer: During the Pleistocene epoch, many cycles of advance and retreat of continental ice sheets occurred. The ice sheets of the last major advance were gone by about 10,000 years ago, the beginning of the Holocene epoch. A popular theory for the cause of the Pleistocene ice ages relies on how variations in the Earth's orbit effect the intensity of the solar energy reaching Earth. Refer to Figure 15.12.

Vital Information from Other Chapters

A review of section Climate Variability in Chapter 15 is essential to understanding what caused the glacial and interglacial cycles during the Pleistocene Epoch. Also review Figure 17.1, Distribution of water on earth.

During Lecture

- Keep the big picture in mind to help with note taking. This chapter tells the story of ice: how glaciers form, move, and create a landscape of unique features. This story has a long history: the many ice ages of the Pleistocene epoch. The chapter suggests a future when our descendents will almost certainly have to face the return of ice and massive glaciation.
- Understanding glacial landscapes is one of the main goals for this lecture. Take notes that will help you understand key landscape features such as the following.

  Glacial features formed by the erosive power of glacial ice (see Earth Issues 21.1 and Figures 21.15 and 21.16)
    - Striations—scratches and grooves—carved in bedrock over which the glacier flowed
    - Cirque
    - U-shaped valley
    - Hanging valley
    - Fjord
    - Arête

  Glacial features formed by deposition of rock material by glacial ice (see Figures 21.17 and 21.18):
    - Glacial moraines—the different types are described in Table 21.1
    - Esker

- Kame
- Glacial erratic
- Kettle
- Varves

For each feature, sketch its essentials and annotate what makes it unique. Write the numbers of figures adapted from the text in the margin so that you can review them later.

After Lecture

Review Notes

Check Your Notes: Have you…

☐ captured the glacial processes? Your notes should say clearly (1) how glaciers form and move and (2) how they erode material.
☐ described the essential features of the glacial landscape? Refer to **During Lecture** for a list of landscape features you should have in your notes on the **During Lecture** section. Be sure to go back to the text for features you missed.
☐ added visual material? Doing simple sketches of the glacial landscape features is a great way to learn them. It will be helpful to have all your features on a single page in your notes for easy review.

Intensive Study Session

Study Tip

The pictures in Chapter 21 are designed as a virtual field trip. Use the pictures to master glacial landscape features. Study each picture until you understand what the feature is and how it differs from other features. (For a list of the landscape features you need to study, refer to **During Lecture.**)

Set priorities for studying this chapter. Give highest priority to activities that involve answering questions. We recommend the following strategy for learning this chapter.

- **Text.** Review the key figures in the chapter. They will help you remember the most important ideas in the chapter. Figures 21.8 and 21.10 will help you understand how glaciers form and move. Figure 21.15 explains how glaciers erode bedrock. Figures 21.14, 21.16, 21.17, and 21.18 and Table 21.1 provide a virtual field trip of the distinctive features of the glacial landscape. Earth Issues 21.1 explains why ice shelves float.

  Sometime before the exam, answer the exercises at the end of the chapter in the text. They are short-answer questions and won't take long if you know the material. They make an excellent review of Chapter 21.
- **Practice Exercises and Review Questions.** Start with Practice Exercise 1, which will help you learn the distinctive features of glacial landscape. Then go to the multiple-choice Review Questions to check your understanding of the lecture. Try to answer each question before you look at the answer.
- **Web Site Online Review Exercises and Study Tools**
  http://www.whfreeman.com/understandingearth6e

  Complete the **Online Quiz.** Pay particular attention to the explanations for the answers.

Exam Prep

Materials in this section are most useful during preparation for quizzes and exams. The **Chapter Summary** and the **Practice Exercises** and **Review Questions** should simplify your chapter review. Read the **Chapter Summary** to begin your session. It provides a helpful overview that should refresh your memory.

Next, work on the **Practice Exercises** and **Review Questions.** Complete the exercises and questions just as you would an exam, to see how well you have mastered this chapter. After you answer the questions, score them. Finally, and most important, review each question that you missed. Identify and correct the misconception(s) that resulted in your answering the question incorrectly.

Chapter Summary

How do glaciers form and how do they move?

- Glaciers form in cold and snowy climates where snow accumulation exceeds the ablation of ice due to melting, sublimation, wind erosion, and iceberg calving. Glacial ice moves by plastic flow and slip along the base, which may be lubricated by melt water. The rate of ice flow typically varies from meters per year to meters per week.
- Glaciers are described as advancing or retreating depending on the balance between snow accumulation and ablation. When ablation exceeds accumulation, the shrinking glacier "retreats" as the toe or terminus moves upslope. When accumulation exceeds ablation, the expanding glacier "advances" as its toe or terminus moves downslope.

Why do ice shelves float?

- Earth Issues 21.1 illustrates how isostasy, the dynamic balance between the forces of gravity and buoyancy, keep ice shelves and bergs afloat in water. The mass of the floating ice is equal to the mass of the water the iceberg displaces. When the ice melts, it simply replaces the water it displaced and therefore there is no change in sea level.

How do glaciers erode bedrock, transport and deposit sediments, and shape the landscape?

- Glaciers are powerful agents of erosion and deposition. Glaciers erode by scraping, plucking, and grinding rock.
- Landscapes sculptured by ice have distinctive features that have provided geologists with evidence for reconstructing the position of ice sheets during the ice ages and for deciphering the existence of ice ages throughout Earth's history. U-shaped and hanging valleys, moraines, arêtes, cirques, drumlins, kames, eskers, striated rock, and other features characterize a glacial landscape.
- Ice-laid deposits of rock material are called till and consist of a heterogeneous mixture of rock, sand, and clay. Accumulations of till are called moraines; each type of moraine is named for its position relative to the glacier that formed it. Ancient tills, called tillites, provide evidence for numerous ancient glaciations during Earth's history.
- Water-laid deposits from glaciers are called outwash and consist of sand, gravel, and fine rock flour.

What are the ice ages and what causes them?

- The ice sheets of the last major advance were gone by about 10,000 years ago, the beginning of the Holocene epoch. Studies of the geologic ages of glacial deposits on land and sediments of the seafloor show that the Pleistocene glacial epoch consisted of multiple advances (glacial intervals) and retreats (interglacial intervals) of the continental ice sheets. Each advance corresponded to a global lowering of the sea level, which exposed large areas of continental shelf; during the interglacial intervals, the sea level rose and submerged the shelves.
- Although the causes of the ice ages remain uncertain, the general cooling of the Earth leading to glaciation appears to have been the result of plate tectonics that gradually moved continents to positions where they obstructed the general transport of heat from the equator to the polar regions.
- A favored explanation for the alternation of glacial and interglacial intervals is the effect of astronomical cycles by which very small periodic changes in Earth's orbit and axis of rotation alter the amount of sunlight received at the Earth's surface. There is also evidence that decreased levels of carbon dioxide in the atmosphere diminished the greenhouse effect, which would contribute to global cooling.

Practice Exercises

Exercise 1: The glacially sculpted landscape

You are hired as a seasonal ranger at a national park with a spectacular glacially sculpted landscape. However, there is not one glacier in the park today. Your job for the summer is to lead natural history hikes along which you interpret the evidence for the past glaciation that helped formed the park landscape. Briefly describe five features along the nature trail that speak to the past glacial episode in this region. Remember that a picture or sketch is worth a thousand words, so a good way to provide a brief description is with a well-labeled diagram.

Features formed by the erosive power of glacial ice

1. ______________________________

____

2. ______________________________

____

3. ______________________________

____

Features formed by deposition of rock material by glacial ice

4. ______________________________

____

5. ______________________________

____

Exercise 2: Your personal budget as a metaphor for a glacial budget

Discuss how the changing balance of cash in your checking account is a good metaphor for an advancing and retreating glacier.

Exercise 3: Glacial advances and retreats

A glacier advances, halts, and retreats. Will the glacier continue to deposit material at its snout while it is halted and even while it is retreating? Discuss.

Review Questions

Answers and explanations are provided at the end of this Study Guide.

1. Glacial ice is most like a(n)
   A. igneous rock. B. sedimentary rock.
   C. metamorphic rock. D. sediment.
2. The force that moves glaciers is
   A. recrystallization. C. lubrication.
   B. melting. D. gravity.
3. As snow is transformed into glacial ice, a transitional phase of densely packed granular snow is called
   A. pack ice.
   B. firn.
   C. alpine ice.
   D. crystalline ice.
   Hint: Refer to Figure 21.7.
4. Glaciers retreat when the
   A. accumulation of snow is less than the ablation off the glacier.
   B. accumulation of snow exceeds the ablation off the glacier.
   C. accumulation of snow is equal to the ablation.
   D. boundary between the zone of accumulation and ablation moves to lower elevations.

5. Moraines are
   A. erosional glacial features carved in bedrock over which the ice flowed.
   B. made from glacial outwash sediments.
   C. deposits of loess carried by wind from recently glaciated regions.
   D. deposits of glacial till.
6. A drumlin is a
   A. block of bedrock not quarried away by the bottom of a glacier.
   B. sinuous ridge of water-deposited glacial debris.
   C. a small depression formed from the melting of a block of ice buried beneath till.
   D. streamlined hill constructed of glacial till.
   Hint: Refer to Figure 21.18.
7. Ragged, knife-edged ridges are commonly found in glaciated mountains. Such a ridge line is called a(n)
   A. horn.
   B. cirque.
   C. col.
   D. arête.
   Hint: Refer to Figure 21.16.
8. When continental glaciers advance over the land surface,
   A. the sea level lowers.
   B. the sea level rises.
   C. plate tectonic processes are especially active.
   D. Europe is significantly warmer.
9. Milankovitch calculated that the eccentricity of the Earth's orbit varies over a cycle of _____________ years.
   A. 10,000
   B. 23,000
   C. 41,000
   D. 100,000
   Hint: Refer to Figure 15.12.
10. Orbital factors that affect the Earth's heat budget primarily affect the
    A. reflectivity of the Earth's upper atmosphere.
    B. amount of solar energy reaching our planet.
    C. composition of the atmospheric gases.
    D. distribution of heat over the globe.
    Hint: Refer to Figure 15.12 and associated text.
11. Which of the following features of a glacial landscape is the product of depositional process rather than erosion?
    A. fjord
    B. kames
    C. hanging valley
    D. cirque
12. Which of the following is NOT characteristic of glacial till?
    A. sand grains of virtually all quartz
    B. lack of clear stratification
    C. very poor sorting
    D. boulder-, cobble-, pebble-, sand-, and clay-sized rock particles
13. Ablation refers to the
    A. melting, calving, sublimation, and erosion of glacial ice.
    B. erosion and deposition of glacial sediments.
    C. changes in sea level associated with glacial and interglacial periods.
    D. glacier advance and retreat.

14. The glacial budget is balanced when the rate of accumulation is equal to the rate of
    A. ablation.
    B. deposition.
    C. advance.
    D. retreat.
15. The last major advance of continental ice over North America reached
    A. the Gulf of Mexico.
    B. California.
    C. south of the Great Lakes.
    D. Florida.
    Hint: Refer to Figure 21.24.
16. Which of the following may have influenced Earth's climate during ice ages?
    A. variations in Earth orbital characteristics
    B. changes in the composition of the atmosphere
    C. plate tectonic movements of the continents
    D. all of the above
17. As a result of the collapse and melting of ice shelves and bergs, like that of the Larson Ice Shelf in 2002, the sea level
    A. rises.
    B. falls.
    C. fluctuates.
    D. remains unchanged.
    Hint: Does the level of water in a glass rise when the ice cubes in the water melt?

CHAPTER 22

Landscapes: Tectonic and Climate Interaction

The physical landscape is baffling in its ability to transcend whatever we would make of it.

—BARRY LOPEZ, *ARCTIC DREAMS*

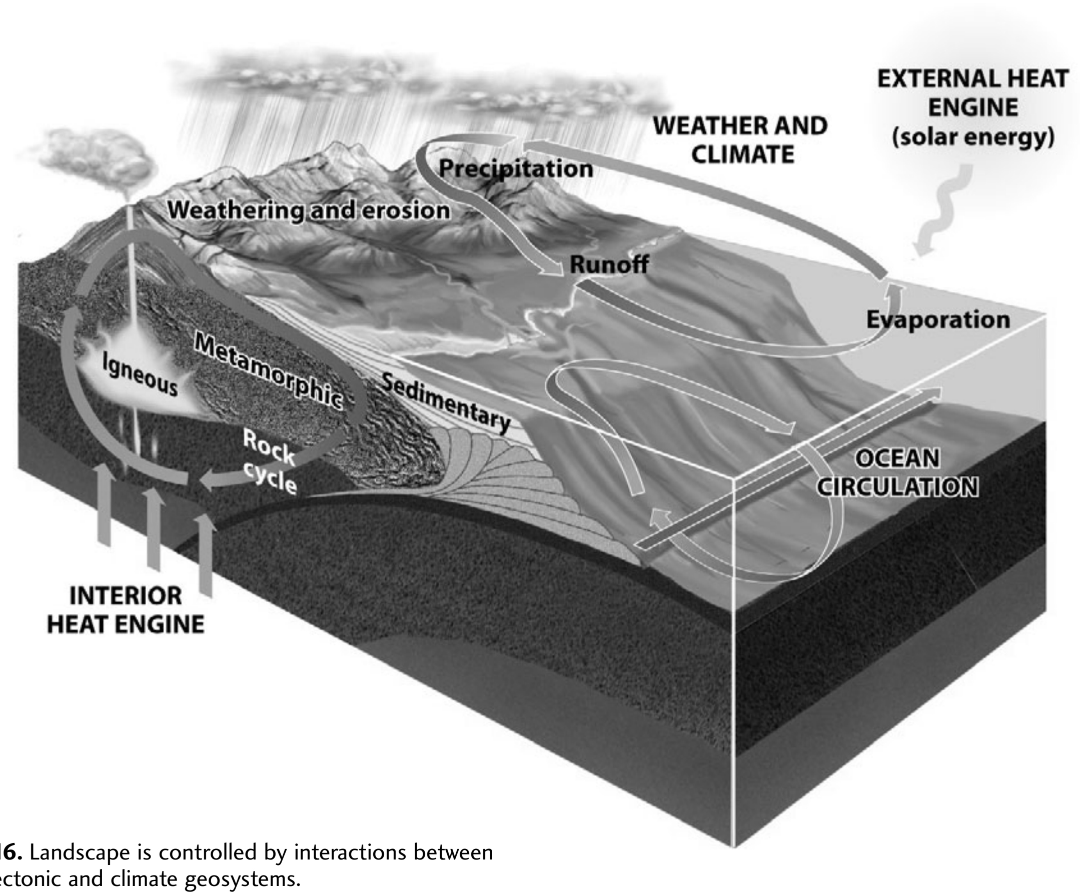


Figure 22.16. Landscape is controlled by interactions between the plate tectonic and climate geosystems.

Before Lecture

Before you attend the lecture, be sure to spend some time previewing the chapter. For an efficient preview, use the **Chapter Preview** questions.

Chapter Preview

- **What are the principal components of landscapes?**
  Brief answer: Landscapes are described in terms of their topography: elevation, the altitude of the surface of the Earth above sea level; and relief, the difference between the highest and the lowest spots in a region. Landscapes also consist of the varied landforms produced by geologic processes such as erosion and sedimentation by rivers, glaciers, mass wasting, and wind.
- **How do the climate and plate tectonic systems interact to control landscape?**
  Brief answer: Tectonics affects the height and distribution of the crust and its composition. Climate affects weathering and erosion. Characteristics of the bedrock influence weathering and erosion rates.
- **How do landscapes evolve?**
  Brief answer: The evolution of landscapes depends strongly on the competition between uplift and erosion. For example, a landscape with high relief will form if tectonic activity is high, which in turn stimulates erosion. Erosion will at first enhance relief, but over time, water, wind, and ice will wear down the high spots and fill in the low spots with sediment.
- **Why don't mountains sink?**
  Brief answer: Like icebergs, mountains float. They float on Earth's mantle, which exerts a buoyant force and counters the force of gravity. During rapid erosion of mountain ranges, summits may be uplifted to even greater heights because the mass of the mountain is reduced during erosion, resulting in isostatic uplift. Refer to Figure 22.18 and Earth Issues 21.1.

Vital Information from Other Chapters

Congratulations! You have reached the point in your mastery of geology at which you will begin to make sense of new landscapes you may encounter during travel or on a hike. Chapter 22 draws heavily on all you have learned previously about tectonics and climate (note the chapter title, Landscapes). For that reason it will be even more important than usual to review other chapters in conjunction with your study of Chapter 22. Use the following quick reference list to expedite your review of important information from previous chapters. Note that this list is organized around the major theme of Chapter 22: *Landforms are shaped by the interaction of tectonic uplift and climate.*

Tectonics

- How convergent margins produce uplift (Figure 2.8)
- Landforms associated with faults and folds (Figures 7.12, 7.13, 7.14, 7.21, 7.22, and 7.23)
- Plate tectonics and sedimentary basins (Figure 5.8)

Climate

- Physical and chemical weathering (Figure 16.10)
- How mass wasting processes shape the landscape (Figure 16.17)
- The relationship among mountains, atmospheric circulation, and deserts (Figures 17.3, 19.1, and 19.15)
- Glacial landscapes (Figures 21.16 and 21.17)

Compared to ice and wind, running water plays the largest role in sculpting the Earth's land surface today. A review of the hydrologic cycle (Figure 17.2) and the material in the last half of Chapter 18 (Figures 18.9, 18.10, 18.24, 18.25, and 18.26), will reinforce your understanding of the information presented in Chapter 22. This review will also help in preparation for a final exam.

Web Site Preview

http://www.whfreeman.com/understandingearth6e
Identify North America's Landforms and *Understanding Landscape Evolution* are **Interactive Exercises** definitely worth completing before or right after your first lecture on this topic.

During Lecture

One goal for lecture should be to leave the room with good answers to the **Chapter Preview** questions.

- To avoid getting lost in details, keep the big picture in mind. Chapter 22 tells the story of how landscapes form. "Uplift proposes and erosion disposes."
- Chapter 22 provides a virtual tour of landforms created by geological processes. During lecture, be alert to tips that will help you sort out links between a landscape and a certain set of geological circumstances.
- Even more important than the landscape features themselves are the processes that form each feature. You already know the processes. Your goal in this chapter is to understand how geologic processes work together to form a particular kind of landscape. Example: The Tibetan plateau and the Himalayan Mountains are supported by buoyant continental crust, thickened during continental collision. Erosional unloading of the southern margin of the Tibetan plateau may contribute to the height of the peaks in the Himalayan range.

After Lecture

Review Notes

The perfect time to review your notes is right after lecture. The following checklist contains both general review tips and specific suggestions for this chapter.

Check Your Notes: Have you…

- ☐ clearly described each landform (mountains, plateaus, Appalachian Valley and Ridge, and so on) and the geological processes that shape them? Use the text to check your notes.
- ☐ added visual material? Suggestions: Make some simple sketches to help you learn the features that identify landforms in the chapter. Work some of the sketches into a comparison chart like the one in Practice Exercise 2. Tip: The answers for Practice Exercise 2, available at the end of this Study Guide, show some good examples of simple landform sketches.
- ☐ created a brief big picture overview of this lecture (using a sketch or written outline)? **Hint:** See Practice Exercise 1.

Study Tip: Learn by drawing

Puting simplified sketches of landscape features into your notes is a helpful way to learn and remember because it activates both visual and kinesthetic learning modalities. Visual learners remember material best after they look at and study a figure. Visual learners learn more if they enrich their notes with visual clues. For kinesthetic learners, memory is activated by the act of drawing. You learn as you look and draw.

Intensive Study Session

- First, get the big picture in mind. Take a look at Figure 22.16, which shows how tectonics and climate interact to produce landscape.
- Next, review the main concepts of the chapter: relief (Figure 22.3); development of ridges and valleys in folded mountains (Figure 22.12); erosion driven by the balance between stream power and sediment load (Figure 22.9); the dynamics of uplift (Figure 22.18); and classic models of landscape evolution (Figure 22.19). You will need to understand these figures to answer the exercises and review questions.

Study Tip for Figure 22.18 and Earth Issues box 22.1.

Study Figure 22.18 and Earth Issues 22.1 as a package. Both relate uplift to climate change. They reinforce each other and make better sense together than they do when read separately.

- Take the visual field tour of landforms. Be sure you understand these landforms and know what they look like: aretes (Figure 22.6), mesas (Figure 22.8), valley and ridge topography (22.12 and 22.13), cuestas (Figure 22.14), hogbacks (Figure 22.15).

  Sometime before your exam, answer the exercises at the end of this chapter. They are short-answer questions and will not take long to complete if you know the material. We recommend working on Thought Questions 1, 3, 4, 8.
- Complete Practice Exercises 1 and 2. You will get the greatest return on your study time by working on these exercises because they will help you remember the most important ideas in the chapter.
- Answer the Review Questions to check your understanding of the lecture. Check your answers as you go, but try to answer the question before you look at the answer. Pay attention to the test-taking tips. They will help you do better on your exams.
- **Web Site Study Resources**
  http://www.whfreeman.com/understandingearth6e

  Complete the **Online Quiz.** Pay particular attention to the explanations for the answers. The **Geology in Practice** exercise Can Erosion Make Mountains Higher? is a good review and will reinforce information presented in this chapter.

Exam Prep

Materials in this section are most useful during preparation for quizzes and exams. The **Chapter Summary** and the **Practice Exercises** and **Review Questions** should simplify your chapter review. Read the **Chapter Summary** to begin your session. It provides a helpful overview that should refresh your memory.

Next, work on the **Practice Exercises** and **Review Questions**. Complete the exercises and questions just as you would an exam, to see how well you have mastered this chapter. After you answer the questions, score them. Finally, and most important, review any question that you missed. Identify and correct the misconception(s) that resulted in your answering the question incorrectly.

Chapter Summary

What are the principal components of landscapes?

- Landscapes are described in terms of their topography: **elevation**, the altitude of the surface of the Earth above sea level; **relief**, the difference between the highest and the lowest spots in a region; and the varied **landforms** produced by erosion and sedimentation by rivers, glaciers, mass wasting, and wind. Elevation is a balance between tectonic activity and erosion rate.

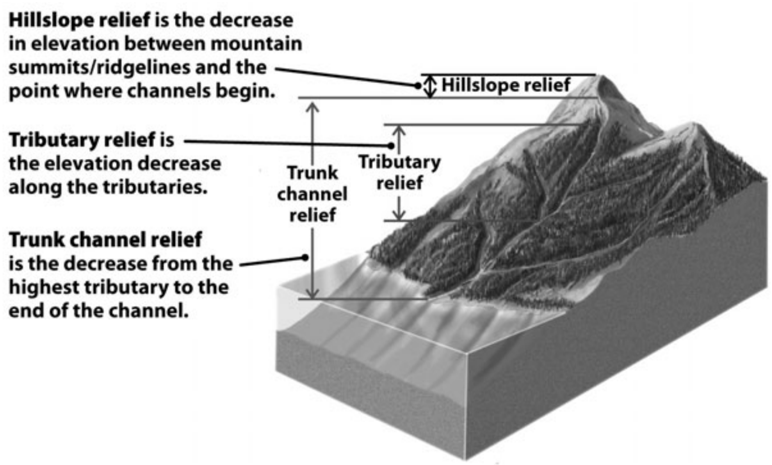


Figure 22.3. Relief is the difference between the highest and lowest elevations in a region. Three types of relief can be defined for a typical mountainous area.

How do the climate and plate tectonic systems interact to control landscape?

- Tectonics (uplift and subsidence), erosion, climate, and the type of bedrock control the evolution of landscapes. Positive and negative feedback mechanisms between tectonic process and climate dynamically adjust to change. Water, wind, and ice act to erode and transport rock material from the high spots and deposit it in the low spots. Refer to Figure 22.18 and Earth Issues 22.1.

How do landscapes evolve?

- The formation of river valleys and bedrock erosion are controlled by a balance between stream power and sediment load. Refer to Figure 22.9.

- Landscapes go through different phases depending on tectonic activity and climate. For example, a landscape with high relief forms if tectonic activity is high, which in turn stimulates erosion. Erosion at first enhances relief, but over time, water, wind, and ice wear down the high spots and fill in the low spots with sediment.
- Current views of landscape evolution emphasize the dynamic equilibrium between erosion and tectonic uplift. Uplift competes with erosion. If uplift is faster, the mountain will rise; if erosion is faster, the mountains are lowered. When tectonics dominates, mountains are high and steep, and they remain so as long as the balance is in favor of tectonics. When the rate of deformation wanes, rates of erosion predominate, resulting in a gradual decrease in both relief and mean elevation.

Why don't mountains sink?

- Like an iceberg floating in water, most mountains are supported by a buoyant, low-density root of continental crust, which floats in the denser mantle. Isostatic rebound of thick continental crust in response to unloading due to differential erosion may cause mountain peaks to rise even higher.

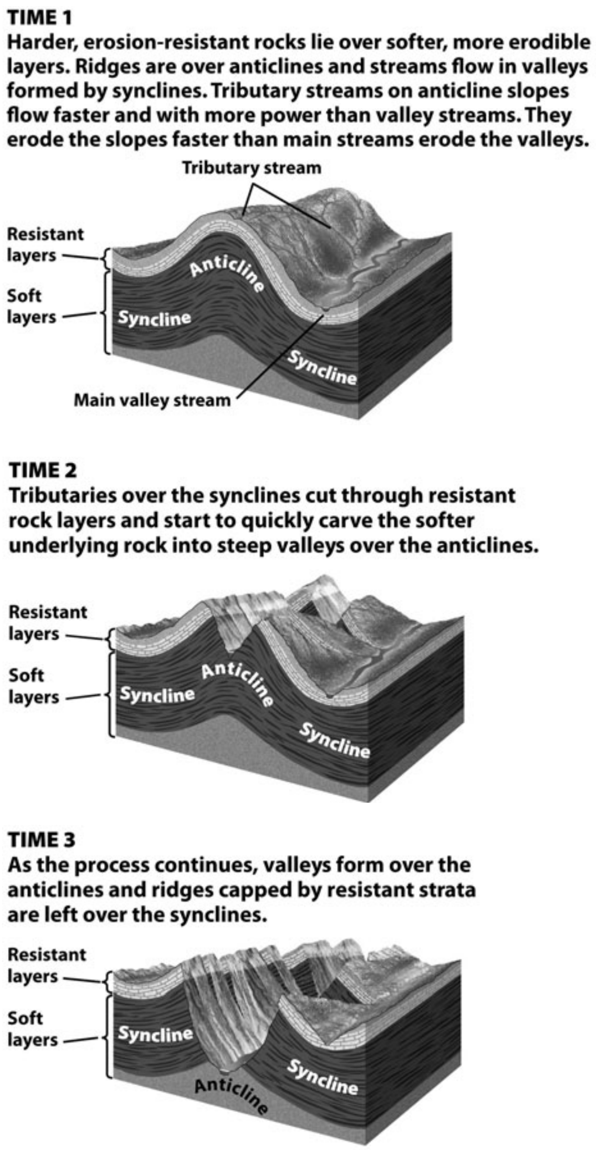


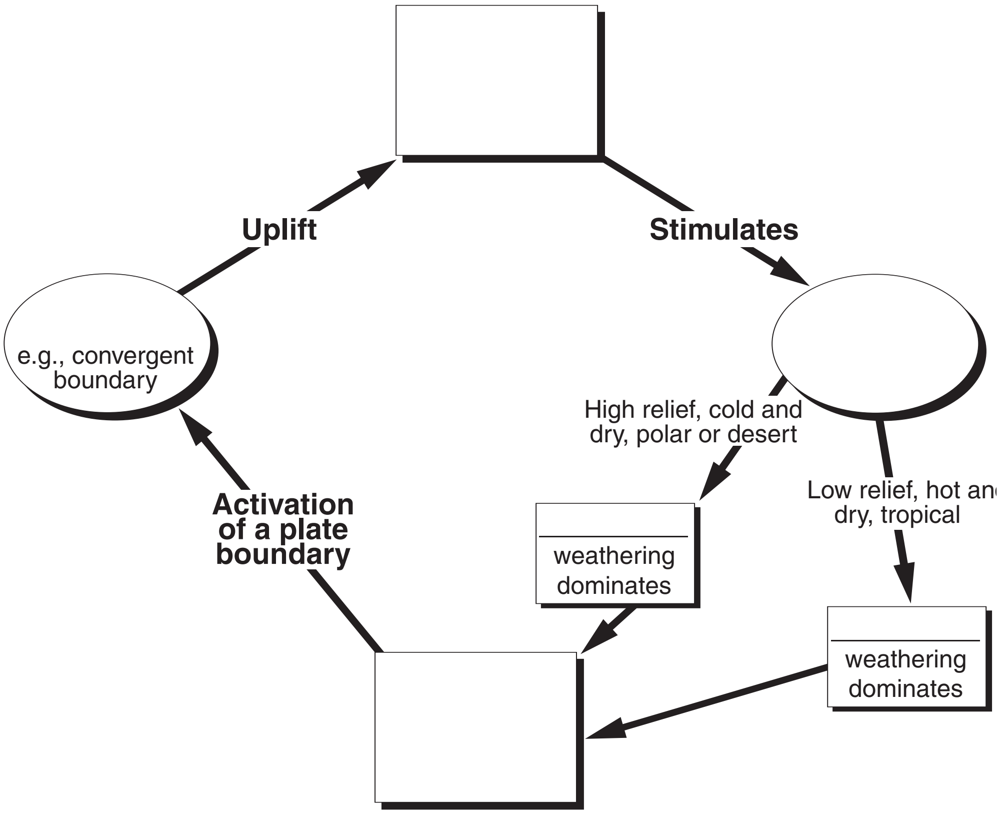
Figure 22.12. Stages in the development of ridges and valleys in folded mountains. In early stages, ridges are formed by anticlines. In later stages, the anticlines may be breached and ridges may be held up by caps of resistant rocks as erosion forms valleys in less resistant rocks.

Practice Exercises

Exercise 1: Landscapes: Tectonic and climate interaction flowchart

To review the basic relationships between landscape relief, tectonic activity (uplift), and erosion, fill in the flowchart with the following words.

Tectonic activity
High relief
Low relief
Erosion
Physical weathering
Chemical weathering



Exercise 2: Comparison of Some of the Landforms

Chapter 22 provides a virtual field trip experience. To master the landforms discussed in this chapter, it will be helpful to develop a comparison chart identifying the important features that distinguish each landform. Fill in the missing information in the column "Important features." **Hint:** Use the text figures, captions, and accompanying text to help you. Then make a very simple sketch of each landform. Sketching is both a thinking tool and a great kinesthetic learning tool. When you draw, you tap the part of the brain that learns by moving.

Landform	Important feature(s)	Sketch (Keep it very simple.)
Mesa (See Figure 22.8.)	A small plateau with _________ slopes on all sides. Held up by _________. ____	
Cuesta (See Figure 22.14.)	A structurally controlled cliff. Beds are somewhat tilted and alternate between weak and resistant layers. The resistant layers get undercut because the weak layers tend to erode faster.	
Hogback (See Figure 22.15.)	A structurally controlled cliff with beds that are _________. Ridge is more or less _________.	
Valley ridge topography (See Figures 22.12 and 22.13.)	In young mountains, upfolds (_________) form ridges and downfolds (_________) form valleys. As tectonic activity moderates and erosion digs deeper into the structures, the _________ may form valleys and syncline ridges.	

Review Questions

1. During the earliest stages of development of a river valley, the valley would have a
   A. simple V-shaped profile.
   B. simple U-shaped profile.
   C. low stream gradient.
   D. well-established floodplain.
   Hint: Refer to Figure 22.9.
2. Elevation is the result of
   A. tectonic activity.
   B. the balance between tectonic activity and erosion.
   C. erosion and deposition.
   D. deposition.
3. Relief is the
   A. difference between the highest point and the lowest point in a region.
   B. difference between the highest point in a region and sea level.
   C. average height of a landscape.
   D. steepness of the slopes.

4. Which of the following are important controls on landscape evolution?
   A. tectonics
   B. climate
   C. type of bedrock
   D. all of the above
5. The Earth has two fundamental levels on its surface. They are the
   A. land and oceans.
   B. crust and mantle.
   C. mountains and trenches.
   D. continental crust and ocean basins.
6. Mountain belts are commonly found in association with
   A. hot spots.
   B. convergent boundaries.
   C. transform faults.
   D. mid-ocean ridges.
7. An example of a relatively short-term positive-feedback process in landscape evolution is
   A. a mountain peak becoming higher as a result of erosion.
   B. uplift causing erosion to slow down.
   C. rivers washing sediments out of subsiding basins.
   D. interactions at convergent boundaries resulting in low relief.
   Hint: Refer to Figure 22.18.
8. The Appalachian Valley and Ridge province is characterized by a landscape controlled by
   A. a series of regional faults that were active millions of years ago.
   B. glacial erosion and deposition, since a continental ice sheet once covered the entire region.
   C. wind erosion and deposition partly constrained by zones of dense vegetation.
   D. an intricate series of anticlines and synclines.
   Hint: Refer to Figures 22.12 and 22.13.
9. Given that erosion by streams is controlled by a balance between stream power and sediment load, then in steep, wet terrain, stream power is
   A. high and sediment is transported away.
   B. low and sediment is transported away.
   C. high and sediment is deposited.
   D. low and sediment is deposited.
   Hint: Refer to Figure 22.9.

Test-Taking Tip: Think logically during exams

Learning should result from thinking rather than from memorization. On exams it is easy to become nervous and experience a brief memory lapse. At such times logical thinking can save the day.

Have you noticed that some test items are written so that you can deduce the answer logically? Consider item 10.

The clue. The fact that A and B are very similar is a clue that one of them is probably the correct answer. (This occurs as a by-product of test construction. As the instructor develops the item, she wants to build in two alternatives and have you decide which alternative is correct.)

The logic. It stands to reason that a formation with steeply dipping beds would be susceptible to erosion. If the cuesta has steeply dipping beds (as stated in A), then it would also be likely to erode faster (as stated in C). But you know that there is only one correct answer, so A and C cannot both be correct. Hence the correct answer is likely to be B. There is, of course, a caveat. Logic is not a substitute for study. Also, when applying logic it is easy to be trapped by some hidden misconception you harbor. So consider logic a tool you can use occasionally, when you need it.

It is always a good idea to have a full toolbox!

10. Cuestas and hogbacks are both long ridges of erosion-resistant rock. The difference between them is that
    A. much more steeply dipping beds form the cuesta.
    B. much more steeply dipping or vertical beds form the hogback.
    C. the cuesta tends to erode faster.
    D. hogbacks are asymmetrical.
11. The debate about the dynamic interactions between uplift and climate is fueled by the observation that global cooling over the last few tens of millions of years coincides with the uplift of the Tibetan plateau. One side of the debate argues that there was negative feedback between uplift and climate because
    A. high erosion rates led to the removal of carbon dioxide—an important greenhouse gas—from the atmosphere, which in turn led to further cooling, increased precipitation, and erosion.
    B. higher erosion rates resulted in higher rates of uplift due to isostatic adjustments.
    C. cooler climates allowed glaciers to grow on the mountain peaks, and the weight of the ice isostatically depressed the mountains.
    D. none of the above.
12. Beryllium-10 is used as a method to date the age of river-terrace surfaces because beryllium-10
    A. is radioactive and its decay is determined by exposure to sunlight.
    B. is slowly leached out of rock once it is exposed at the surface.
    C. is slowly released from the rocks as they are uncovered by erosion.
    D. accumulates in the upper surface of the rock the longer it is exposed at the surface to cosmic ray bombardment.

CHAPTER 23

The Human Impact on Earth's Environment

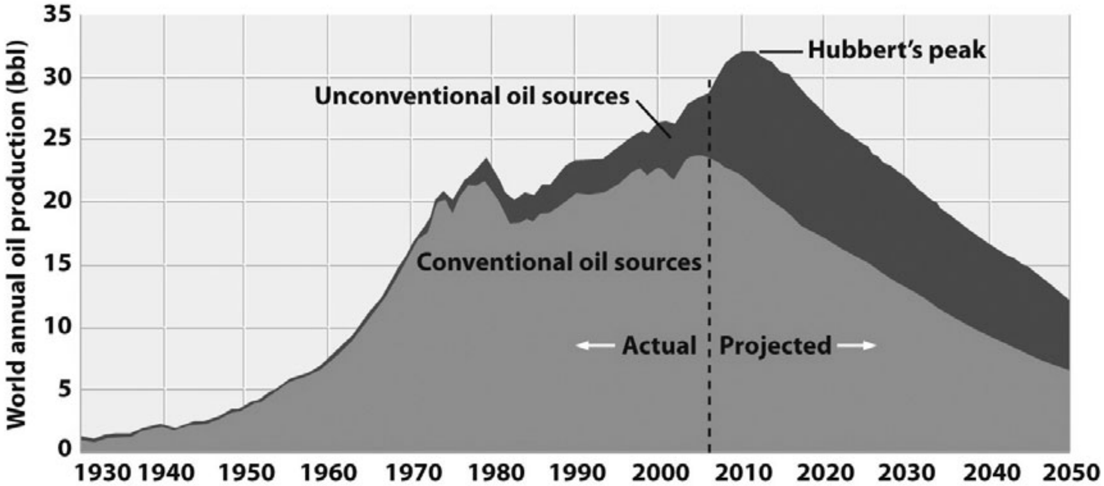


Figure 23.12. A pessimistic projection of world oil production, showing Hubbert's peak occurring in 2007. Note: Optimists believe that oil production will actually continue to rise due to improvements in technology.

Before Lecture

Before you attend lecture, be sure to spend some time previewing the chapter. For an efficient preview, use the **Chapter Preview** questions.

Chapter Preview

- **What is the origin of oil and natural gas?**

  Brief answer: Oil and natural gas form from organic matter deposited in marine sediments. The organic matter is pressure cooked as the sediments are buried, and the organic materials are transformed into liquid and gaseous hydrocarbons. Figure 23.8 illustrates how the organic fluids migrate and accumulate in geologic traps.

- **Why is there concern about the world's oil supply?**

  Brief answer: Oil is a nonrenewable resource and it is being used faster than natural processes generate it. The key issue is not when oil runs out but when oil production stops rising. Refer to Figure 23.12 and the accompanying discussion of the controversy concerning Hubbert's peak.

- **What is the origin of coal and how big a resource is it?**

  Brief answer: Coal is formed by the compaction and mild metamorphism of buried terrestrial wetland vegetation. Coal has supplied an increasing proportion of U.S. energy needs since 1975. Refer to Figures 23.14 and 23.15.

- **What are the prospects for alternative energy sources?**

  Brief answer: Alternative sources include nuclear, hydroelectric, wind, solar, biomass, and geothermal. Taken together, these sources currently provide only about 14 percent of world energy needs. With advances in technology and safety plus reductions in cost, renewable sources of energy and nuclear power can become major sources of energy in this century.

- **What is acid rain?**

  Brief answer: Acid rain is rain that contains sulfuric and/or nitric acid and is formed when emissions from the burning of fossil fuels react with rainwater.

- **What is ozone depletion, and why should it concern us?**

  Brief answer: Ozone absorbs harmful ultraviolet radiation streaming in from the Sun. Used as refrigerants and in industrial processes, CFCs are chemicals that reach the upper atmosphere and react with ozone faster than ozone is generated.

- **How much global warming will there be in the twenty-first century, and what will be the consequences of it?**

  The range accepted by most experts is from 1.4 to 5.6 degrees centigrade. Consequences will include rising sea level and shrinking ice caps at the poles, as well as species extinction and shifts in habitat and ecosystems. Refer to Figures 23.23 and 23.26 and Table 23.1.

- **What should be the goal of energy and environmental policies?**

  Brief answer: Policies should guide the nations of the world through the transition from hydrocarbon fuels to less polluting, sustainable energy sources. In particular, carbon dioxide emissions should be reduced to decrease the impact of global climate change.

Vital Information from Other Chapters

The formation of oil, natural gas, and coal involves sedimentary and metamorphic processes that you learned about in Chapters 5 and 6. The carbon cycle, greenhouse effect, and discussions of the climate change in Chapter 15 are essential background material for Chapter 23. Toxic and nuclear waste contamination brings us back to issues related to groundwater and stream transport, discussed in Chapters 17 and 18.

During Lecture

- Keep the big picture in mind as you take notes. Chapter 23 tells the story of energy resources that power our economy and how the activities of our civilization affect our environment. Problems such as the depletion of petroleum as an energy resource and the potential for climate change that arises from energy consumption are explored. Human activities are becoming an increasingly important factor influencing the functions of Earth systems, so much so that some scientists argue that we are plunging our world into a new geological epoch, the Anthropocene. Focus on understanding the components, fluxes, and feedbacks within each system.
- Because this chapter covers the human impact on Earth's environment, which is linked to cultural, social, and economic issues, there may be opportunities for discussion or for debate activities. Previewing the chapter will prepare you to take part in these activities.
- The instructor may make use of a discussion or debate to address some of these issues. Summarize the important social issues and arguments in your notes. Pay particular attention to capturing arguments that contradict your own. Circle these arguments and return to them later for study and consideration. True learning often involves changing our conceptions (and particularly our misconceptions).

We Americans think we are pretty good!
We want to build a house, we cut down some trees.
We want to build a fire, we dig a little coal.
But when we run out of all these things,
then we will find out just how good we really are.

—Will Rogers

After Lecture

Review Notes

The perfect time to review your notes is right after lecture. The following checklist contains both general review tips and specific suggestions for this chapter.

Check Your Notes: Have you…

- ☐ written a summary of what is covered in this lecture? Your summary should say something significant about how human activities change the global environment and the potential for global warming during your lifetime. Suggestion: Write a brief position paper on an Earth issue that concerns you. Ask yourself what Earth system information in Chapter 23 is relevant to the issue. Try to develop a position that is based on reason and is consistent with existing science.
- ☐ captured arguments about how we should use our nonrenewable energy and materials that came up in the lecture or during classroom discussions or debate?
- ☐ created a brief big picture overview of this lecture and chapter?

Intensive Study Session

Set priorities for studying this chapter. Give highest priority to activities that involve answering questions. We recommend the following strategy for learning this chapter.

- **Text.** This is a chapter with unusually powerful implications for our future as human beings. To gain an overview of those implications, read the sections called Energy Sources and Rise of the Fossil-Fuel Economy and examine Figures 23.3, 23.5, 23.6, 23.7, 23.10, , 23.11, 23.12, and 23.15. Then read the two Earth Policy features. Earth Policy 23.1 deals with toxic and nuclear waste contamination. Think about the implications of these figures. It is time well spent.
- Review the key figures on the formation of energy resources. They illustrate the formation of oil (Figure 23.8) and coal (Figure 23.14). You have to understand these figures to answer the review questions.
- **Review Questions.** Answer the Review Questions to check your understanding of the lecture. Check your answers as you go, but try to answer each question before you look at the answer. Notice the test-taking tips that are interspersed with the questions. They are designed to help you do better on your next exam.
- **Web Site Study Resources**
  http://www.whfreeman.com/understandingearth6e

  Complete the **Online Quiz**. Pay particular attention to the explanations for the answers. The **Geology in Practice Exercise** *The Tempest in the Teapot—Finding Oil* illustrates how oil reservoirs are discovered in the context of a bit of history.

  Did you know that it takes about two pounds of coal to produce the energy for you to copy a megabyte of music off the internet, and that this action releases four pounds of carbon dioxide into the atmosphere? Learn all about it in the **Geology in Practice** exercises.

Exam Prep

Materials in this section are most useful during preparation for exams.

Final Exam Prep

Each semester, in one week, you get to take an exam in each of your courses. Most of the exams are comprehensive finals that cover the entire semester. Dealing with finals week successfully can be a challenge. Here are some tips that will ensure that you do your best work during finals week.

Tips for Surviving Finals Week

- Be organized and systematic. Use the **Final Exam Prep Worksheet** (Appendix B) to help you get organized for finals. Use the **Eight-Day Study Plan** (Appendix A) for every course in which the final exam will be an important factor in determining your grade.
- Stick to priorities. Say no to distractions.
- Build in moments of relaxation. Take regular short breaks, exercise, and be sure to get enough sleep.
- Be confident. By now you have built up good study habits. You are a competent learner.

The **Chapter Summary** and the **Review Questions** should simplify your chapter review. Read the **Chapter Summary** to begin your session. It provides a helpful overview that should refresh your memory.

Next, work on the **Review Questions.** Complete the questions just as you would for an exam, to see how well you have mastered this chapter. After you answer the questions, score them. Finally, and most important, review any question that you missed. Identify and correct the misconception(s) that resulted in your answering the question incorrectly.

Exam Prep Tip: Get Organized for Finals Week

The end of semester is approaching. It's time to get organized for taking exams in all your courses. Take a look at the **Final Exam Prep Worksheet** (Appendix B). There you will find many useful ideas about how to be successful as you enter the home stretch of your semester.

Our entire society rests upon—and is dependent upon—our water, our land, our forests, and our minerals. How we use these resources influences our health, security, economy, and well-being.

—John F. Kennedy, February 23, 1961

Chapter Summary

What is the origin of oil and natural gas?

- Oil and natural gas form from organic matter deposited in marine sediments. The organic materials are buried as the sedimentary layers grow in thickness. Heat, pressure, and bacterial action transform the organic matter into fluid hydrocarbons. The fluid hydrocarbons tend to migrate out of the source rock and accumulate in geologic traps that confine the fluids within impermeable barriers. Refer to Figure 23.6.

Why is there concern about the world's oil supply?

- Oil is a nonrenewable resource: it will be depleted faster than nature can replenish it.
- Petroleum resources will be significantly depleted within about a century.

What is the origin of coal, and how big a resource is it?

- Coal is formed by the compaction and mild metamorphism of buried wetland vegetation. The process by which coal forms begins with the deposition of plant matter. Protected from complete decay and oxidation in a wetland environment, the deposit is buried and compressed into peat. Subjected to further burial, peat undergoes mild metamorphism, which transforms it successively into lignite, subbituminous and bituminous (soft) coal, and anthracite (hard) coal. As the deposit becomes more deeply buried, the temperature rises and structural deformation may occur. Refer to Figure 23.14.
- Domestic coal resources in the United States would last for a few hundred years at current rates of use—about a billion tons per year.
- Environmental concerns associated with the use of coal include mine reclamation, pollution, acid emissions that are precursors of acid rain, and carbon dioxide (a greenhouse gas) emissions.

What are the prospects for alternative sources of energy?

- Alternative energy sources include nuclear, geothermal, hydroelectric, wind, biomass, and solar sources.
- Taken together, these sources currently provide only 14 percent of world energy needs.
- As with fossil fuels, there are significant economic, technological, environmental, and political concerns associated with alternative energy resources.

What is acid rain?

- Acid rain is produced mainly from emissions of sulfur-containing gases. Acid rain can cause noticeable damage to forest and lake ecology, fabrics, paints, metals, and building materials.

What is ozone depletion, and why should it concern us?

- A well-defined, large-scale zone of ozone depletion has formed within the stratosphere due to complex interactions with chlorofluorocarbon (CFC) compounds. Stratospheric ozone shields Earth's surface from damaging ultraviolet radiation and this shield is being compromised due to ozone depletion. The Montreal Protocol is an international treaty that appears to have dealt successfully with this environmental disaster.

How much global warming will there be in the twenty-first century, and what will be the consequences?

- The range accepted by most experts is from 1.4 to 5.6 degrees centigrade.
- Consequences will include a rising sea level and shrinking ice caps at the poles, as well as species extinction and shifts in habitat and ecosystems. Refer to Figures 23.23 and 23.26.

What should be the goal of energy and environmental policies?

- Policies should guide the nations of the world through the transition from hydrocarbon fuels to less polluting, sustainable energy sources. In particular, carbon dioxide emissions should be reduced to decrease the impact of global climate change. More efficient use of energy, greater use of natural gas, safer nuclear energy, and clean coal technology would facilitate this transition.

Review Questions

Answers and explanations are provided at the end of the Study Guide.

1. What is the sequence from low to high grade for the transformation of plant matter into hard coal?
   A. plants, peat, lignite
   B. peat, lignite, bituminous, anthracite
   C. bituminous, anthracite, peat, lignite
   D. anthracite, bituminous, lignite, peat
   Hint: Refer to Figure 23.14.

Test-Taking Tip: Use what you know to guess what you don't know

When confronted with an exam item like Review Question 1, you often don't have to remember the entire sequence to answer the item correctly. Suppose, for example, that you remember for sure that anthracite is the final high-grade product in the series. In that case you can check B with confidence even if you can't remember the rest of the sequence.

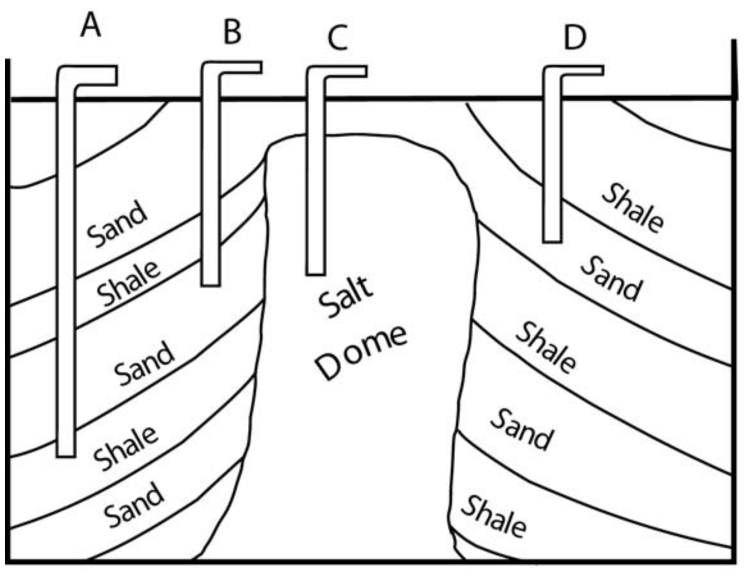
2. The following are all energy sources. Which one is NOT a fossil fuel?
   A. natural gas
   B. coal
   C. uranium
   D. oil
3. Which of the following is NOT a consequence of fossil fuel consumption?
   A. mine reclamation
   B. ozone depletion in our atmosphere
   C. disposal of residual ash from the burning of coal
   D. acid rain
4. Oil and natural gas are mostly found in sedimentary rocks deposited in
   A. the deep ocean.
   B. river deltas and on the continental shelf.
   C. wetlands.
   D. large lakes.
5. All of the following are effective oil traps EXCEPT
   A. faults.
   B. anticlines.
   C. salt domes.
   D. horizontal sedimentary and volcanic beds.
   Hint: Refer to Figure 23.7.
6. Oil production in the United States reached a maximum in
   A. 1960.
   B. 1970.
   C. 1980.
   D. 1990.
7. The most important source of U.S. energy is
   A. coal.
   B. nuclear power.
   C. oil.
   D. hydroelectric power.
   Hint: Refer to Figure 23.5.
8. How many U.S. gallons are contained in one barrel of oil?
   A. 16 gallons
   B. 25 gallons
   C. 42 gallons
   D. 55 gallons
   Hint: Refer to Figure 23.7.
9. The United States ranks ________ in oil reserves.
   A. first
   B. second
   C. eighth
   D. tenth
   Hint: Refer to the text section Distribution of Oil Reserves and Figure 23.10.
10. Important factors contributing to the formation of coal from vegetation are
    A. heat and oxidation.
    B. compaction by burial and heat.
    C. biological activity and dissolution.
    D. hydrothermal alteration and metamorphism.

11. From what process is coal derived?
    A. the decay of marine plants and animal matter
    B. the burial, compression, and heating of plant matter deposited in wetlands
    C. deposition and metamorphism of marine limestones
    D. transport of organic matter by rivers to their delta
    Hint: Refer to Figure 23.14.
12. Acid rain forms when __________ from the combustion of coal and petroleum combines with rainwater.
    A. hydrogen
    B. sulfur dioxide
    C. oxygen
    D. nitrogen
13. The potential for chemical weathering is __________ by acid rain.
    A. not effected
    B. decreased
    C. increased
    D. neutralized
14. The occurrence of acid rain is most influenced by the
    A. release of radioisotopes by nuclear power plants.
    B. burning of high-sulfur coals.
    C. burning of low-sulfur coals.
    D. weathering of feldspars.

Test-Taking Tip: Use what you know to guess what you don't know

The presence of two alternatives dealing with the same thing (in this case "sulfur coals") is a hint that one of them is probably the correct answer.

15. Predict which well would give the best potential for oil and gas production.



    A. well A
    B. well B
    C. well C
    D. well D
    Hint: Refer to Figure 23.8.

16. Why do scientists suspect that CFCs are the source of ozone depletion in the stratosphere?
    A. CFCs contain chlorine, which reacts vigorously with ozone, while measurements of ozone in the stratosphere show it decreasing at the same time that CFCs are increasing.
    B. CFCs form a mixture with volcanic gases in the lower atmosphere, which rises to the stratosphere and reacts with ozone.
    C. CFCs concentrate UV radiation, splitting apart ozone molecules.
    D. CFCs increase the albedo of the stratosphere, which reduces the solar radiation required for the production of ozone.
17. Ozone is a very reactive gas, so as a pollutant in the lower atmosphere, ozone presents a significant health hazard. Why does ozone exist in the stratosphere?
    A. It constantly is leaking from the troposphere, where it is produced, up to the stratosphere.
    B. It is formed from the release of gases out of the micrometeoric dusts that bombard the upper atmosphere.
    C. It is formed continuously in the stratosphere by solar radiation, and it cannot mix or react with other gases because of the thin atmosphere at that altitude.
    D. It is produced constantly from the oceans and rises through the troposphere to the stratosphere.
18. The increase of the average temperature on Earth is linked to burning fossil fuels because the
    A. burning process consumes oxygen.
    B. burning process consumes CO_2.
    C. burning process generates CO_2.
    D. smoke given off by burning insulates the Earth.
19. Toxic and radioactive chemicals leaking from the Hanford Superfund site have
    A. remained confined to the Hanford site.
    B. migrated in the aquifer to the Columbia River.
    C. been successfully cleaned up.
    D. reached Seattle.
    Hint: Read Earth Issues 23.1.
20. If we continue our reliance on fossil fuels, projections of atmospheric carbon dioxide concentrations in 2100 are likely to be about ________ and the average surface temperature will likely rise about ________ more than in 1990.
    A. 600 ppm and 3°C
    B. 950 ppm and 4.5°C
    C. 500 ppm and 2°C
    D. 750 ppm and 3°C
    Hint: Refer to Figure 23.22.

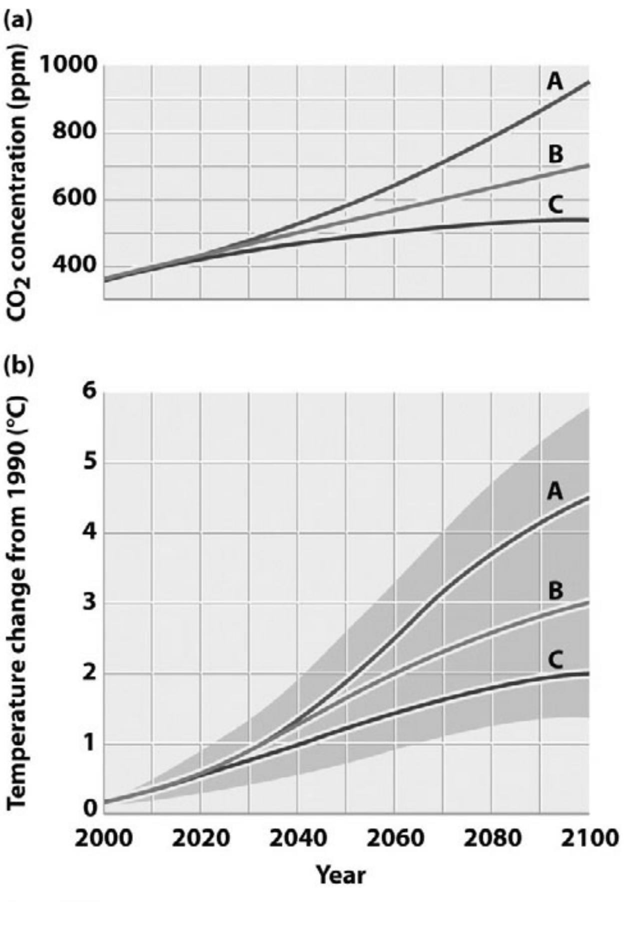


Figure 23.23. Projections of (a) atmospheric carbon dioxide concentrations and (b) average surface temperatures for the next 100 years.

APPENDIX A

Eight-Day Study Plan*

(Make a copy for every exam you take.)

Here is a guide you can use to prepare for your exams. Everyone develops their own approach to preparing for exams; feel free to adapt these ideas to your particular needs and situation.

The basic idea is to conduct your preparation in a systematic fashion with focus on the most important material. Our plan accomplishes this by dividing the material equally and suggesting how to incorporate the Exam Prep materials provided in this Study Guide for each text chapter.

8 Days Before the Exam: Get Organized!

Step 1: Clarify the task. Determine what type of exam you'll be taking by briefly answering the following questions.

1. This exam will cover (list each chapter to be covered):

   ____

   ____

   ____

2. Material and kinds of skills to be particularly emphasized (list chapters/ideas/skills the instructor said would be particularly important):

   ____

   ____

   ____

3. Question format will be (check one that applies):
   - ☐ Multiple choice
   - ☐ True–false
   - ☐ Essay
   - ☐ Thought problems
   - ☐ Other (specify)______________________________

*Adapted with permission from the University Learning Center, University of Arizona.

4. Review session is scheduled for (enter date here and be sure to attend):________________

Step 2: Divide the material you must review into four equal Parts: A, B, C, and D.

7 Days Before the Exam: Review Part A. Begin your review with the material in Part A. Do the following for each chapter you review.

1. **Chapter Summary.** To get yourself started, read the Chapter Summary (**Exam Prep** section of this guide) for the chapter you want to review.
2. **Review Questions.** Answer the Review Questions (**Exam Prep** section of this guide) to see where you are with the material. Force yourself to answer all questions for the chapter without referring to the answer key. Correct your answers only after you have tried all the questions. Be sure to review carefully any questions you missed. Correct the misconception that resulted in the error.
3. **Lecture Notes.** Review your lecture notes and the annotations you made in the margins by asking yourself questions.
4. **Practice Exercises.** This may be a good time to redo some of the Practice Exercises in this Study Guide.
5. **Review visual materials and key figures.** Review the visual material in your notes. Test yourself by seeing if you can reconstruct key text figures from memory.
6. **Self-Test.** Spend as much of your study time as possible quizzing yourself.

6 Days Before the Exam: Review Part B. Repeat the instructions for Day 7. If you have problems with the material, see the instructor at the next open office hour.

5 Days Before the Exam: Review Part C. Repeat the instructions for Day 7. If you have problems with the material, see the instructor at the next open office hour.

4 Days Before the Exam: Review Part D. Repeat the instructions for Day 7. If you have problems with the material, see the instructor at the next open office hour.

3 Days Before the Exam: Review all four parts. Review Parts A, B, C, and D fully. Prioritize your time. Focus on important material that will be covered. Work hardest where you are least sure of yourself. If you have problems with the material, see the instructor at the next open office hour.

2 Days Before the Exam: Review all four parts. Review Parts A, B, C, and D fully. Prioritize your time. If you have problems with the material, see the instructor at the next open office hour.

Night Before the Exam: Be sure you get the amount of sleep you need to be alert and perform at your best. You don’t need to cram. Just stay focused.

Zero Hour: You have prepared well. Allow yourself to be confident. Stay focused and confident during the exam. Use your best-test taking strategies.

APPENDIX B

Final Exam Prep* Worksheet

(**To be completed 3 weeks prior to final exam**)

1. **Course sheets:** In your notebook set up a separate sheet of paper for each course you are taking. Label the top of each sheet with the course and the grade you presently have (be realistic, not hopeful).
2. **Date:** Note the date of the final under each course name.
3. **Comprehensive finals:** Mark with a "C" each course with a comprehensive final.
4. **Exam format:** Identify the format of the exam (multiple choice, essay, and so on) under the date of the final for each course.
5. **Task:** Identify the levels of thinking expected. **Hint:** Previous midterms are your ultimate resource. List all kinds of questions. Estimate what percent of total points will be devoted to each kind of thinking.
   - Application to real-world situations
   - Problem solving
   - Critical thinking
   - Understanding principles
   - Memory of basic facts
6. **Rank finals in importance:** In the upper right-hand corner of each sheet, rank in order the most critical and important final to the least important final—the final that will make the least difference in your grade. (Be aware of how much impact your final exam has on your overall class grade.)

*Adapted with permission from the University Learning Center, University of Arizona.

7. **List What the Test Will Cover:** For each course on each sheet, list everything the test will cover; remember which exams are comprehensive.
   - ☐ Handouts?
   - ☐ Chapters? (Which ones?)
   - ☐ Lectures?
   - ☐ Discussions?
   - ☐ Other?

   Check your syllabi to be sure you have not left our any important material.

8. Draw a line beneath this list. Then list what you still have left to do for that particular course.
   - ☐ Which chapters do you still have to preview?
   - ☐ Which lecture notes do you need to review and update?
   - ☐ Which Practice Exercises and Review Questions do you need to complete?
   - ☐ Which labs do you still have to finish?
   - ☐ What papers do you still have to write?

9. Draw another line. Now list the test preparation strategies you will use to study for the exam—study groups or study patterns, self-questioning using the annotations, mapping, charting, questions and answers, concept cards, going over old tests and quizzes, and making up your own problems.

10. Now fill in the calendar by identifying exams, finals, and due dates for papers. Each day you need to do something from no. 8, but you will also need to study and review for the finals at least two hours a day. Be sure to use all of your available times—weekends, waiting time, and so on.

Work Toward These Goals

- ☐ Finish all work under no. 8 (Chapter Previews, Practice Exercises, Review Questions, and so on) one week prior to your first final. Review all lecture notes by asking yourself the questions out loud or by having someone quiz you five days prior to your first final (allow two to three hours).
- ☐ Divide the work that remains so that you do an Eight-Day Study Plan for each course that you assigned a high priority in no. 6.
- ☐ Remove the distractions from your life. This is not the week to be captured by TV or other addictions. Stick to your priorities. Tell friends and family that you need to focus all your energy on your finals until they are over.
- ☐ Avoid burnout. Build time into your schedule for adequate sleep, relaxation, and exercise.

Answers to Practice Exercises and Review Questions

Chapter 1

Answer to Practice Exercise

A. The highest point on Earth is Mount Everest in the Himalayan mountains of Asia.
B. The lowest point on Earth is the Marianas Trench in the Pacific Ocean south of Japan.
C. The Marianas Trench is 2182 meters lower relative to sea level than Mount Everest is high.
D. The total topographic relief on Earth is the sum of the highest and lowest points: 11,030 meters deep + 8,848 meters high = 19,878 meters (65,216 feet).

Answers to Review Questions

1. B. A hypothesis provides an opportunity for feedback and testing.
2. A. A hypothesis is a tentative explanation that can help focus attention on plausible features and relationships of a working model. If a hypothesis is eventually confirmed by a large body of data, it may be elevated to a theory. Theories are abandoned when subsequent investigations show them to be false. Confidence grows in theories that withstand repeated tests and are able to predict the results of new experiments.
3. B. He measured the difference in the angle of sunlight hitting the Earth on the summer solstice at two different places in Egypt.
4. C. The present is the key to the past. Geologic processes we see in action today have worked in much the same way throughout geologic time. The principle of uniformitarianism does not mean that all geologic phenomena are slow.
5. C. The mantle represents 67.1% of Earth's mass. Refer to Figure 1.9.
6. A. The crust is thickest on the continents. The thickest crust stands the highest. Refer to Figure 1.11.
7. D. Silicon is more abundant in the crust. Refer to Key Figure 1.12.

8. D. Movement of the plates is a result of convection in the mantle. Refer to Figure 1.15. It is important to distinguish between a result and a cause. Plate tectonics is a result of convection in the mantle, but density differences caused by heating and gravity are what drive convection and cause plate tectonic motions.
9. C. The Earth's magnetic field is caused by the geogdynamo, created by convection in the outer liquid core and electrical currents.
10. A. Earth's magnetic field reverses (the poles flip) at irregular intervals.
11. A. Heated matter rises under the force of buoyancy because it is less dense.
12. B. The Big Bang occurred about 540 million years ago, and in an interval of perhaps less than 10 million years, eight entirely new branches of the animal kingdom were established.

Chapter 2

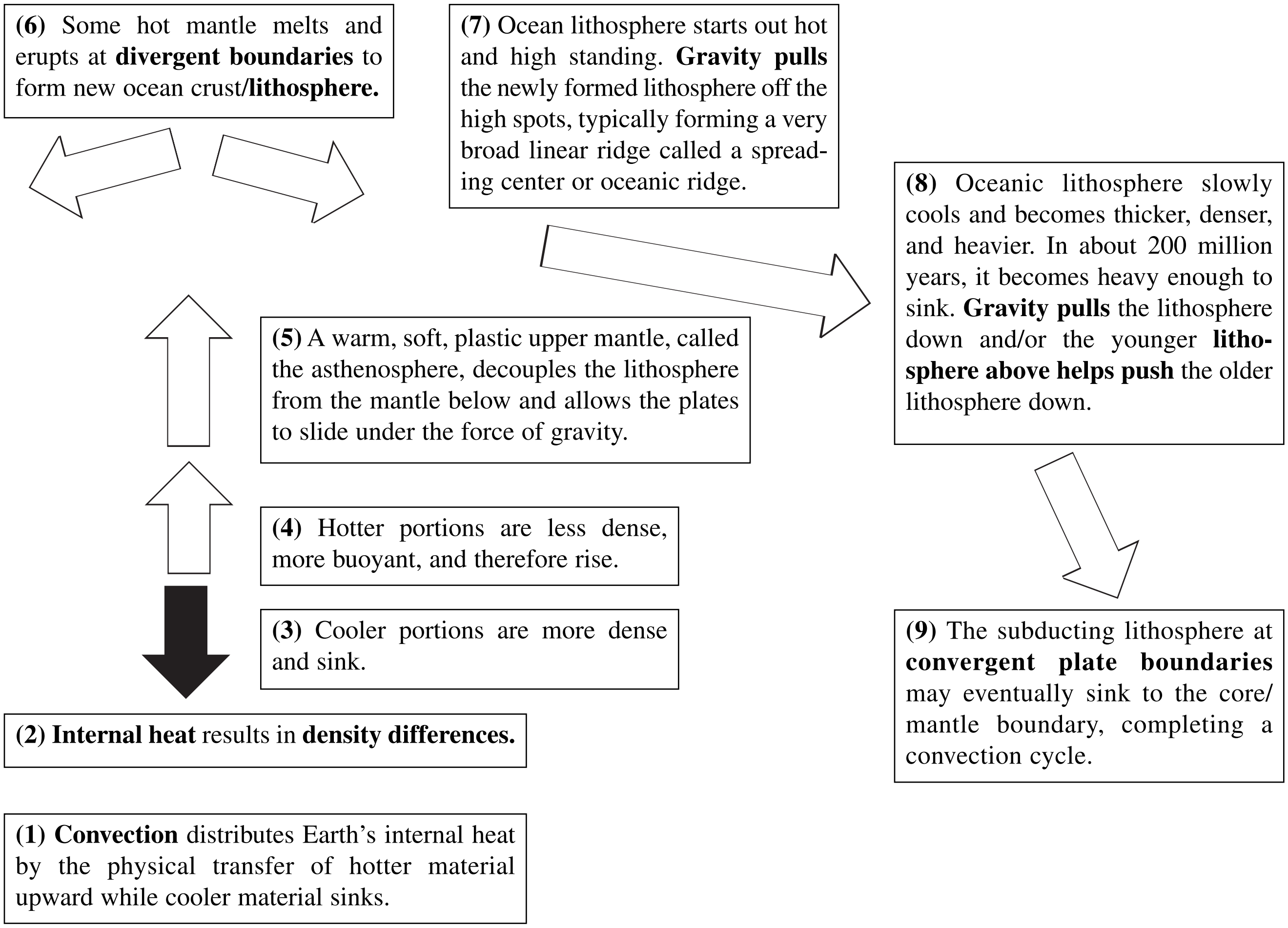
Answers to Practice Exercises

Exercise 1: Characteristics of active tectonic plate boundaries

Characteristics	**Divergent** See Figures 2.7, 2.8, 2.9, and 2.10.	**Convergent** See Figures 2.7 and 2.8. **Ocean/ Ocean**	**Ocean/ Continental**	**Collision**	**Transform** See Figures 2.7, 2.8, and 2.11.
Examples	Mid-Atlantic Ridge, African Rift Valley, Red Sea, and Gulf of California	Japanese islands Marinas Trench Aleutian Trench	Peru-Chile Trench Andes Mountains Cascade Range	Himalayas and Tibetan Plateau	San Andreas Fault
Topography	*oceanic ridge, rift valley, ocean basins, ocean floor features offset by transforms, seamounts*	*trench, island arc*	trench, volcanic arc, and high mountains	very high plateau and mountains	*offset of creek beds and other topographic features that cross the fault*
Volcanism	present	*present*	present	not characteristic	*not characteristic*

Exercise 2: Construct a conceptual flowchart or diagram illustrating how plate tectonics works

Key elements in the flowchart or diagram to review and clearly understand should be the roles of differential heating (which creates density differences), buoyancy (a force created by density differences), and gravity, all of which generate convection within the Earth's mantle.



Answers to Review Questions

1. A. Volcanism at the oceanic ridges builds the seafloor.
2. A. Refer to Figures 2.12 and 2.15.
3. B. Figure 2.7 shows that the rate of plate motion today varies from a few centimeters to 15 centimeters per year.
4. D. The typical plate motion along most transform faults is horizontal slip (shearing). However, along curves in the transform fault, transextension (forming a depression) and transcompression (forming mountains) may be generated.
5. A. Refer to Figure 2.8.

6. C. The Hawaiian islands formed over a hot spot in the middle of the Pacific ocean plate. Some hot spots, such as in Iceland, are located coincidentally adjacent to a spreading center. Most hot spots on Earth are not directly associated with plate boundaries.
7. A. The Atlantic coast of North America is a passive continental margin, which is not associated with an active plate margin.
8. D. Pangaea began to break up during the Jurassic Period. Refer to Figure 2.16.
9. B. Mid-oceanic ridges or spreading centers are divergent boundaries where the crust is extending (pulling apart) and mafic magmas are intruding upward from the asthenosphere to feed basaltic volcanism that is building new ocean floor.
10. A. Refer to Figure 2.8.
11. C. Volcanism is not characteristic of transform plate boundaries. Some volcanism, typically minor amounts, may occur in association with transform faults where transextension is occurring.
12. C. Refer to Figure 2.16.
13. D. See Figure 2.16.
14. A. Refer to Figure 2.12.
15. B. This age becomes more interesting when you compare it to the age of the oldest rocks on the continents, which is 4.0 *billion* years. Refer to Figure 2.15.
16. B. Refer to Figure 2.15.
17. A. Refer to Figure 2.8.
18. B. Refer to Figures 2.7 and 2.8.
19. C. Refer to Figure 2.10.
20. A. Refer to Figure 2.12.
21. A.
22. D.

CHAPTER 3

Answers to Practice Exercises

Exercise 1: Crystal structures of some common silicate minerals

A. single chains of silica tetrahedra
pyroxene (augite)
two good cleavage planes intersecting at about 90°.

B. double chains of silica tetrahedra
amphibole (hornblende)
two good cleavage planes intersecting at about 60° and 120°.

C. sheets of silica tetrahedra
mica (muscovite)
excellent cleavage in one direction. Refer to Figure 3.17.

Exercise 2: Major mineral classes

1. *silicate* (*double-chain*)
2. oxide of magnesium and aluminum
3. silicate (sheet)
4. calcium carbonate
5. hydrated calcium sulfate
6. silicate (framework)
7. native element (carbon)
8. calcium/magnesium carbonate
9. silicate (framework)
10. oxide of aluminum
11. sodium halide
12. iron oxide
13. native element (carbon)
14. iron sulfide
15. silicate (sheet)
16. calcium sulfate
17. silicate (single-chain)
18. iron sulfide
19. oxide of aluminum
20. silicate (framework)
21. native element (silver)
22. silicate (framework)
23. silicate (isolated tetrahedra)
24. silicate (sheet)

Exercise 3: Identifying minerals by their physical properties

A. muscovite

B. pyrite

C. malachite

D. orthoclase

E. calcite

F. gypsum

Exercise 4: Rock cycle review

A. Plate tectonic settings for magma generation are:

hotspots/mantle plumes
divergent boundaries
convergent boundaries

B. Types of igneous rocks

Extrusive: Fast cooling, fine grained

Intrusive: Slow cooling, coarse grained

C. Rock and mineral particles are transported and laid down as sediments by running water, wind, and ice.

D. Two processes that convert loose sediments into rock are compaction (burial) and cementation.

E. The two main types of sedimentary rocks and their constituents are:

Siliclastic: Rock and mineral fragments

Chemical/biochemical: precipitation of minerals previously dissolved during weathering

F. Following are the four major conditions (geologic settings) that result in metamorphic rocks:

Contact metamorphism associated with intrusions of magma
Regional metamorphism associated with plate collisions
Ultra-high-pressure metamorphism deep within the lithosphere
High-pressure, low-temperature metamorphism associated with subduction zones

G. No. The rock is not melted during metamorphism, although a minor amount of melt "sweat" may be generated during high-grade metamorphism. Igneous rocks are formed from the solidification of melts (magmas).

Answers to Review Questions

1. D. Chloride is an anion and easily gains an electron from sodium, which loses an electron to become a cation. With one extra electron, chlorine has the electron configuration of the noble gas argon. On losing an electron to chlorine, sodium has the electron configuration of the noble gas neon.
2. D. Graphite and diamond are both composed of pure carbon but have significantly different crystal structures.
3. B. A rock is an aggregate of one or more minerals.
4. C. All minerals are crystalline solids.
5. D. By definition, minerals are inorganic. Are graphite and diamond minerals? Yes. They are both made from pure carbon—a common element in organic material. However, graphite and diamond are not produced by biological processes. Graphite is typically found in metamorphic rocks, and diamond originates in the Earth's mantle.
6. B. Glass is an amorphous material that lacks a crystal structure. Native copper, diamond, and water ice all fit the definition of a mineral.
7. B. Silicate minerals are the most common mineral group in the Earth's crust and mantle. The Earth's core is thought to consist mostly of an iron-nickel alloy.
8. B. Refer to Figure 3.11.
9. C. Mica, like muscovite, is a sheet silicate.
10. B. Refer to Table 3.1 and Appendix 4.
11. A. Clay minerals have a sheet silicate structure.
12. A.
13. B. Quartz is a silicate and calcite is a carbonate.
14. B. Cleavage is the tendency for minerals to break along planes of weaker chemical bonds within their crystal structure.
15. A. The physical characteristics of a mineral are determined by its composition, the nature of its chemical bonds, and the crystal structure. Although graphite and diamond are both pure carbon, their crystal structures and the chemical bonds within the crystal structures are significantly different.
16. B. Chemical bonds typically exhibit a mixture of ionic and covalent characteristics. Bonds with a more covalent character are stronger and the bond length is shorter. Bonds with a more ionic character are weaker and the atoms tend to be farther apart.
17. D. Cations of similar sizes and charges tend to substitute for one another and to form compounds having the same crystal structure but different chemical compositions. Cation substitution is common in silicate minerals.
18. A. Compared to ionic bonds, covalent bond length is shorter and covalent bond strength is higher.
19. B. Plutonic rocks solidify from melts called magmas. Refer to Figures 3.24 and Figure 3.28.
20. C. Most magmas are generated from the melting of silicate rocks within the Earth's crust and mantle. On rare occasion, a magma composed of carbonates erupts on the Earth's surface. On Io, the moon of Jupiter, sulfur magmas erupt from about ten active volcanoes. Io's eruptions can shoot fountains of sulfur compounds 360 km high.
21. A. An igneous rock with a coarse texture, where individual mineral grains (crystals) are visible without magnification, forms when the rock crystallizes slowly beneath the Earth's surface. Solidification of a magma body may take tens to hundreds of thousands of years within the crust, and millions of years more to cool after complete crystallization. To expose a coarse grain igneous (plutonic) rock at the Earth's surface requires significant uplift and erosion of the rocks that once sat on top.

22. D.
23. A. Layering is characteristic of sedimentary rocks. Some volcanic rocks, like lava flows and volcanic ash and tuff, also form layers.
24. D. Contact metamorphism is associated with magma intrusions.
25. A. Weathering creates sediments.
26. D. Mountains are a result of subduction and continents colliding.

CHAPTER 4

Answers to Practice Exercises

Exercise 1: Igneous rock textures

Texture term/sketch description

A. phaneritic/coarse-grained, large interlocking crystals
B. phaneritic/visible crystals but not as coarse grained as sample A
C. porphyritic/mixed cooling history causes large and very small crystals
D. aphanitic/fine grained—crystals may not be visible without magnification, even then looking like tiny dots

Exercise 2: Distribution of igneous rocks within the Earth

Major layer in the Earth	Example igneous rock	General compositional group	General chemical composition
Continental crust (For continental crust, there are two appropriate answers.)	*Granite*	Felsic	More Si, Na, K Less Fe, Mg, Ca
	Andesite/diorite	*Intermediate*	Intermediate
Ocean crust	Basalt/gabbro	Mafic	More Fe, Mg, Ca Less Si, Na, K
Mantle	Peridotite	Ultramafic	*Less Si, Na, K* *More Fe, Mg, Ca*

Exercise 3: Predicting the change in composition in a crystallizing magma

A. 1. Silica content increased
   2. Iron content decreased

Explanation: Refer to Figure 4.6, which illustrates how mafic (iron- and magnesium-rich) silicate minerals crystallize first in a cooling magma. As iron becomes tied up in the crystallizing solid phase (olivine and pyroxene), the remaining liquid becomes progressively enriched in silica.

B. 1. Silica content increased
   2. Iron content decreased

Explanation: Refer to Figure 4.6, which illustrates how mafic (iron- and magnesium-rich) silicate minerals crystallize first in a cooling magma. As iron and calcium become tied up in the crystallizing solid phase, the remaining liquid becomes progressively enriched in silica and sodium.

Exercise 4: Sequence of mineral crystallization in a solidifying magma

Refer to Figures 4.4, 4.6, and 4.7.

A. LESS. The presence of iron and magnesium in the magma greatly influences the complexity of the silicate structure because the iron and magnesium act to "poison" the polymerization of the silica tetrahedra, preventing more complex silica tetrahedra crystalline structures. Since much of the iron and magnesium is incorporated into the early-formed crystals, as illustrated in Figures 4.6 and 4.7, minerals that crystallized later in the history of the solidification of the magma tend to be depleted in iron and magnesium, enriched in silica, and have more complex silicate structures.
B. LAST. Refer to the explanation for A.
C. MORE. Refer to the explanation for A.

Exercise 5: Partial melting and magma composition

A. LOWER. Refer to Figures 4.6 and 4.7.
B. DEPLETED. Much of the iron and magnesium in a magma is incorporated into the early-formed crystals, as illustrated in Bowen's reaction series. Minerals that crystallized later in the history of the solidification of the magma tend to be depleted in iron and magnesium and enriched in silica.
C. ENRICHED. Refer to the explanation for B and Figures 4.6 and 4.7.

Exercise 6: Predicting the composition of magma generated in subduction zones

A. MORE. As illustrated by Bowen's reaction series, silicate minerals with more silica content have lower melting temperatures. So a partial melt will be enriched in silica relative to the igneous rock from which it was generated.
B. LESS. Silicate minerals rich in iron and magnesium have higher melting points and are the last to melt compared to minerals lower on the Bowen's reaction series diagram. Therefore a magma generated from a partial melt will be enriched in silica and depleted in iron and magnesium relative to the bulk composition of the original rock from which the melt was generated.
C. MORE. Figures 4.6, 4.7 and 4.16 are very helpful. Na and K concentrate in minerals with greater amounts of silica. So they are enriched in that they have lower melting temperatures and crystallize late in the cooling history of the magma.
D. LESS. A partial melt will always have more silica and less iron/magnesium than the parent rock from which it is generated. Therefore it will be less mafic.

Answers to Review Questions

1. A. Many students mistakenly choose B or C as the answer. However, grain size is just one of two criteria for the classification and naming of igneous rocks. Composition (mineral content) is the other criterion.
2. D. Rhyolite is an aphanitic volcanic rock and granite is a phaneritic plutonic rock. Their cooling histories are different and therefore their textures are different. However, they have the same general composition (felsic).
3. B. Rhyolite contains the most silica of the rocks listed. Fissure eruptions may be composed of a great variety of lavas, but they are typically basaltic.
4. A. Gabbro is the intrusive equivalent of basalt, which is extrusive.
5. D. The distinction between intrusive (plutonic) and extrusive (volcanic) rocks is grain size, which is determined by the rate of crystallization.

6. A. Pyroxenes like augite are a common mineral in basalts. They are a ferromagnesium mineral with a single-chain silicate crystal structure.
7. A. Refer to Figures 4.4, 4.6, and 4.7.
8. B. Slow cooling typically produces larger crystals. Rapid cooling produces finer crystals. An igneous rock with a mixture of coarse- and fine-grained minerals formed under conditions where the cooling history was mixed. Both volcanic and plutonic rocks exhibit porphyritic texture. A porphyritic volcanic rock erupts from a magma that has begun to crystallize—crystals already exist within the magma. Early-formed crystals are literally carried to the surface by the remaining melt, which cools quickly on erupting at the Earth's surface. A porphyritic texture in a plutonic rock may be a result of its cooling history or changes in pressure and other conditions that influence crystal growth within the magma chamber.
9. D. Table 4.1 is a good reference for this question.
10. B. If no new magma is ejected into the magma chamber, the composition of the magma may change over time because of fractional crystallization and the segregation of the earlier-formed iron-rich minerals by settling from the melt. The remaining magma becomes progressively enriched in silica and depleted in iron and magnesium.
11. C. Olivine and calcium-rich plagioclase are the first minerals to crystallize from a magma with a mafic composition. Refer to Figures 4.4, 4.6, and 4.7.
12. B. A batholith is a very large body of igneous rock. Batholiths are found in the cores of mountain belts.
13. D. Quartz and olivine do not crystallize from the same magma body. If there was enough iron in the original magma, the silica is consumed in the formation of the ferromagnesium minerals and plagioclase feldspars. The magma completely solidifies before pure quartz can crystallize. A parent magma with enough silica to generate quartz will not contain enough iron and magnesium to generate olivine.
14. A. Intrusive (plutonic) rocks are typically coarser grained because of slower cooling. Extrusive (volcanic) rocks are finer grained because of quicker cooling rates. Cooling rates are not the only factors that influence the grain size of igneous rocks. Rapid changes in pressure within a magma chamber can induce rapid crystallization and therefore fine-grained crystals within an intrusive rock. High water content in residual fluids from a solidifying magma can enhance crystal growth and size.
15. C. Refer to the discussion on *Plutons* in the textbook.
16. D. Refer to the discussion on *Plutons* in the textbook.
17. B. Refer to Figures 4.13 and 4.15.
18. B. Figures 4.6 and 4.7 illustrate how the residual liquid within a magma chamber becomes progressively enriched in silica and depleted in iron as the crystallization of early-formed minerals uses up the available iron.
19. B. Refer to Figure 4.15.
20. D. Subduction at convergent plate margins produces large amounts of andesites. In fact, andesites are named after the Andes Mountains in South America because they are very abundant there. Magmas generated within the upper mantle, such as those at divergent plate boundaries and hot spots, are typically mafic. Refer to Figures 4.13, 4.15 and 4.16.
21. B.
22. A. Refer to Figure 4.15.
23. B. This is the most unlikely hypothesis because melting within a mantle plume, like the hot spot Hawaii, is thought to be caused by decompression of hot ultramafic rock, which generates basalt.
24. C. To melt a solid in a kitchen you heat it up on the stove. Rocks within the Earth are already relatively hot but most are still solid. Reduction in pressure (decompression) and the addition of water (fluid induction) cause rocks to melt within the Earth. Refer to Figures 4.15 and 4.16f.

CHAPTER 5

Answers to Practice Exercises

Exercise 1: Common sedimentary environments

Alpine or glacial river channel: sand and gravel
Dunes in a desert: fine sand
Flood plain along a broad meander bend: silt and clay (mud)
River delta along a marine shoreline: sand, mud, calcified organisms (seashells)
Continental shelf: sand and mud
Deep sea adjacent to a continental shelf: mud
Shoreline beach dunes: sand, gravel, calcified organisms
Tidal flats: sand and mud
Organic reef: calcified organisms

Exercise 2: Grain sizes for clastic sedimentary rocks

Grain size	**Common Object**	**Sediment**	**Rock type**
Coarse	football or bus	*boulder gravel*	conglomerate
↑	plum or lime	gravel	*conglomerate*
	pea or bean	gravel	conglomerate
	coarse-ground pepper or salt	sand	*sandstone*
↓	fine-ground pepper or salt	sand	sandstone
Fine	talcum powder or baby powder	mud, silt, clay	siltstone, mudstone shale, claystone

Exercise 3: Clastic and chemical sediments and sedimentary rocks

Statement	Sediment type	Sedimentary rock example
Composed largely of rock fragments	clastic	sandstone, graywacke, conglomerate
Precipitated in the environment of deposition	chemical	evaporite, phosphorite
Important source of coal	biochemical	peat
Often formed by diagenesis	*chemical*	*dolostone and phosphorite*
Formed from abundant skeleton fragments of marine or lake organisms, such as coral, seashells, and foraminifers	biochemical	limestone
Produced by physical weathering	clastic	conglomerate, sandstone, siltstone, shale
Produced from rapidly eroding granitic and gneissic terrains in an arid or semi-arid climate	clastic	arkose sandstone

Answers to Review Questions

1. D. Shale, sandstone and conglomerate are clastic rocks. Dolomite, chert, limestone, coal and gypsum are chemical/biochemical rocks.
2. D. See Table 5.3
3. D. Sand is a term that refers solely to a particular range of grain sizes. It does not imply any specific composition. Quartz and feldspar are common constituents of sand grains

because they are common minerals in the Earth's continental crust. Carbonates, like limestone, dolostone, and fragments of seashells, can also make up sand grains.

4. D. See Figure 5.1.
5. B. There is no known marine life that precipitates dolomite. Dolomite can be precipitated inorganically in seawater, not fresh water.
6. A. Refer to Figure 5.16.
7. A.
8. A.
9. D. Cross-bedding is a feature produced as sediment is deposited by currents of air or water.
10. D. Carbonate sediments are deposited in warm water. Carbonates dissolve in cold water because their solubility is linked to the amount of carbon dioxide dissolved in the water. The solubility of carbon dioxide increases as the temperature of the water decreases.
11. A. Refer to Figure 5.20.
12. B. See Table 16.2.
13. D. Figure 5.20 will help.
14. C. See Table 5.1.
15. D. See Table 5.1. Ultimately, the weathering of most silicate minerals, except quartz, produces clays that become compacted into shale. See Figure 5.16.
16. B. Refer to Figure 5.15.
17. A. Refer to Figure 5.22 and Earth Issues 5.1.
18. D.
19. A.

CHAPTER 6

Answers to Practice Exercises

Exercise 1: Classification of metamorphic rocks based on texture

Parent rock	Metamorphic rock	Texture (foliated/ granoblastic)
shale	slate	*foliated*
quartz-rich sandstone	quartzite	granoblastic
shale, impure sandstone, and many kinds of igneous rocks	*granulite*	granoblastic
granite	schist and gneiss	foliated
limestone	marble	granoblastic
carbonate-rich sedimentary rocks	*hornfels*	granoblastic
basalt (mafic volcanics)	*amphibolites and greenstones*	granoblastic
igneous and metamorphic rocks	*migmatite*	foliated

Exercise 2: Comparing igneous, sedimentary, and metamorphic rocks

Major mineral composition	Texture	Rock type (igneous, sedimentary, metamorphic)	Rock name (granite, sandstone, marble)
calcium carbonate	*nonfoliated*	metamorphic sedimentary	marble limestone
quartz, K and Na feldspar, mica, and amphibole	*phaneritic*	igneous (plutonic)	granite
clay	*fine-grained clastic*	sedimentary	mudstone, shale
pyroxene, calcium feldspar, and olivine	aphanitic, porphyritic	igneous (volcanic)	*basalt*
quartz	*nonfoliated*	metamorphic	quartzite
pebbles and cobbles of a variety of rock types	clastic	sedimentary	cconglomerate
fragments of seashells and fine mud	bioclastic, biochemical	*sedimentary*	limestone
quartz, muscovite, chlorite, and garnet	foliated	*metamorphic*	*schist*

Answers to Review Questions

1. D. If the rock is melted, it is an igneous rock. Some metamorphic rocks, such as migamtite, get hot enough to "sweat" quartz.
2. B.
3. B. Refer to the section Metamorphic Textures.
4. B. Refer to Figures 6.5 and 6.6.
5. A. Refer to Figures 6.5 and 6.6.
6. C. Metamorphic rocks characteristically exhibit either foliated or granoblastic textures.
7. D. Although mineralogy may be altered by metamorphism, typically there is little to no change in bulk composition of the rock.
8. D. Even preexisting metamorphic rocks can be metamorphosed.
9. B. Slate → phyllite → schist → gneiss is the correct sequence from fine-grained to progressively coarser grained metamorphic rocks. All rocks listed in this sequence are foliated.
10. A. Refer to Figure 6.9.
11. C. Meteorite impact of the lunar surface is an example of shock metamorphism.
12. D. Refer to Figure 6.9.

13. B. Gneiss has the same mineralogical composition as granite. Its distinctive characteristic is foliation. Granite is a common parent rock for gneiss.
14. C. Both slate and gneiss are foliated metamorphic rocks. Slate is lower in grade, and thus is much finer grained.
15. D. Refer to Figure 6.4.
16. A. Refer to Figure 4.6.
17. B. The intrusion of a hot magma body causes contact metamorphism.
18. B. As illustrated in Figure 4.7, quartz softens at relatively low temperatures. Oval quartz pebbles could have been stretched into the cigar-shaped features by low-grade metamorphism.
19. C. Refer to Figure 6.9.
20. A. Refer to Figure 6.13 and the Continent–Continent Collisions section in the text.

CHAPTER 7

Answers to Practice Exercises

Exercise 1: Silly Putty

Behavior of Silly Putty	Behavior of rock	Type of force	Geologic structure produced by this style of deformation
Snaps into pieces	brittle	*tensional*	fault or joints
Bends	*ductile*	compressional	folds
Bounces	*elastic*	*compressional*	

Exercise 2: Geologic structures

A. reverse fault
B. compressional
C. convergent

D. anticline
E. compressional
F. convergent

G. normal fault
H. tensional
I. divergent

J. strike-slip fault
K. shearing
L. transform

M. syncline
N. compressional
O. convergent

Exercise 3: Anticline versus syncline

A. In an anticline the youngest rock layer is on the outside of the fold, whereas in a syncline the youngest rock layer is in the middle of the fold.
B. Refer to Figures 7.12, 7.13, and 7.14.

Exercise 4: Identifying geologic structures

A. anticline
B. syncline
C. thrust
D. reverse
E. normal

Answers to Review Questions

1. C. Solids that break are called brittle. Whether a solid behaves brittlely depends on its composition, temperature, and confining pressure and the rate of application of directional forces.
2. A. Refer to Figure 7.3.
3. B. The San Andreas is a right-lateral strike-slip fault. It also represents a transform plate boundary.
4. B. Refer to Figures 7.8, 7.19, 7.20, and 7.23.
5. B. Joints are fractures along which there is no appreciable movement. Faults are fractures along which there is appreciable offset.
6. D. All other conditions mentioned would favor brittle behavior.
7. A. Basalt is an igneous rock with interlocking fine-grained silicate minerals that have a high melting point. Therefore, basalt tends to behave brittlely. Rocks with high clay or calcium-carbonate content tend to behave ductilely.
8. C. Columnar jointing is fracturing caused by shrinkage during cooling of an igneous rock.
9. D. Normal faults are a result of brittle behavior in response to tension.
10. B. Thrust faults are caused by compressional forces typical of what is generated at convergent boundaries like continental collisions.
11. A. Refer to Figure 7.3.
12. B. Refer to Figures 7.13.

Chapter 8

Answers to Practice Exercises

Exercise 1: Determining the succession of geologic events

A. 12. Even though the black dike does not cut all rock units in the diagram, it does cut the granite and layer 1, which is above all other layered rock units. Therefore, the dike is younger than the granite and layer 1. If the dike was not shown cutting the granite, the relative ages of the dike and the granite could not be resolved. Radiometric dates on the two igneous rock bodies would resolve their ages.

B. 10. Layer 10 is the oldest in the outcrop. It is at the bottom of a tilted sequence of layered rocks that go from layer 10 (the oldest) to layer 3 (the youngest of the sequence), assuming that this whole sequence has not been completely overturned.

C. Yes. Layer 3 is older than the dike (unit 12). Even though the dike does not cut layer 3, it does cut the unconformity that cuts layer 3, and it also cuts layers 2 and 1, which are above layer 3.

D. Not possible to know. Because the black dike cuts both the granite (unit 11) and layer 1, we can say that layer 1 and the granite are older than the dike. However, the granite may have intruded into the rock layers before or after the deposition of layer 1. There is no way of telling whether the granite is older or younger than layers 4, 3, 2, or 1. A radiometric date on the granite and layer 1, which is a lava flow, would help to resolve this question.

E. 1. Unit 1 is older than unit 12 but younger than unit 11. You do not even have to calculate radiometric ages to answer this question. Just look at the trend in the abundance of the radioactive parent atoms or accumulation of the daughter atoms. The rock with the greatest amount of parent atoms (and least amount of daughter atoms) is the youngest. The rock with the lowest amount of radioactive parent atoms and the largest accumulation of daughter atoms is the oldest. Because the abundance of radioactive parent atoms in unit 1 falls between units 11 and 12, the radiometric age of unit 1 would be some number of years between the ages of units 11 and 12. Unit 11 has the fewest radioactive parent atoms remaining; therefore, it is the oldest.

Exercise 2: Ordering geologic events

This is a clear illustration of the principle of superposition and cross-cutting relationships at work. Using the principle of superposition, we see that the limestone must have been deposited before the shale and the shale before the sandstone. Likewise, these beds must have existed before being first cut by the dike and second by the fault.

Youngest	Faulting
	Dike intrudes
	Deposition of sandstone
	Deposition of shale
Oldest	Deposition of limestone

Exercise 3: Marker events for the Geologic Time Scale

Eon	Era	Period	Epoch
Phanerozoic		*Quaternary*	*Holocene*
Humans evolve	Cenozoic	*Tertiary*	*Pleistocene*
Dinosaur extinction event			Pliocene
	Mesozoic	Cretaceous	Miocene
		Jurassic	Oligocene
		Triassic	Eocene
	Paleozoic	Permian	Paleocene
		Pennsylvanian	
		Mississippian	
		Devonian	
		Silurian	
		Ordovician	
Evolutionary Big Bang		Cambrian	
Proterozoic			
Oxygen buildup in atmosphere			
First nucleus-bearing cells develop			
Archeon			
Earliest evidence of life			
Major phase of continent formation completed			
Hadean			
End of heavy bombardment			
Moon forms			
Earth accretion begins			

Exercise 4: Geologic Time Scale mnemonic

There is no "correct" answer to this question. Any mnemonic device that you will find useful in remembering the different epochs and periods of the Geologic Time Scale is an acceptable answer.

Answers to Review Questions

1. B. The rock layer at the top of an undeformed sequence of rock layers is the youngest in the sequence.
2. D. Cenozoic, Mesozoic, Paleozoic. Refer to Figure 8.14.
3. B. Paleocene, Eocene, Oligocene, and Pliocene are the epochs of the Tertiary period in the Geologic Time Scale. Remember that the Pleistocene and Holocene are epochs within the Quaternary period. Refer to Figure 8.14.
4. B. Cambrian, Ordovician, Silurian, Devonian, Mississippian, Pennsylvanian, Permian. Refer to Figure 8.14.
5. D. Deposition, deformation, erosion, deposition. Refer to Figure 8.8.

6. A. Rock layer 3 is deposited on top of layer 2 and the 60-million-year-old pluton A. Based on superposition, layer 3 is younger than 60 million years. Layer 3 is also cut by the 34-million-year-old pluton B. Based on this cross-cutting relationship, layer 3 has to be older than 34 million years.
7. C. Refer to the Measuring Absolute Time with Radioactive Clocks section of Chapter 8.
8. C. Refer to the Measuring Absolute Time with Radioactive Clocks section of Chapter 8.
9. D. Refer to Figure 8.14.
10. B. Radiocarbon can be used to radiometrically date carbon-containing materials like charcoal if the sample is younger than about 70,000 years old. Refer to Table 8.1.
11. B. Because radiocarbon has a short half-life (5730 years), the level of radiocarbon decays below the detectable limit in samples older than about 70,000 years. Refer to Table 8.1.
12. C. Given a half-life of 1 billion years, for every billion years that elapses, the number of radioactive atoms decreases by half. Therefore after 1 billion years there are 500 left from the original 1000 atoms; after 2 billion years there are 250 out of the 500 left; after 3 billion years there are 125 out of the 250 left.
13. D. To correctly interpret this question it is important to distinguish between observation (data) and inference. The radiocarbon age of 3000 years is data derived from laboratory analysis of the charcoal sample. The result of the analysis represents the approximate time that has elapsed since the organism (in this case wood) died and was no longer exchanging carbon dioxide with the environment. It is reasonable to infer that the charcoal formed when inhabitants at the site burned wood for cooking and heating. It is also reasonable to assume that the wood was not dead for a long time before it was harvested for fuel. If these assumptions are correct, then the radiocarbon date represents the approximate time for the occupation of the site. However, the charcoal could have formed from a forest fire decades or centuries earlier than human occupation. Or the wood harvested for fuel may have been dead and lying on the ground for hundreds or even thousands of years. In arid regions where decay is very slow, dead wood can lie on the ground for hundreds to thousands of years. If "old" wood happened to be used to fuel the fires at this site, then the radiocarbon age could be significantly older than the time of occupation.
14. A. The Geologic Time Scale was constructed over about the last 200 years by geologists using mainly fossils, superposition, and cross-cutting relationships to establish the relative ages for thousands of rock outcrops around the world. In about the last 50 years, the Geologic Time Scale has been calibrated using radiometric methods to date mostly igneous and metamorphic rocks.
15. A. Review the section Measuring Absolute Time with Radioactive Clocks in Chapter 8.
16. A. Refer to Figure 8.16.
17. A. Loss of daughter atoms, such as lead, generated from the decay of radioactive parent atoms, such as uranium, would result in a date that was younger than the actual time that has elapsed since the rock solidified. One important assumption that is made when interpreting radiometric dates is that the mineral or rock has remained a closed system—no elements have been added to or removed from the mineral except by radioactive decay. If this assumption holds, then the radiometric date typically represents the time that has elapsed since the rock solidified from a magma.
18. C. Weathering and alteration of rock samples by metamorphism can cause a redistribution of radioactive parent atoms and the daughter atoms produced by decay of the parent. This redistribution usually causes uncertainty in the radiometric date. Therefore, geologists typically radiometrically date the freshest rock samples that have been the least affected by subsequent geologic events. Sample C in the middle of the lava flow is the least likely to be affected by weathering, like sample A, or contact metamorphism, like sample B.
19. B. Because the radiometrically dated cobble is included in the conglomerate layer, the layer has to be younger than the cobble—the cobble had to form before it could become a part of the conglomerate. The radiometric date represents a maximum age for the conglomerate, which has to be younger than any included component. If geologists really wanted to get a better estimate for the age of the conglomerate, they would need to do radiometric dates for as many cobbles of different igneous rocks as possible to find the

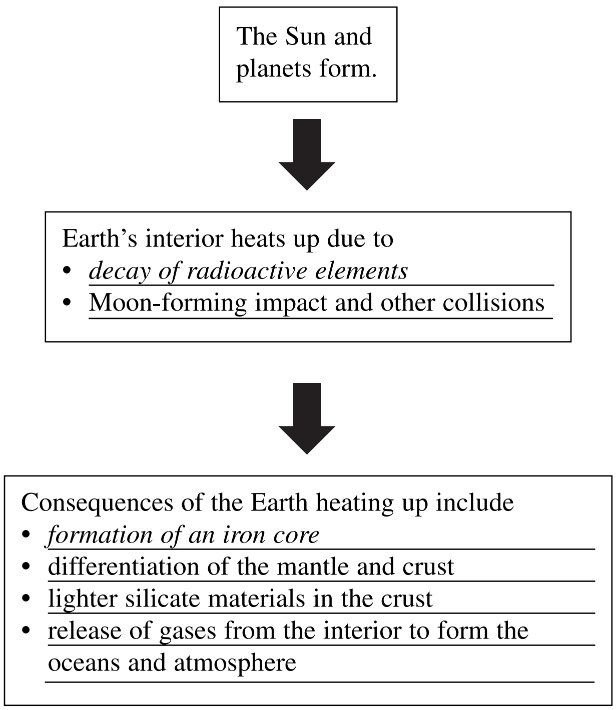
date of the youngest cobble included in the layer. In this way, they could focus on the approximate age of the sedimentary layer using the radiometric dates on igneous inclusions and the principle of included fragments.

20. A. Cross-cutting relationships tell us that the dike and lava flow must be the last event to have occurred. Using the principle of superposition we can see that the first events must be the deposition of the lower shale, then the limestone–shale–sandstone sequence, so these events cannot be the most recent. Cross-cutting relationships again inform us that the fault and pluton are the next events, though which is more recent than the other is inconclusive, as neither cuts the other. Finally, the dike cuts all the preceding rock units, extruding the lava flow at the surface—the final rock unit. Refer to the sections on reconstructing geologic history from the stratigraphic record in the text for a discussion of these concepts.
21. D. D is the best answer, although one might be inclined to answer C, based on superposition. Archeologists will commonly use radiocarbon ages to bracket the age of an archeological site if no datable material is found in the site itself. Again, it is important to distinguish between observation (the data) and inferences (the interpretation). The radiocarbon date represents the time that has elapsed since the wood died. Perhaps the wood died during a forest fire, and the charcoal was washed away from the burned area and deposited in a layer that covered the fire pit. If this is the case, then the radiocarbon date would be younger than the fire pit. Although charcoal is soft, it is chemically very stable and remains well preserved in sediments. It is also possible that the charcoal weathered out of some sedimentary layers that are actually much older than the fire pit and ended up incorporated in the layer that covers that pit. In this case, the radiocarbon date would be misleading because the charcoal was actually significantly older than the fire pit but ended up in a soil layer above the fire pit because it was recycled from eroding older sediments.

Chapter 9

Answers to Practice Exercises

Exercise 1: The evolving early Earth



Exercise 2: Evidence of water on Mars

Discuss four lines of evidence revealed by recent probes for water on Mars.

Evidence of past and/or present water on Mars includes

Geomorphology
- Channel networks
- Meandering patterns
- Landforms that suggest past glacial processes

Mineral and rock composition/chemistry
- Iron oxide minerals, e.g., hematite (produced by rusting of iron-rich minerals, like pyrite)
- Gypsum (a sulfate mineral deposited by evaporation of water)
- Jarosite (an iron-rich sulfate mineral)

Sedimentology and stratigraphy
- Layered sedimentary rocks

Note: Look for Web sites that discuss evidence of water ice at the Marian poles.

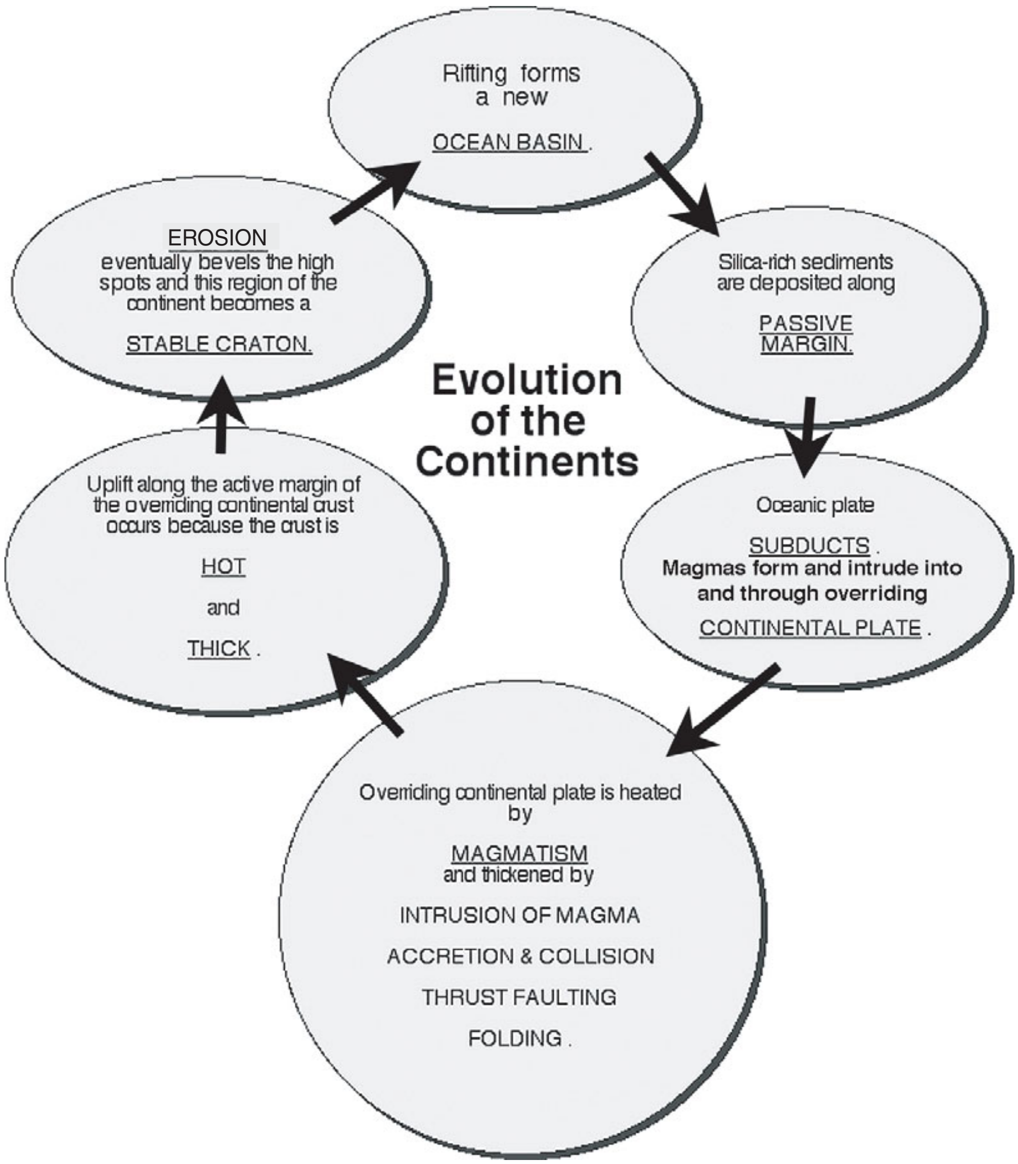
Answers to Review Questions

1. D. Gravitational attraction caused the dust and condensing material to collide and clump together (sticky collisions). Refer to Figure 9.2.
2. B. The heat generated by the decay of radioactive elements continues to heat the Earth today.
3. C. Volcanic degassing accounts for all major gases in the Earth's atmosphere except oxygen. Oxygen is a by-product of photosynthesis. Refer to Figure 1.12.
4. B. Figure 1.9 provides time lines for the early history of the Earth.
5. B. The Earth's core, mantle, and crust are thought to have formed when much of the Earth melted. Melting allowed materials within the earth to segregate (differentiate) according to their density—heavier matter sinks toward the center. Refer to Figure 1.6.
6. D. Refer to Figure 9.16.
7. A. The inner terrestrial or rocky planets are distinctly more compact—denser—than the outer gaseous planets. The density of Saturn is less than that of liquid water. If an ocean were big enough, Saturn would float.
8. D.
9. B.
10. A.
11. C. Refer to Table 9.2.
12. D. Some atmospheric oxygen molecules diffuse into the upper atmosphere, where solar radiation transforms them into ozone. Ozone absorbs UV radiation before it reaches the surface where it can damage plant and animal cells. Oxygen is not essential to all life. In fact, some life forms find oxygen toxic. Because oxygen gas is very reactive, its presence probably would have reduced the likelihood for the chemical evolution of life in the earliest history of Earth. Lucky for us, the Earth began as an oxygen-free planet. Oxygen readily reacts with hydrogen to form water, but the amount of free hydrogen in Earth's atmosphere is minuscule; therefore, this reaction is not significant. Refer to Chapter 11.

CHAPTER 10

Answers to Practice Exercises

Exercise 1: Evolution of the continents



Exercise 2: Ocean crust versus continental crust

Characteristics	Ocean crust	Continental crust
Composition	Mafic	Felsic to intermediate
Rock type(s)	Homogeneous basalt, gabbro, and pelagic sediments	*Very heterogeneous—can contain any rock but dominantly granitic and gneissic with a cover of sediments*
Density	*3.0 g/cm^3*	*2.7 g/cm^3*
Thickness	*10 km*	15–65 km
Age	175 million years or younger with older fragments caught up within continents	*The ages of continental crust spans 4 billion years.*
Topographic features	*Abyssal floor* *Ridge with axial rift* *Trenches* *Sea Mounts* *Hot-spot island chains* *Plateaus*	craton or shield stable platform continental margin coastal plain continental shelf and slope mountain belts sedimentary basins
Structure/ Architecture	A model for the structure of the ocean crust is the ophiolite suite: deep-sea sediments, basaltic pillow lavas and dikes, and gabbro. (**Note:** peridotites are part of the mantle lithosphere, not the ocean crust.)	*The architecture of the continents is complex. It consists of preexisting cratons, accreted microplates, island arcs, volcanic arcs, suture zones, ophiolite suites, and belts representing ancient orogenic zones. Sediments cover basement rock in the interior platform of the continent.*
Origin	mafic magmatism and volcanism at the ocean ridge system	*orogenic processes and accretion of preexisting crustal blocks along convergent plate boundaries*

Answers to Review Questions

1. C.
2. A. Convergent plate margins. Refer to Figure 10.12.
3. C. Passive continental margins are located far from active plate boundaries.
4. C. The oldest known continental rock is radiometrically dated at 4 billion years old. It is the Acasta gneiss from the Slave Province in Canada. Refer to Figure 10.22.
5. D. Refer to the section How Continents Grow.
6. C. Refer to Figure 10.18.
7. A. Refer to Figure 10.11.
8. B. Refer to Figures 10.1 and 10.8.
9. C. Young orogenic belts are characterized by hotter and thicker crust.
10. A. Refer to Figure 10.11 and the section The North American Cordilleran.
11. B. The Andes Mountains along the west coast of South America are an active orogenic system associated with the subduction of ocean crust beneath the South American continent.
12. A. Orogeny refers to the collection of processes, typically active at convergent plate boundaries, that form mountains. Rifting leads to the formation of a new ocean basin.
13. C. Refer to the section The Appalachian Fold Belt.
14. B. See the section The North American Cordilleran.

15. A. The Cordillera is a younger mountain belt compared to the Appalachians. In fact, portions of the Cordillera are still involved in orogenic processes. The western North American crust sits higher than the Appalachians because the Cordillera crust is thicker and hotter, and tectonic processes remain very active.
16. D. Widespread and relatively thick accumulations of coral-rich limestones, sandstones, and shale are characteristic of a passive continental margin or a sedimentary basin within a continental platform.
17. A. Thicker continental crust typically stands higher. Hotter crust also stands higher because heat lowers the density of the rock material.
18. B. In a sense, mountains are made from mountains. Most of the sediments eroded from previous orogenic systems ultimately end up along a continental margin where it eventually is deformed and uplifted by the evolution of an active convergent boundary. Some sediments are probably subducted, but most are deformed and entangled in thrusting and metamorphism during orogeny. Some sediments may be carried to depths where they melt. Melts derived from sediments are typically felsic, not mafic, and crystallize within the crust to form granitic rocks. Except for regions adjacent to the continental margin, most ocean floor is surprisingly lacking in sediment. This is partly because the ocean floor is young and continually being recycled by plate tectonics and because sedimentation rates in the deep ocean are very slow.
19. B. Rifting breaks up a continent and forms a new passive margin on which sediments accumulate. Eventually, with the development of subduction adjacent to the passive margin, orogeny is initiated. Orogenic processes thicken the overriding crust, which then begins to rise due to a buoyant balance between the mountain root and the denser mantle in which it sits. Can you think of a good reason why subduction is likely to eventually occur adjacent to an old passive continental margin?
20. C. Refer to Figure 10.8.
21. B. Refer to the section How Continents Grow.
22. A. The Andes Mountains along the west coast of South America are in a more youthful stage of orogeny than the North American Cordillera and exhibits a great number of similarities to past geologic circumstances in western North America. Today geologists actively study the Andes as a way of traveling back in time to the earlier Cenozoic history of the North American Cordillera.
23. B. Refer to Figure 10.20.
24. A. Refer to Figure 10.24.
25. D. Refer to Figure 10.6.

Chapter 11

Answers to Practice Exercises

Exercise 1: How organisms and the Earth interact

Life's impact on Earth	Life process(es) generating the impact	Description of the interaction and impact
O_2 in Earth's atmosphere	Byproduct of photosynthesis	Green plants and algae use energy in the atmosphere from sunlight to convert water and carbon dioxide to carbohydrates, such as sugar, and oxygen. Oxygen is released to the atmosphere.
Greenhouse effect: Cooling	*Extraction of carbon from oceans and atmosphere by shell-producing and photosynthetic organisms*	The extraction of carbon dioxide from the atmosphere and oceans by photosynthetic organisms and shell-producing organisms, like clams and coral, draws down the amount of CO_2 in the Earth's atmosphere and oceans. Carbon dioxide is a heat-trapping molecule. Reducing the amount of CO_2 in the atmosphere reduces the greenhouse effect.
Greenhouse effect: Warming	*Respiration and metabolism of anaerobic microbes. Refer to Table 11.2 and textbook page 246.*	The metabolism of some organisms produces carbon dioxide and methane, which are both heat-trapping gases that contribute to global warming.
Mineral precipitation	Microbial precipitation of pyrite occurs in the anaerobic zone of sediments containing iron-bearing minerals. Some microbes, insect and animals precipitate magnetite (iron oxide). Phosphate can accumulate in microorganisms in sediments.	Microbial precipitation of pyrite occurs in the anaerobic zone of sediments containing iron-bearing minerals. Some microbes, insect, and animals precipitate magnetite (iron oxide). Phosphate can accumulate within microorganisms within sediments.
Mineral dissolution	*"Sulfate eating" microbes*	*Hydrogen, hydrogen sulfide, and methane gases may be produced.*

Answers to Review Questions

1. A. In contrast, heterotrophs get food by feeding directly or indirectly on producers.
2. A. You are what you eat. This is true for all organisms whether they eat simple carbon-bearing molecules like carbon dioxide and methane or large carbohydrate molecules.
3. C. Refer to Table 11.2.
4. B. The alternative answers are characteristic of bacteria and archaea.
5. C. Refer to Figures 8.14 and 11.5.
6. D. Stromatolites are sedimentary structures produced by microbial mats. The outer layer of the microbial mat contains photosynthetic autotrophs, which release oxygen gas as a byproduct of their metabolism. Microbial mats form stomatolitic structures even today, but the abundance of stromatolite structures today is limited by the presence of mollusks that feed on microbial mats and by other environmental factors.
7. D. Banded iron formations formed over an interval of geologic time during which oxygen was released by photosynthetic algae into an oxygen-poor ocean that was rich in dissolved iron.
8. A.
9. D.
10. B. Refer to the textbook section Origin of Life and the Oldest Fossils.

11. D. Refer to Figure 11.13.
12. B. Refer to textbook Figure 11.19.
13. B. Abundant oxygen gas in the atmosphere would be evidence for photosynthetic life on the planet. There is no other process known that can account for abundant oxygen gas in a planetary atmosphere because oxygen is very reactive and needs to be continually replenished. Even though methane would react rapidly with oxygen in the atmosphere, minor amounts would be evidence for life processes, especially microbial metabolic processes. It would be even more exciting to find evidence for the presence of liquid water, but the next best thing is the existence of water ice. Where there is water ice there may also be some liquid water, if not at the surface, maybe in the shallow subsurface where at least microbial life may flourish.

CHAPTER 12

Answers to Practice Exercises

Exercise 1: Lava types—their properties, eruption styles, deposits, landforms, association with plate tectonics, and hazards

Characteristics	Basalt (mafic)	Andesite (intermediate)	Rhyolite (felsic)
Properties			
eruption temperature	1000 to 1200°C	*intermediate*	800 to 1000°C
silica content	low (≈50%)	*intermediate*	*high (≈77%)*
gas content	*low, up to a few percent*	*variable*	high (up to ≈ 15%)
viscosity	*low-fluid magma*	*intermediate*	high—very viscous
typical flow velocity	*0.7 to 30 m/minute*	*9 m/day*	*less than 9 m/day*
typical flow length	*10 to 160 km*	*8 km*	*less than 1.5 km*
typical flow thickness	*5 to 15 m*	*30 m*	*200 m*
Eruption styles	*typically not very explosive*	explosive	typically very explosive
Deposits	*flood basalt* fissure flow pahoehoe and aa flows pillow lava cinder	*lava flow* *dome* *pyroclastic flow—tuff and welded tuff*	dome *obsidian dome* pyroclastic flow—tuff and welded tuff
Landforms	shield volcano lava plateau *cinder cone* *small caldera*	*composite volcano* *summit crater* *caldera* *cinder cone*	composite volcano large caldera summit crate
Association with plate tectonics	divergent boundaries *hot spots*	convergent boundaries	convergent boundaries
Hazards	lava flow explosive in contact with water hot gases	*lava flow* *pyroclastic/ash flow* *explosive blast* *hot gases* *mudflow*	explosive blast *pyroclastic/ash* *hot gases* mudflows (lahars)

Exercise 2: Volcanoes at plate tectonic boundaries

Volcano or volcanic area	Type of volcano (shield, composite, caldera)	Magma type (mafic, intermediate, felsic)	Magmatic (plate tectonic) setting divergent, convergent, hot spot
Hawaii	shield	mafic	hotspot/mantle plume
Tonga Islands	*composite*	*intermediate and felsic*	*convergent/subduction*
Columbia Plateau	flood basalts	*mafic*	*hot spot*
Santorini (Thera), Greece	*caldera*	intermediate/felsic	convergent
Mayon, Philippines	composite	intermediate/felsic	convergent
Iceland	shields/fissures	mostly mafic	*divergent and hot spot*
Yellowstone	caldera	intermediate/felsic	continental hot spot
Krakatoa, Indonesia	composite/caldera	intermediate/felsic	convergent
North Island, New Zealand	composite	intermediate/felsic	convergent
Crater Lake, Oregon	composite/caldera	intermediate/felsic	convergent
Japan	composite	intermediate/felsic	convergent
Aleutian Islands, Alaska	composite	intermediate/felsic	convergent
Mariana Islands	composite	intermediate/felsic	convergent
Kilimanjaro, Africa	composite	intermediate/felsic	continental rift/hot spot
Pinatubo, Philippines	composite	intermediate/felsic	convergent
Katmai, Alaska	*composite and caldera*	intermediate/felsic	convergent
Mount Rainier, Washington	composite	intermediate/felsic	convergent
Tambora, Indonesia	*composite and caldera*	intermediate/felsic	*convergent*
Vesuvius, Italy	composite	intermediate/felsic	convergent

Answers to Review Questions

1. D. Cooling rate determines the size of the mineral grains within lava flows. If minerals already exist in the magma chamber before an eruption occurs, the lava will erupt with larger crystals floating in it and solidify into a volcanic rock with a mixture of grain sizes, known as a porphyry.
2. B. Table 4.2 provides basic compositional trends for igneous rocks. Rhyolite contains up to about 77 percent silica. Basalt is mafic with about 50 percent silica.
3. B. Water makes up 70–95 percent of the vapor content of a magma, followed by carbon dioxide and sulfur dioxide.
4. B. Refer to Figure 12.13.
5. B. Hawaii has many classic examples of shield volcanos. Refer to Figure 12.14.
6. C. Refer to Figure 12.14.
7. B. The higher silica content of rhyolitic lavas results in a much higher viscosity, which favors very thick lava flows or domes. Refer to Figure 12.14.
8. D. Refer to Figure 12.14.
9. B. Andesitic volcanoes are commonly associated with convergent plate boundaries. Partial melting of the subducting slab or materials above the subducting slab typically generates intermediate magmas.
10. B. The Hawaiian Islands are a chain of volcanoes generated as the Pacific plate moves over a hot spot in the mantle.
11. D. Magmas rich in silica and dissolved gases cause the most explosive volcanic eruptions. Increasing silica content progressively increases the viscosity of the magma.

More viscous magmas are more likely to plug the throat of a volcano until pressure builds up high enough to cause an explosive eruption.

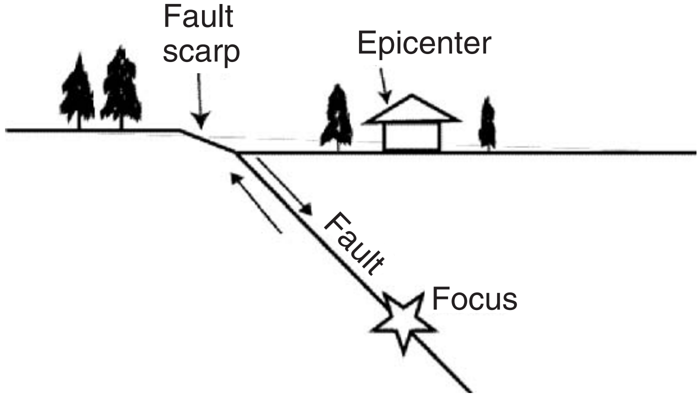
12. A. Shield volcanoes are formed predominantly by basaltic lavas, which are more fluid and therefore tend to spread out. Composite volcanoes are constructed predominantly from intermediate and felsic lava flows, domes, and pyroclastic flows. Intermediate and felsic lavas are more viscous and form thicker flows than basalt.
13. D. Refer to Figure 12.15.
14. C. Refer to textbook sections on flood basalts and fissure eruptions.
15. B. Refer to Figures 12.13 and 12.14.
16. D. Refer to Figure 12.23.
17. B. Refer to the textbook section Reducing the Risks of Hazardous Volcanoes.
18. A. Basaltic eruptions occur along the oceanic ridge system and form the ocean crust.
19. A. Hot spots are surface expressions of magma plumes coming up from the ultramafic mantle. These plumes are basaltic in composition. The composition of hot-spot volcanism may become more felsic if the magma plume rises through continental crust, as it does under Yellowstone. Hot spots like Hawaii and Yellowstone occur within the middle of crustal plates. Hot spots are also located along divergent plate boundaries as in Iceland.
20. B. Andesites (intermediate magmas) erupt commonly at convergent plate boundaries where oceanic crust is subducting beneath continental crust. One example of where this process is happening today is beneath the Cascade Range of volcanoes, which extends from northern California through Washington. Mount St. Helens is within the Cascades.
21. C. Refer to Figure 12.14.
22. B. If a volcano is fed by one large magma chamber without any additional injections of magma from below, then the remaining melt in the magma chamber becomes progressively enriched in silica and depleted in iron and magnesium as the magma solidifies. Younger lava flows are enriched in silica relative to flows that erupted when more of the magma was molten. With a higher silica content and a lower iron content, younger lava flows are less mafic and more viscous (less fluid).
23. B. Refer to the section Lavas and Other Volcanic Deposits in the textbook.
24. B.

Chapter 13

Answers to Practice Exercises

Exercise 1: Earthquake focus versus epicenter

This is a normal fault.



Exercise 2: Characteristics of seismic waves

Figure 13.7 and the textbook section Seismic Waves will be helpful.

Characteristic	P (primary) waves	S (secondary) waves	Surface waves
Relative speed	fastest	*second fastest*	slowest
Motion of material through which wave propagates	compressional—push/pull	shearing	*rolling/elliptical and sideways motions*
Medium through which wave will propagate	solids liquid gas	solids only	*confined to the Earth's surface*
Analogy with common wave forms	sound waves	*S waves propagation is difficult to visualize. It is somewhat analogous to the way cards in a deck of playing cards slide over each other as you shuffle the deck.*	ocean waves

Exercise 3: Factors that amplify the damage caused by an earthquake

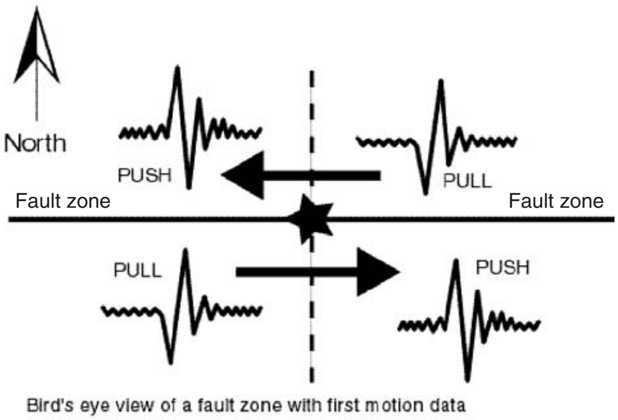
Factors that amplify the damage caused by an earthquake follow.

- The magnitude of the earthquake. Obviously, a larger magnitude earthquake tends to be more destructive, but many other factors besides magnitude can contribute to the potential for destruction.
- The duration of the earthquake. Earthquakes that last longer usually cause more damage. Consider this analogy: The longer you push someone on a swing, the greater the swing back and forward. Likewise, if structures experience a longer duration of pushes and pulls by seismic waves, the more they will sway and the greater the potential for damage.
- The ground acceleration caused by the earthquake. Faster ground acceleration is likely to cause more damage. Rapid ground acceleration may have contributed to the destructiveness of the Northridge, California, earthquake in 1994.
- Depth to the focus of the earthquake. The energy of seismic waves dissipates with distance from the focus.
- Proximity to a coastline where a tsunami may hit. Refer to Earth Issue 13.3.
- Fires ignited by ruptured gas and power lines. The fire started during the 1906 San Francisco earthquake caused far more damage to the city than did the seismic waves themselves.
- Liquefaction of water-rich soils and sediments that are typically associated with coastal regions and developments. Liquefaction was a big factor in the damage caused to Anchorage, Alaska, during the 1964 earthquake.
- Preexisting building designs and codes for the community.
- Landslides and unstable slopes.

You may come up with other reasonable factors.

Answers to Review Questions

1. B. Refer to Figure 13.3.
2. B. An earthquake propagates from the focus of the earthquake. The epicenter is the location on the surface directly above the focus.
3. A. P waves travel fastest and surface waves travel slowest.
4. C. Three. Refer to Figure 13.9.
5. C. The Richter scale measures the amount of ground motion.
6. D. The Richter Scale for earthquake magnitude is exponential. With every unit of increase in magnitude, such as from 4 magnitude to 5 magnitude, the ground motion increases by a factor of 10.
7. C. P waves, like sound waves, travel through solids, liquids, and gases.
8. B. S waves travel only though solids.
9. B. Earthquakes are strongly associated with all active plate tectonic boundaries. Refer to Figure 13.12 and the text section The Big Picture: Earthquakes and Plate Tectonics.
10. B. Producing a seismic risk map would be a first step in earthquake risk assessment.
11. D. Water-saturated stream delta sediments exhibit liquefaction in response to the shaking from an earthquake.
12. C. 3000 kilometers based on the seismic travel-time curves in Figure 13.9.
13. C. Deep-focus earthquakes do not occur in association with divergent boundaries. How do you explain this observation?
14. C. Texas has the lowest seismic risk compared to the other regions listed. See Figure 13.21.
15. B. Refer to illustration below. Notice that the arrows are pointing west and east to reflect the pushing and pulling of the land.



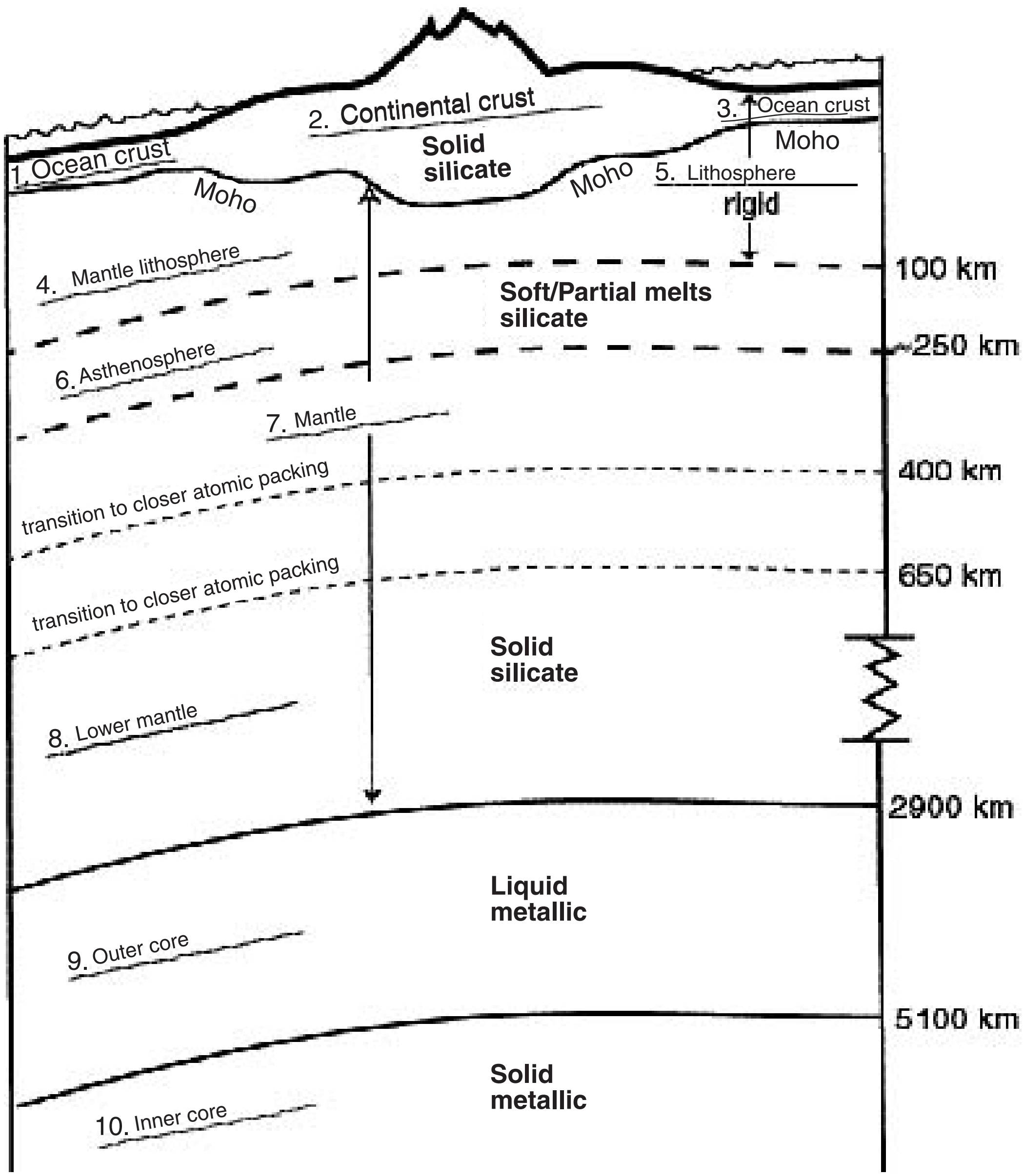
Bird's eye view of a fault zone with first motion data for P waves arriving at seismograph stations during an earthquake. The star marks the epicenter. Dashed line is a north-south reference line plotted on this map with the first motion.

16. Left-lateral strike slip fault

Chapter 14

Answers to Practice Exercises

Exercise 1: The Earth's interior layers



Exercise 2: The characteristics of Earth's Internal layers

Layer	Volume (% of total)	Mass (% of total)	Density (g/cm^3)	Physical state	Composition	Observations and evidence that support the characteristics of the layer
Crust	0.60	0.42				
Continental crust	0.44	0.25	≈ 2.7	Solid	Felsic and intermediate	Very heterogeneous. 40–65 km thick. Formed at convergent boundaries by orogenic processes.
Ocean crust	0.16	0.17	≈ 3.0	Solid	Mafic silicates	Very homogeneous. About 10 km thick. Formed at divergent plate boundaries from partial melting of ultramafic mantle rocks.
Mantle	83.02	67.77	3.3–5.7		Ultramafic, (peridotite)	
Mantle lithosphere				Rigid, solid	Ultramafic silicates (mostly peridotite)	Crust and mantle lithosphere make up Earth's tectonic plates. Thickness ranges from 0 km at spreading centers to 200 km beneath continents. S-wave velocities speed up through it.
Asthenosphere				Weak, plastic, solid	Ultramafic silicates (mostly peridotite)	Weak zone. A few percent melting. Reaches close to the surface at spreading centers and deepens under older seafloor. S-waves slow down and are partially absorbed.
Lower mantle				Solid	Ultramafic	Abrupt increase in S-wave velocities at 400- and 650-km mark changes in mantle structure—collapse of the atomic structure of minerals.
Core		31.79				
Outer core	15.68		9.9–12.2	Liquid	Mostly iron and nickel	P waves slow down; S waves are completely blocked. Iron–nickel composition is consistent with bulk density of the Earth.
Inner core	0.70		12.6–13.0	Solid	Mostly iron and nickel	P waves suddenly speed up at 5100 km. S waves are transmitted through inner core. Composition also consistent with the natural abundance of iron and meteorites.

Exercise 3: Evidence for the asthenosphere and its significance

A. Lines of evidence for the asthenosphere:
   - Low-velocity zone—Seismic waves travel slower through the asthenosphere than they do in shallower layers, suggesting that this zone may be closer to the melting temperature of the rock and therefore softer. Refer to Figures 14.8 and 14.10.
   - Post-glacial isostatic rebound—Isostatic adjustments of the crust require plastic flow in some part of the mantle to account for the displacement of the crust by the mantle as the crust is pushed down by the weight of the ice.
   - Reduction in the frequency and magnitude of earthquakes between depths of 175 and 350 km would be explained by a more ductile zone that is less likely to break, and, if it does break, it does so with less buildup of elastic strain energy.
   - When the projected geothermal gradient is lotted with the melting-point curve for the rock thought to be in the mantle, the two curves converge and almost touch at a depth of 100 to 150 km. This suggests that the rocks at this depth, due to the combined effects of temperature and pressure, are at or very close to melting.

B. The presence of an asthenosphere may be a prerequisite for plate tectonics. The soft, ductile asthenosphere allows the rigid lithosphere to decouple and move independently from the mantle. Refer to your work on Practice Exercise 2 for Chapter 2.

Answers to Review Questions

1. C. Earth's core is about one-half the radius of the planet. See Figure 14.7: In the illustration, Earth's center is at 6,000 km depth, and the outer core is at 3,000 km depth.
2. B. Refer to Figure 1.11. The ocean basins exist on Earth because the ocean crust is thinner and denser than the continental crust. Therefore, the ocean crust sits lower.
3. C. Ultramafic or peridotite.
4. B. Earth's tectonics plates are large fragments of the lithosphere, a rigid layer consisting of the crust and uppermost mantle.
5. C. Continental crust is very heterogeneous in composition. Nevertheless, its average composition is felsic to intermediate.
6. D. The lithosphere is thought to be a rigid layer that rests on a plastic, weak asthenosphere.
7. B. S waves do not pass through the outer core.
8. C. The metallic core has the highest density.
9. C. Earth's north magnetic pole is located between Greenland and Baffin Island, not at the Earth's pole of rotation—the North Pole. Refer to Figure 14.12.
10. C. The electro-dynamo theory explains the Earth's magnetic field as a consequence of electrical currents moving in the fluid, metallic outer core. The silicate minerals in the asthenosphere are not nearly as good conductors of electricity. Therefore, the flow of electrical currents and the associated magnetic field are much weaker in the asthenosphere.
11. B. The asthenosphere is thought to be a weak, plastic zone within the upper mantle that may be partially melted.
12. B. Refer to Figure 14.16.
13. A. Refer to Figure 14.10.
14. C. The mantle–core boundary is marked by the most significant change in composition.
15. A. The thickest continental crust on Earth lies beneath the Tibetan plateau, Himalayan mountains, and portions of the Andes mountains.
16. B. Refer to Figure 14.18.
17. D.

18. D. If a significant portion of the lower mantle were molten, we should see lots more volcanic activity on the Earth's surface in addition to tectonic plate boundary volcanism.
19. A. Seismic wave velocities depend on the elasticity, rigidity, and density of materials. These properties depend on the composition, physical state, and compactness of the atomic structure of the material.
20. C. Refer to Figure 1.16.
21. B. The Moho was first detected by an abrupt increase in seismic wave velocities due to the change from lower-density crustal rocks to the more dense ultramafic rocks within the mantle.
22. A.
23. D. Refer to Figure 14.17.
24. A. Refer to Figures 14.1 and 14.2.
25. D.
26. D. Plates are located in the lithosphere. Their motion is driven in part by the force of gravity as cold, heavy crust sinks, dragging the plate behind it. As the plates sink at convergent boundaries, an opening is created for hot magma to rise through at the diverging boundary. The driving forces of plate tectonics are manifestations of mantle convection in the sense that they involve hot matter rising in one place and cold matter sinking in another. See Chapter 2, "Where do the plate-driving forces originate?

CHAPTER 15

Answers to Practice Exercises

Exercise 1: Conceptual map/Flowchart of a climate factor

Climate is a complex system with many factors potentially influencing it. You might choose one of the following as a focus for your conceptual flowchart:

High mountains → rain shadow effect

El Niño → wet weather in the eastern equatorial Pacific

Gulf Stream → transfers a tremendous amount of heat to northern Europe

Earth's Orbital (Milankovitch) characteristics → cyclical changes in the amount of energy reaching Earth

Volcanic eruption injects dust and aerosols into atmosphere → increase in albedo → Earth cools

Volcanic eruption releases tremendous amounts of carbon dioxide gas → enhanced greenhouse effect → Earth's surface heats up

There are many other factors.

Exercise 2: Release of carbon dioxide from the burning of fossil fuels

A. An increase in CO_2 enhances the greenhouse effect and results in warmer surface conditions. Warmer surface conditions increase evaporation rates and more water vapor goes into the atmosphere. More water vapor in the atmosphere may result in more cloud cover.

B. An increase in cloud cover may produce a negative feedback because cloud cover typically has a cooling effect on surface conditions. So the impact of increased cloud cover is opposite to that of increasing CO_2 in the atmosphere.

Exercise 3: Flow of carbon through Earth's systems and reservoirs

Carbon fluxes	Brief description of flux	Direction of flux	Climatic impact/ implications
Photosynthesis and precipitation of carbonates	*Carbon is fixed in living organisms, which ultimately contribute to organic matter in sediments, coal, and oil.*	*Carbon flows from the atmosphere and oceans into rock—the lithosphere.*	Less greenhouse gas in atmosphere results in a cooling.
Sedimentation	*Calcium and carbonate ions combine to produce calcium carbonate, which can precipitate and collect to form limestone or help cement other rock particles.*	Carbon is drawn out to the atmosphere and ocean and precipitated as sediment.	*Climate cools.* *Carbon dioxide is drawn out of the oceans and atmosphere. The loss of CO_2 from the oceans will result in a reduction of CO_2 in the atmosphere.*
Volcanism	*CO_2 is typically the second most abundant gas released during volcanic eruptions.*	*CO_2 is released from the lithosphere into the atmosphere and oceans.*	*An increase in CO_2 in the atmosphere enhances the greenhouse effect and warms the Earth's surface.*
Chemical weathering	*CO_2 in rainwater combines with minerals in rock to form calcium carbonate.*	*Carbon flows from the atmosphere and oceans into the crust.*	*Climate cools.* *Carbon is being drawn out of surface environments and stored in the crust. Uplift of high plateaus and mountains may enhance this flux.*
Metamorphism	*Heating, recystallization, and decomposition of rocks during metamorphism can release large amounts of CO_2.*	*Carbon flows from the rocks (the crust) into the atmosphere and oceans.*	*Climate warms.* *Increased levels of CO_2 in the atmosphere enhances the greenhouse effect, which acts to trap heat energy and slow down the loss of heat to space.*
Human activities: Combustion of fossil fuels	*The burning of fossil fuels releases large amounts of CO_2 into the atmosphere.*	*Carbon flows from the lithosphere (coal, oil, and gas) into the oceans and atmosphere.*	An increase in CO_2 in the atmosphere enhances the greenhouse effect and warm the Earth's surface.

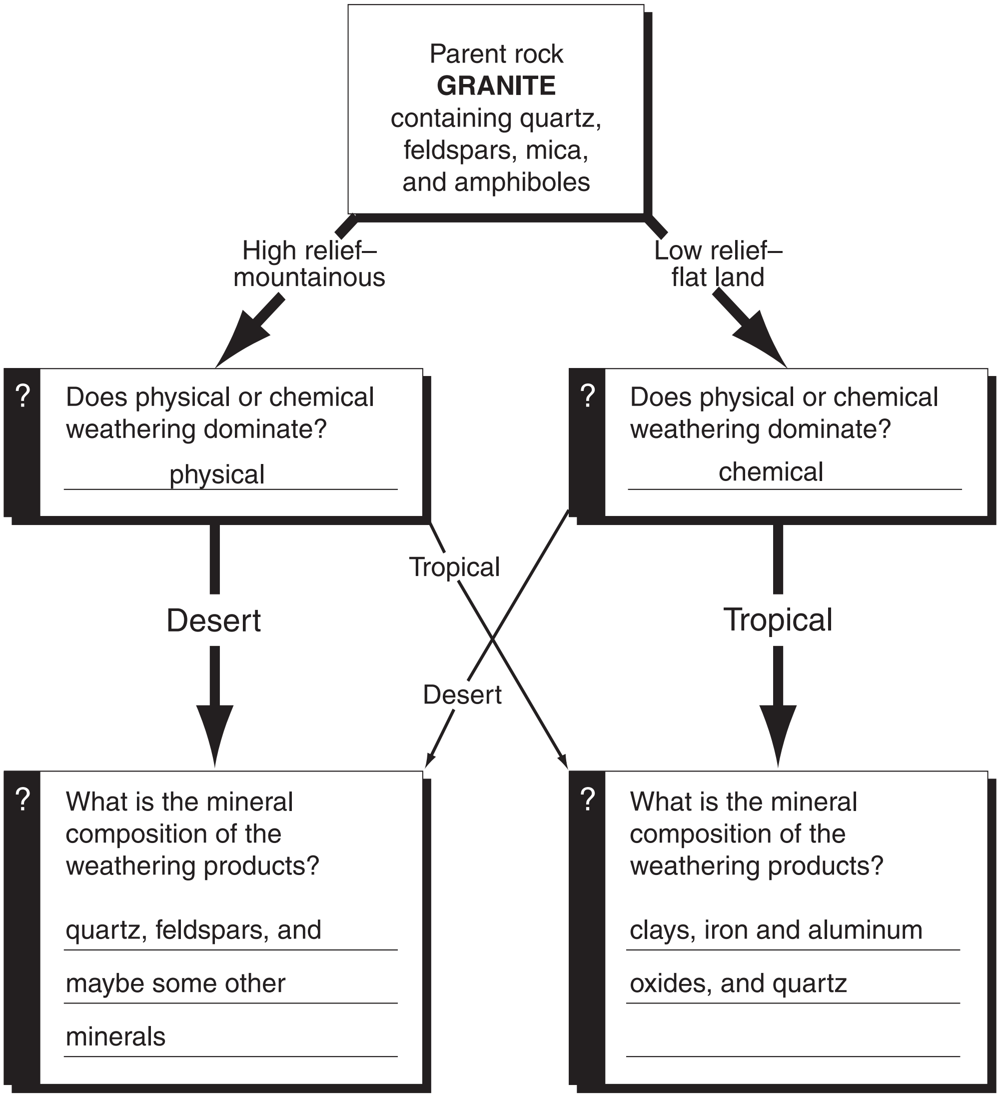
Answers to Review Questions

1. A. The Earth's atmosphere is about 78% nitrogen gas. Refer to the textbook section Components of the Climate System.
2. A. Carbon dioxide is transparent to visible light and absorbs heat (infrared radiation). Refer to Figure 15.7.
3. A. Refer to Figure 15.19.
4. B. Refer to the section Carbon Budget in your textbook.
5. B. Volcanic eruptions are not associated with El Niño events.
6. A. As the oceans become warmer, carbon dioxide solubility decreases. Therefore, more carbon dioxide will be released, which is a positive effect. A positive effect adds carbon dioxide to the atmosphere; a negative effect subtracts it.
7. C. Carbon dioxide is a greenhouse gas.
8. A. The greenhouse effect significantly influences surface temperatures for planets with atmospheres.
9. C. Living organisms. Keep in mind the definition of flux: the flow of chemicals from one reservoir to another. Refer to Figure 15.16.
10. D. At present burning of fossil fuel by humans contributes far more atmospheric carbon than does deforestation. The other alternatives (plant uptake and ocean gas exchange) represent in part a response to human activity. Normally there is a balanced carbon flow between plants and atmosphere and between oceans and atmosphere. See Figure 15.14. Human activities are disrupting this balance, so the climate system responds by absorbing more carbon into the oceans and increasing plant production on land. Refer to Figure 15.17.
11. A. Troposphere.
12. D.
13. B.
14. A. Refer to Figure 15.15 and the section Carbonate Weathering and Precipitation in the textbook.
15. A. 0.6°C.
16. B. Refer to Figure 15.7.
17. D. Refer to Figure 15.12 and the textbook section Milankovitch Cycles.

Chapter 16

Answers to Practice Exercises

Exercise 1: Physical and chemical weathering



Exercise 2: Inventory of the different kinds of mass wasting

Kind of mass wasting	Composition of slope (consolidated vs. unconsolidated and wet vs. dry)	Characteristics
Rock avalanche	Large masses of rocky materials	Speed: Running or a speeding auto Slope angle: Steep slopes Triggering event(s): Earthquakes Notes: Occur in mountainous regions where rock is weakened by weathering, structural deformation, weak bedding, or cleavage planes
Creep	Soil	Speed: Walking Slope angle: Any angle Triggering event(s): None Notes: Influenced by the kind of soil, climate, steepness of slope, and density of vegetation
Earthflows	Soils and fine-grained rock materials, such as shales and clay-rich rocks	Speed: Walking or running Slope angle: *Any angle* Triggering event(s): *Intense rainfall* Notes: *Fluid-like movement*
Debris flow	Rock fragments supported by a muddy matrix	Speed: Running or speeding auto Slope angle: *Any angle* Triggering event(s): Intense rainfall Notes: Contains coarser rock materials compared to earthflows.
Mudflow	*Mostly finer rock materials with some coarser rock debris with large amounts of water.*	Speed: *Speeding auto* Slope angle: Any angle Triggering event(s): Intense rainfall or catastrophic melting of ice and snow by a volcanic eruption Notes: *Contains large amounts of water*
Debris avalanche	*Water-saturated soil and rock*	Speed: Speeding auto Slope angle: Steep Triggering event(s): Earthquakes Notes: Occurs in humid, mountainous regions
Slump	Unconsolidated rock material	Speed: *Walking or running* Slope angle: *Any slope* Triggering event(s): *Rainfall* Notes: Debris slide moves faster than a slump
Solifluction	*Surface layers of soil*	Speed: *Walking* Slope angle: *Any angle* Triggering event(s): Freeze–thaw Notes: Occurs only in cold regions when water in the surface layers of the soil alternately freezes and thaws; water cannot seep into the ground because deeper layers are frozen.

Exercise 3: Water's Role in Mass Wasting

Some sample reasonable answers

1. Water lubricates, especially if the ground is saturated (all pore spaces are filled with water), by reducing the internal friction between rock particles. In unconsolidated rock material a small amount of water increases surface tension, which actually helps to weakly "glue" the damp, loose material together. Too much water keeps the particles apart and allows them to move freely over one another. Therefore, saturated sand, in which all pore spaces are occupied by water, runs like a fluid and collapses to a flat pancake shape (refer to Figure 16.13).
2. Water (hydrostatic) pressure may become great enough to separate the grains or promote the slippage of beds past one another. Refer to the textbook section Water Content.
3. Water is a major agent in physical and chemical weathering, which promotes mass wasting. Weathering promotes mass wasting by chemically and physically weakening rock.
4. Freezing and thawing are two specific roles that water plays in causing solifluction, a kind of mass movement. Refer to the textbook section Unconsolidated Mass Movements. Undercutting and oversteepening of hillslopes by erosion is another way water enhances mass wasting. Flowing water in rivers and frozen water in glaciers are powerful agents of erosion. Rivers typically erode on the outside of river bends. Erosion can undercut and oversteepen the riverbank and adjacent hillslope.
5. Water-saturated rock materials rich in clays or loose sand may be transformed into fluid slurries by a process called liquefaction. Refer to the textbook section Triggers for Mass Movements.

Exercise 4: Evaluation of slope stability

A. Possible factors that enhance the potential for mass movement at the homesite shown

- The house is built on a cut-and-fill foundation: the house is built partly on a cut into the bedrock of the slope and partly on the gravel fill derived from the cut. A cut-and-fill foundation is particularly susceptible to slope failure because the material that has been bulldozed into place is very loose.
- The house and associated possessions add weight to the slope.
- Watering the lawn will enhance the potential for slope failure.
- The presence of a spring indicates that the slope beneath the house is saturated with water. Water adds weight to the slope and acts as a lubricant.
- Traffic on the road below the house adds weight and creates vibrations in the ground, which may compromise slope stability.
- The slope consists of sedimentary rocks that have a dip parallel to the slope. Bedding planes are zones of weakness within these layers increasing the potential for slope failure.
- The orientation of the rock fabric within the slope enhances the potential for slope failure. Shale is an especially soft and weak sedimentary rock. Slope failure is likely to occur along the shale layer that dips parallel to the slope. Even the foliation within the gneissic bedrock parallels the hillslope. Planes of weakness within a rock typically occur parallel to the rock's textural fabric.
- If the slope was undercut by the road builders, the slope stability will be compromised.

B. This is an inherently unstable slope. A slope ordinance probably should have restricted building on this slope. However, given that the house is already there, here are some reasonable approaches to decreasing the risk for slope failure.

- Don't water the lawn, or replace the lawn with a ground cover that requires no watering and sends down deep roots.
- Drain water from the slope above and from the roof away from the gravel fill beneath the house.

- At some expense, rock bolts could be installed to help stabilize rock layers.
- Maintain a good cover of vegetation on the slope above and below the house.
- Put in a retaining wall along the road below the house and be sure that the wall does not restrict the drainage of water out of the slope.

Answers to Review Questions

1. D. Oxygen is the principal chemical agent for oxidation reactions. Water is the universal solvent, and carbon dioxide combines with water to form carbonic acid. All three play an important role in chemical weathering. Nitrogen gas occurs as a molecule of two atoms of nitrogen. The nitrogen molecule is relatively nonreactive.
2. A. Silica in solution, iron oxides, and clay minerals are all products of chemical weathering. Feldspar is a framework silicate mineral, which crystallized from magma.
3. D. The weathering products of many silicate minerals include clay. However, quartz is pure silicon dioxide and is relatively resistant to weathering. Where chemical weathering is intense, as in the tropics, even quartz will dissolve.
4. C. Limestone and the calcium carbonate cement of the sandstone are very susceptible to dissolution reactions in wet climates but are more resistant to weathering in dry climates. Shale is a soft sedimentary rock made from compacted clay and typically weathers rapidly. A silica-cemented quartz sandstone might be as resistant to weathering as granite.
5. A. Rusty streaks represent the oxidation of iron-bearing minerals. The other answers are examples of physical weathering.
6. B. Rainfall is naturally acidic due to carbonic acid, which forms when carbon dioxide from the atmosphere dissolves in water. Water passing through soils rich in organic matter dissolves additional carbon dioxide from the decay of the organic matter and becomes more acidic.
7. A. Refer to Figure 16.4 in your textbook.
8. D. Table 16.2 shows that calcite, the major mineral in limestone, is very soluble in wet conditions.
9. A. Refer to Figure 16.5.
10. A. Refer to The Role of Water in Weathering: Feldspar and Other Silicates.
11. C. Chemical weathering is most intense in hot and wet regions.
12. B. Soil gases can be rich in carbon dioxide released by the decay of organic matter and life processes. Water percolating down through soils rich in organic matter becomes more acidic as it dissolves the carbon dioxide in soil gas. Increased acidity of the water enhances chemical weathering reactions.
13. D. Relative to other silicate minerals, olivine is very susceptible to chemical weathering. Its simple (less polymerized) silicate crystal structure of single tetrahedra bonded with cations of iron and/or magnesium is easily attacked by chemical agents.
14. C. Pollution and gases from volcanic eruptions combine with rainfall to enhance the rain's acidity. Before air pollution controls, rainfall in some regions of the United States was as acid as lemon juice. Acids are powerful chemical agents. Chemical weathering is greatly enhanced by increasing the acidity of water.

15. D. As the carbonate cement dissolves, the quartz sand grains will fall away from the rock surface, but weathering will have little impact on the quartz grains themselves. Quartz is a very stable mineral on the Earth's surface.
16. C. Soil fertility depends on the availability of mineral nutrients, which are released by chemical weathering from rock-forming minerals. When chemical weathering is very slow, nutrients remain tied up in the silicate minerals within the rock and are not easily extracted by plant roots. In regions where chemical weathering is intense, most of the mineral nutrients are washed out of the soil. Therefore, fertile soils form where weathering occurs at moderate rates. The parent rock is another important influence on soil fertility. Weak soils developed on quartz sandstone are likely to be nutrient-poor because quartz is pure silicon dioxide and lacks vital mineral nutrients such as potassium, calcium, iron, or magnesium for plant growth.
17. D. Granite is composed mostly of feldspars and quartz. Clay minerals are a major product of the chemical weathering of feldspar. Quartz is very resistant to weathering.
18. The sandstone obelisk deteriorated so quickly after being moved from Egypt to New York City because the climate in New York is significantly wetter than the climate in Egypt. As naturally acidic rain dissolves the calcium carbonate cement, the surface of the sandstone deteriorates. Other factors that may have contributed to the enhanced weathering of the obelisk include acid rain generated by air pollution and frost wedging, since freeze/thaw conditions are common in New York during the winter.
19. A. Site D may have the best view of the shoreline and site B the best ocean view, but site A is on the most stable ground.
20. B. Mass movements occur when the force of gravity exceeds the strength of the slope materials.
21. A. Undercutting by a river or waves will oversteepen a hillslope and enhance the potential for slope failure. Since water can act as a lubricant and also adds weight to the slope materials, draining the slope will reduce the weight of the slope material and increase friction, thereby reducing the potential for slope failure.
22. C. Talus refers to the blocks of rock that collect at the base of a steep slope or cliff.
23. D. The angle of repose for most loose sands is about 35°. The angle of repose varies significantly with a number of factors, one of which is the size of the particles (refer to Figure 16.13).
24. B. Bedding, joint planes, or a foliation fabric all are potential planes of weakness within rock. The orientation of any of these fabrics parallel to the hillslope compromises slope stability (refer to Figure 16.13).
25. C. Refer to Figure 16.13.
26. A. Solifluction is a result of repeated freezing and thawing.
27. C. Draining the water from the landslide area would help to reduce the weight of the slope materials and reduce the potential lubricating effects of water.
28. D. Bedding planes, joint planes, and textural fabrics like foliation are zones of weakness within rock. If they parallel the hillslope, the potential for slope failure is enhanced.
29. B. Refer to the section Unconsolidated Mass Movements in your textbook.
30. D. The barren slopes left by the wildfires will enhance the potential for all the hazards listed.

Chapter 17

Answers to Practice Exercises

Exercise 1: Evaluating rock materials as potential aquifers

Rock material	Porosity (high, medium, low)	Potential as an aquifer (good, moderate, poor)
Loose, well-sorted, coarse sand	High	Good
Silt and clay	*Low*	Poor
Granite and gneiss	Low—Interlocking grains of silicate minerals provide for little pore space.	*Poor*
Highly fractured granite	*Medium*—Fracturing can significantly increase pore space and improve Permeability.	Moderate
Sandstone	*Medium*—The cement that holds the sand grains together reduces pore space. Nevertheless, sandstones are typically good aquifers.	Moderate to good
Shale	Low—Fracturing will increase pore space but permeability may still remain low. Shales are typically aquicludes.	Poor
Highly jointed limestone	Medium—Fracturing and the formation of a cavern system within the limestone can greatly enhance the porosity and permeability of limestones. Caverns serve as an open plumbing system for groundwater.	*Moderate to good*

Exercise 2: Evaluating groundwater wells

Well A—potential for

1. pollution—High, because the water table slopes toward well A, and upslope is the outhouse. The cone of depression produced by pumping well A enhances the potential for pollution by creating a larger gradient in the water table between well A and the outhouse.
2. artesian flow—None. Well A will exhibit no artesian flow because the aquifer is neither confined nor sloping.
3. discharge—High, because the aquifer is a porous and permeable sandstone of large volume and well A is drilled deep into the aquifer.

Well B—potential for

4. pollution—Low, assuming that the house does not release pollutants, because the water table slopes away from well B and the outhouse is lower. The cone of depression around well B is small and not an issue.
5. artesian flow—None. Well B will exhibit no artesian flow because the aquifer is neither confined nor sloping.
6. discharge—Potentially high, as long as the water table does not lower.

7. long-term supply—Low. Because well B is shallow, a lowering of the water table, due to a change in climate or due to pumping from wells A and B at rates that exceed recharge, could compromise the productivity of well B.

Well C—potential for

8. pollution—Low, because there is no source of pollution shown for the confined sandstone aquifer.
9. artesian flow—High, because the aquifer for well C is a tilted and confined layer of sandstone and the recharge area for the aquifer appears to be higher in elevation than the top of the well.
10. discharge—High, because with high mountains to the east there should be good recharge of this artesian aquifer. The shale layers above and below the sandstone confine the porous and permeable sandstone and thereby allow for the development of significant water pressure within the aquifer. Refer to Figure 17.12.

Answers to Review Question

1. B. Evaporation from the oceans is more than six times that from the land surface. Refer to Figure 17.2.
2. D. Polar ice caps and glaciers contain about 2.97% of all water on Earth. This is the second largest reservoir for water. Refer to Figure 17.1.
3. A. Refer to Figure 17.1.
4. C. Rock particles typically can compact more efficiently as grain size decreases, which reduces porosity and permeability. Refer to Figure 17.9 and Table 17.2.
5. B.
6. C. Permeability is the ability of a solid to allow fluids to pass through it. Generally, but not always, permeability increases as porosity increases. Permeability also depends on the sizes of the pores, how well they are connected, and how tortuous a path the water must travel to pass through the material.
7. A. A stalactite holds "tight" to the ceiling.

Memory Tip

You can easily remember the difference between a stalactite and a stalagmite because stalactites hold "tight" to the ceiling and stalagmites "might" reach the ceiling of a cave.

8. C. Carbonate rocks, like limestone, are susceptible to dissolution. A wet climate favors cave formation.
9. D. An aquifer is a rock that will yield a good flow of groundwater.
10. C. Refer to the section Water Deep in the Crust in Chapter 17.
11. D. Shales are typically aquicludes.
12. D. Porosity and permeability both influence how much water an aquifer can produce. Porosity represents the total amount of pore space in which groundwater can be stored. Permeability is linked to porosity and represents the ability of water to flow through the rock. Some shales and lava flows have moderate to high porosity but very low permeability because the pore spaces are not interconnected. Some rocks, like granite, are moderately permeable because of extensive fracturing. However, their porosity may be low because the fracturing is very tight.
13. B. Loose sand typically exhibits high porosity and permeability because the round sand grains cannot pack together very efficiently. Refer to Figure 17.9.
14. A. Refer to Figure 17.14.
15. B. Rivers that flow continuously are fed by springs from a shallow groundwater table that intersects the stream channel. Refer to Figure 17.14.
16. A. Refer to Figure 17.12.

17. D. Refer to Figure 17.12.
18. B. Sand and gravel typically exhibit a high porosity and permeability.
19. D. Sandstones are typically good aquifers. Since water flows downhill, it tends to collect and recharge aquifers located beneath topographically low spots like valleys.
20. B. The cone of depression around well B has lowered the water table enough that effluent leached from the outhouse will flow toward well B even though the topography slopes toward the river. Refer to Figures 17.15 and 17.23.
21. B. Well B will be the most productive water well because it taps into a larger sandstone aquifer. Well A is not likely to be productive since it bottoms out in a shale that typically has very low permeability. Well C will yield water since it bottoms out in the sandstone above a shale unit that creates a perched water table. The volume of water from well C will be limited.
22. C. Refer to Figure 17.17.
23. A. The spring is least likely to be contaminated by the outhouse because it is produced from a perched water table well above and independent of the aquifer that is affected by the pollutants from the outhouse.
24. C. h/l for A = 0.04, B = 0.03, C = 0.05, and D = 0.006.

Chapter 18

Answers to Practice Exercises

Exercise 1: Stream velocity

Variable affecting stream velocity	Relationship of variable to stream velocity	Analogy
Gradient—the slope of the stream channel	As gradient decreases, stream velocity decreases. Velocity is proportional to the gradient. Note: In headwaters of streams (in the mountains where gradient is highest), other factors (decreased discharge and increased channel roughness) will counter the effect of the high gradient.	*You tend to walk faster down a steeper slope.*
Discharge—the amount of water in the stream channel	As discharge increases, stream velocity increases. Velocity is proportional to the discharge. Note: Surprisingly large objects can move a river during a flood.	*Will you move into a new house slower or faster if you have more people helping you?—faster.*
Sediment load	As the availability of sediment increases, the stream velocity will decrease. Note: Various factors, such as the bedrock, a landslide, erosion of soil from a burned area, and construction, can influence the availability of sediment load.	*Typically, will you travel faster or slower if you are carrying more in your backpack?—slower.*
Channel characteristics		
• Channel roughness	*As channel roughness increases, velocity will decrease.*	*Cross-country hiking without a trail tends to slow one down.*
• Channel shape	*The stream has more contact with the channel surface if the channel shape is very wide or very narrow. More contact with the channel will increase drag and decrease velocity.*	*When you have more contact with the ground surface, you move slower. Crawling is slower than walking.*

Exercise 2: Relationship between stream flow and groundwater

Streams in desert regions typically flow intermittently, and streams in more temperate regions, like New England, flow year-round, because effluent streams are fed by springs from a water table that intersects the stream channel. The water table is well below the channel of an influent stream, which flows in response to rainfall but quickly dries up as runoff from a storm decreases. Infiltration of stream flow into the channel bottom sediments may help to recharge the groundwater table beneath the channel.

Exercise 3: How do rivers cut through mountain ranges?

Two ways a river can cut through a topography obstruction like a mountain range:

A. **Antecedence,** where the river existed before the present topography was created and maintained its original course despite changes in the underlying rocks and topography

B. **Superposition,** where the river was established at a higher level on a uniform surface before eroding down and superimposing itself on a buried geologic structure, like an anticline

Answers to Review Questions

1. B. Gravity is the force that drives water down hill.
2. B. Discharge is the volume (typically measured in cubic feet or meters) of water flowing past a point on the stream channel for a given interval of time (typically seconds).
3. A. Velocity is directly proportional to gradient. An increase in slope increases velocity if all other factors do not counter the change in slope.
4. B. Stream velocity is the most important variable determining the behavior of a stream.
5. A. The change in elevation was 200 feet over the 200 miles canoed. 200 feet / 200 miles = 1 foot per mile.
6. B. Refer to Figure 18.8.
7. A. Stream competency is a measure of the size of particles a stream can transport. Stream capacity is a measure of the amount of sediment load a stream can transport.
8. B. Coarser particles, like pebbles, settle out before sand and silt.
9. B. The outer bank around a meander is much more likely to be eroded because stream velocity is fastest around the outside of the meandering channel where water depth is greater. On the inside of a meander, water depth is lower, velocity slows, and the stream is more likely to deposit sediment and form a point bar. Refer to Figure 18.3.
10. C. An increase in rainfall or in stream gradient or a lowering in base level increase the stream's velocity and give the stream renewed ability to downcut. Typically, the stream entrenches its channel along its preexisting meandering course.
11. C. Refer to Figure 18.25.
12. C. Regular addition of sediment load is likely to cause the stream velocity in the disturbed stretch to decrease due to the increased availability of load and a reduced gradient. A reduction in velocity may induce deposition.
13. D. The net effect of straightening out the river channel by cutting off a meander bend is to increase the gradient of the stream channel in the cutoff section. An increase in gradient will result in an increase in velocity and increased potential for channel erosion.
14. D. A 50-year flood event has a 2% chance of occurring in any year over a 50-year period.
15. D. This may surprise you, but stream velocity typically increases downstream. The reduction of stream gradient is countered by the increase in discharge from tributary channels. The lazy old Mississippi River runs faster past Vicksburg, Mississippi, than upstream at St. Louis, Missouri.

16. C. A lowering of base level increases the stream gradient, giving the stream renewed ability to erode and transport rock material. Erosion will begin in the vicinity of the change.
17. B. Refer to Figure 18.26 and associated text. Answers A and C are incorrectly stated because velocity would decrease with a decrease in gradient, and an increase in discharge would result in erosion, not deposition.
18. D. Choices A–C are all possible results of regional uplift, which would raise the headwaters of the drainage system, which would increase stream gradient and enhance the potential for stream erosion. See Figures 18.2 and 18.27.
19. A. House A is located on the outside of a meander bend, which is most susceptible to bank erosion. Refer to Figure 18.3.

Chapter 19

Answer to Practice Exercise

Exercise: Sand dune types

Dune type	Characteristics	Sand supply	Wind direction/strength
Barchan	Crescent-shaped with arms pointing downwind. Slip face is a concave curve advancing downwind.	Limited	Unidirectional/strong
Transverse	Long, wavy ridges oriented at right angles to the prevailing wind	Abundant	Unidirectional/strong
Blowout	Crescent-shaped with arms pointing upwind (into the wind). Slip face forms a convex curve advancing downwind.	*Limited to moderate*	*Unidirectional/gusty*
Linear (See Figure 19.8.)	Long, straight ridges more or less parallel to general direction of wind.	Moderate	Variable direction/ moderate to strong

Answers to Review Questions

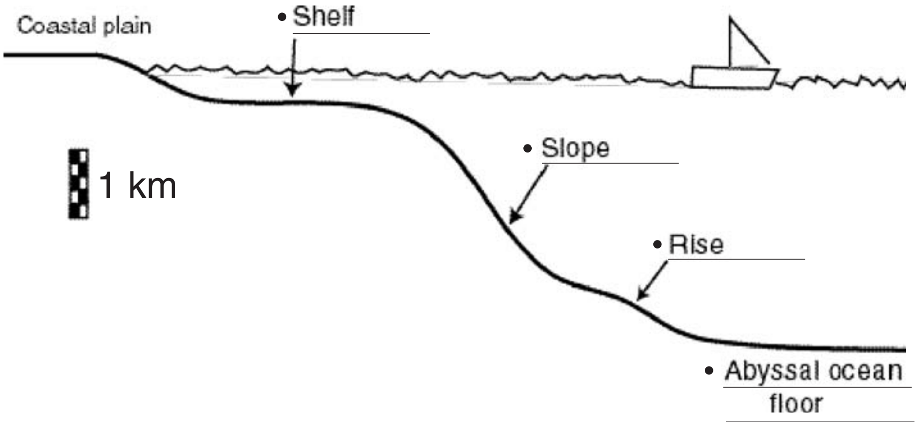
1. D. Refer to Figure 19.1 and the text section Wind Belts.
2. A. Rising air is characteristic of equatorial latitudes where the sun's radiation is more concentrated. As the air rises, it cools and releases abundant rainfall typical of tropical regions. The other three answers all contribute to desert conditions.
3. D. Refer to Figure 19.11.
4. D. Refer to Figure 19.11 and the text section How Sand Dunes Form and Move.
5. C. Refer to Figure 19.19. Because it is so flat and smooth, a playa (dried lake bed) in the Mojave Desert east of Los Angeles is a regular landing site for space shuttles.
6. A. Loess is fine wind-blown dust.
7. B. Refer to Figure 19.7.
8. B. Silt and clay are carried in suspension. Sand is typically transported by saltation, sliding, and rolling.
9. B. Refer to Figure 19.1 and the text section Wind Belts.

10. D. The arms of the barchan point downwind. Since the wind is blowing from south to north, the arms are pointing north and the town is in the opposite direction.
11. B (south). The arms of blowout dunes point into the wind (upwind). Since the wind blows inland from the coast, the arms of the dune point to the beach.
12. D. All the answers are appropriate.
13. desert varnish. Refer to Figure 19.17.

CHAPTER 20

Answers to Practice Exercises

Exercise 1: Profile from the shoreline to the ocean floor



B. The profile characterizes a passive continental margin. Refer to Figures 20.18 and 20.19 and associated text.

Exercise 2: Passive versus active continental margins

A passive margin is a continental borderland far from an active plate boundary. In contrast, active margins are associated with subduction zones and transform faults. The volcanic activity and frequent earthquakes give these narrow and tectonically deformed continental margins their name. Continental shelves are broad and relatively flat at passive continental margins and are narrow and uneven at active margins.

A. passive
B. passive
C. active (subduction/convergent plate boundary)
D. passive
E. active
F. passive

Answers to Review Questions

1. C. The wind generates most of the waves in the oceans.
2. C. The edge of the continent is rarely if ever the shoreline. The edge is the continental slope and rise, which may be hundreds of kilometers from the shoreline.
3. A. Mafic volcanism at the oceanic spreading centers generates new ocean crust.

4. D. Wave refraction is the tendency of a wave to bend into the shoreline it approaches. Waves bend as the wave bottom “drags” on the shallowing bottom before the shoreline, slowing that portion of the wave down. See Figures 20.2 and 20.3.
5. A. Refer to Figure 20.1.
6. A. Mafic volcanism at divergent plate boundaries generates the basaltic seafloor crust, which is, over time, buried in pelagic sediments.
7. A. Seamounts are extinct submarine volcanoes made mostly of basalt.
8. B. Refer to Figure 20.1.
9. D. 4000 to 6000 meters is the depth of the abyssal ocean floor.
10. A. The sea level appears to be rising about 4 millimeters per year.
11. A. Turbidity currents, often triggered by earthquakes, plunge down the continental slopes. They are flowing masses of turbid muds suspended in water, denser than the clear water above them. See Figure 20.19.
12. A. Refer to Figure 20.4.
13. C. The groin will block the drift of sand past your beach in the surf zone. Robbed of a continuous supply of sand, longshore currents will carry sand from your property, which will not be replenished by the sand supply up current. Your sandy beach is likely to disappear in a few years.
14. B. Wave energy is focused on points and headlands by wave refraction.
15. C. Refer to Figure 20.14 illustrating the sand budget—the dynamic balance between inputs and outputs of sand along the shoreline.
16. A. Rip currents are generated by rapidly moving backflows and run perpendicular to the beach. Therefore, the best way to escape from the grip of a rip tide is to swim parallel to the beach, unless you are up for some long-distance swimming.
17. C. Reef-forming corals require sunlight to grow and do not thrive in water much deeper than 20 meters. Therefore atolls begin as fringing reefs around a volcanic island. Over time, as the volcanic island slowly subsides, the coral reef grows upward, maintaining a shallow marine environment. Refer to Figure 5.22 and Earth Issues 5.1.
18. C. Refer to Figures 20.2 and 20.3.
19. A. Refer to Figures 20.2 and 20.3.
20. C. Turbidity currents (flows) are agents of erosion and deposition of sediment along the continental slope and adjacent ocean floor. Refer to Figure 20.19.
21. The longshore current will flow parallel to the beach in the surf zone and to the left, since the waves are coming in at an angle from the lower right. The best answer has the arrow close to the beachfront in the surface zone. See Figures 20.2 and 20.3.
22. A. Refer to Figure 20.27.

Chapter 21

Answers to Practice Exercises

Exercise 1: The glacially sculpted landscape

The text section Glacial Landscapes and Figures 21.16, 21.17, and 21.18 will be very helpful for completing the brief descriptions of glacial features. A list of possible glacial features that might be found and interpreted by a seasonal ranger include the following.

Features formed by the erosive power of glacial ice

- Striations—scratches and grooves—carved in bedrock over which the glacier flowed.
- Cirque
- U-shaped valley

- Hanging valley
- Fjord
- Arête

Glacial features formed by deposition of rock material by glacial ice

- Glacial moraines—the different types are described in Table 21.1.
- Drumlins
- Esker
- Kame
- Kettle
- Varve
- Kettle

All of these glacial features are described in the textbook and are appropriate answers.

Exercise 2: Your personal budget as a metaphor for a glacial budget

See the text section Glacial Budgets: Accumulation Minus Ablation.

A personal checkbook is a good metaphor for the dynamic balance between accumulation and ablation on a glacier. For example, if you deposit money into your checking account faster than you withdraw it, the cash balance grows. Similarly, as snow accumulates faster than the rate of ablation (loss), the glacier expands and advances. If you withdraw money from your checking account faster than you deposit it, your account shrinks. Similarly, if a glacier's rate of ablation exceeds the rate of accumulation, the glacier will shrink and retreat upslope. It might disappear altogether if ablation exceeds accumulation for an extended period.

Exercise 3: Glacial advances and retreats

Rarely does a glacier actually remain stationary. Driven by the force of gravity, glacial ice and the rock material that it carries are moving downhill. The words advance, retreat, and halt are used to describe the movement, or location, of the toe, or terminus, of the glacier; they do not refer to the actual movement of glacial ice within the glacier. The terminus of the glacier will remain stationary (halt), retreat up the valley, or advance down the valley depending on the glacial budget. Refer to Figure 21.8. For example, if the snow accumulating in the upper reaches of the glacier equals the loss (ablation) of glacial ice from the lower and warmer reaches of the glacier, the size of the glacier will remain constant and the glacial terminus will remain stationary. Nevertheless, the glacial ice is still flowing downslope with rock material and may pile up a sizeable end moraine. Refer to Table 21.1.

Answers to Review Questions

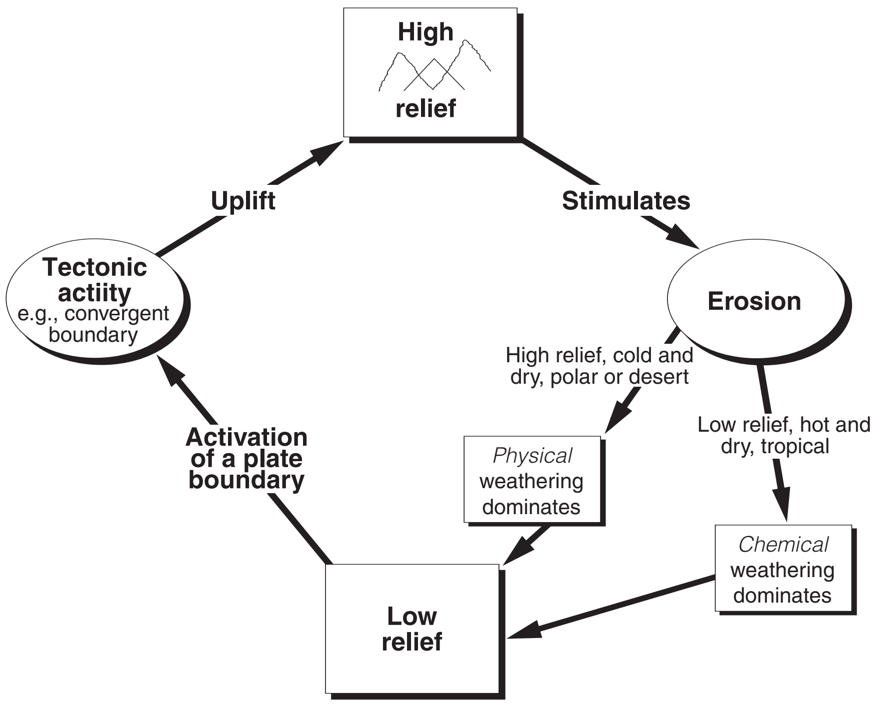
1. C. Glacial ice best fits the general definition of a metamorphic rock. Refer to the section Ice as a Rock in your textbook.
2. D. Gravity is the force that pulls glacial ice downhill. In response to gravity, glacial ice moves by plastic flow and basal slip.
3. B. Refer to Figure 21.7.
4. A. Refer to Figure 21.8.
5. D. Moraines are deposits of till. Refer to text section Glacial Sedimentation and Sedimentary Landforms and Table 21.1.
6. D. Drumlins are streamlined hills of till and bedrock. Because drumlins parallel the direction of ice movement, they can be used to reconstruct the direction of movement for the ice sheet.
7. D.
8. A. Water is tied up as glacial ice on land. Therefore, the sea level drops.
9. D. Refer to Figure 15.12.

10. B. Refer to 15.12.
11. B. Kames are small hills of sand and gravel dumped near or at the edge of the ice. Refer to Figure 21.18.
12. A. Since glacial ice is capable of carrying rock particles of a great variety of sizes, and since physical weathering dominates in glacial environments, it is very unlikely for a glacial till to consist of pure quartz sand.
13. A.
14. A. Refer to Figure 21.8.
15. C. Refer to Figure 21.24.
16. D. Each factor listed plays a role in climate change and needs to be considered as a component of a model that attempts to describe the cause of the ice ages.
17. D. The mass of the floating ice is equal to the mass of the water the iceberg displaces. When the ice melts, it simply replaces the water it displaces, so there is no change in the sea level.

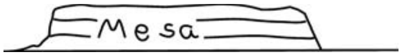
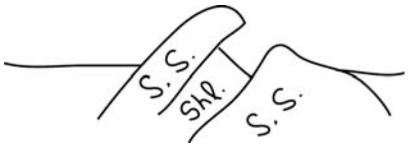
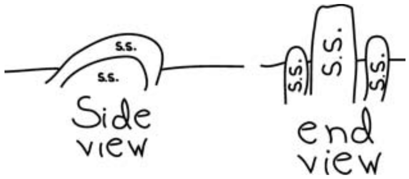
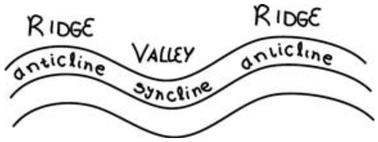
CHAPTER 22

Answers to Practice Exercises

Exercise 1: Landscapes: Tectonic and climate interaction flowchart



Exercise 2: Comparison of some landforms

Landform	Important feature(s)	Sketch (Hint: Keep it very simple)
Mesa (See Figure 22.8.)	A small plateau with steep slopes on all sides. Held up by underformed Sedimentary layers or lava flows.	
Cuesta (See Figure 22.14.)	A structurally controlled cliff. Some what tilted beds alternating weak and resistance to erosion. Typically undercut and asymmetrical.	
Hogback (See Figure 22.15.)	A structurally controlled cliff with beds that are steeply dipping to vertical. A ridge is more or less symmetrical.	
Valley ridge topography (See Figures 22.12 and 22.13.)	In young mountains, upfolds (anticlines) form ridges and downfolds (synclines) form valleys. As tectonic activity moderates and erosion digs deeper into the structures, the anticlines may form valleys and syncline ridges.	

Answers to Review Questions

1. A. River valleys begin with a V-shaped profile. As the sides of the steep valley retreat and the floor of the valley widens, a floodplain and relatively flat-floored valley will evolve. The gradient in a youthful river system is steep but decreases though time unless other geologic events are superimposed on the history of the drainage. Glaciers carve U-shaped valleys. Refer to Figure 22.9.
2. B. Elevation is the result of the balance between tectonic activity (uplift and subsidence) and erosion.
3. A. Refer to Figure 22.3.
4. D. Tectonic activity, erosion, climate, and type of bedrock are important controls on landscape evolution.
5. D. Earth's surface has two fundamental levels, the continents, which on average are about half a mile above sea level, and the ocean floor, which on average is about 2.5 miles below sea level.
6. B. Although mountains form at all four of these tectonic settings, the longest and highest mountain ranges form at convergent plate boundaries.
7. A. Refer to Figure 22.18.
8. D. Refer to Figures 22.12, 22.13, and 22.19.
9. A. Refer to Figure 22.9.
10. B. Refer to Figure 22.15.
11. A. Refer to Earth Issues 22.1.
12. D.

CHAPTER 23

Answers to Review Questions

1. B. Refer to Figure 23.14.
2. C. Uranium is not a fossil fuel.
3. B. Ozone depletion in our atmosphere is largely influenced by the release of chlorofluorohydrocarbons (CFCs), synthetic chorine, and fluorine compounds used widely in aerosols and refrigerants through much of the last century.
4. B. Oil and gas form from organic matter derived from marine organism that thrive in shallow coastal waters.
5. D. Refer to Figure 23.8.
6. B. U.S. oil production reached a maximum in 1970 and is now in decline.
7. C. Refer to Figure 23.5.
8. C. Refer to Figure 23.7. There are 42 gallons to a barrel of oil, of which about half is refined into gasoline for automobiles. From the rest come jet fuel, diesel and other fuels, solvents, lubricants, greases, and asphalt.
9. D. See the section Distribution of Oil Reserves and Figure 23.10.
10. B. Refer to Figure 23.14.
11. B. Refer to Figure 23.14.
12. B. Sulfur dioxide combines with rainwater to form sulfuric acid, a major component of acid rain. For this reason, low sulfur coals are environmentally more favorable to burn.
13. C.
14. B. Sulfur dioxide generated by burning fossil fuels high in sulfur content is the major source of acid in rain. The sulfur dioxide combines with rainfall, which is already slightly acidic from the dissolved carbon dioxide to produce sulfuric acid.
15. B. Well B is most likely to produce oil because it is drilled into a tilted sand layer, which is confined by the salt dome. Hydrocarbons are likely to accumulate in sand because of its high porosity and permeability. Because salt deposits are essentially nonporous and impermeable, the dome would seal off the sand layer and prevent the fluid hydrocarbons from escaping to the surface. Well A is drilled in shale, which can be a good source rock for hydrocarbons, but its low permeability makes it a very poor reservoir rock. Well D is drilled into a sand layer that is not sealed off by the salt dome. Therefore, hydrocarbons would migrate along the well D sand layer to the surface and be lost. Refer to Figure 23.8.
16. A. Refer to the text section Stratospheric Ozone Depletion.
17. C. Refer to the text section Stratospheric Ozone Depletion.
18. C. Burning fossil fuels releases CO_2, a greenhouse gas, into the atmosphere.
19. B. Refer to Earth Issues 23.1.
20. B. Refer to Figure 23.23.