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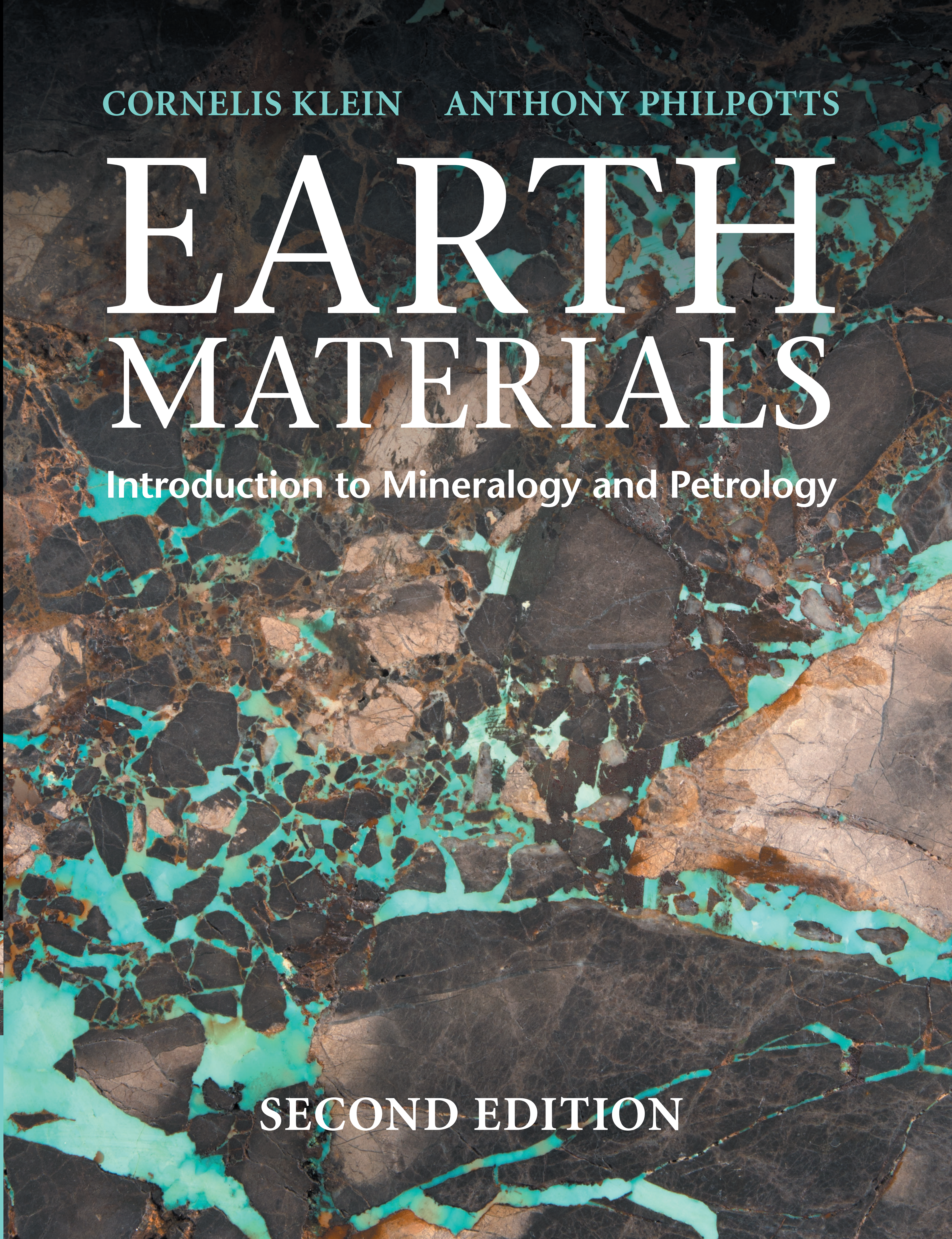

CORNELIS KLEIN ANTHONY PHILPOTTS

EARTH MATERIALS

Introduction to Mineralogy and Petrology

SECOND EDITION

Earth Materials

Introduction to Mineralogy and Petrology

This concise, accessible, market-leading textbook brings together the wide-ranging fundamentals students need to understand rocks and minerals, and shows them how they relate to the broader Earth, materials and environmental sciences. Designed specifically for one-semester courses, it is beautifully illustrated in full colour to explain the key concepts in mineralogy and petrology. This revision has been fully updated based on classroom experience. Including a completely new chapter providing an elementary introduction to thermodynamics, kinetics, radioactive decay and absolute dating, this new edition also features new mineral descriptions and many new stunning color photographs. A new section on hydraulic fracturing and discussion of some of its most serious potential environmental consequences has also been added. Stunning photos of mineral specimens and rock thin sections help students build a core understanding, whilst close intergration of clear illustrations with engaging text create a highly effective learning experience.

Cornelis (“Kase”) Klein was Professor in the Department of Earth and Planetary Sciences at the University of New Mexico, Albuquerque. He received his B.Sc. and M.Sc. in geology from McGill University, Canada, and his Ph.D. from Harvard University, also in geology. He was a member of the Geology faculty at Harvard University, Indiana University, Bloomington, and the University of New Mexico: he taught courses in mineralogy at all these universities. His published books include *Manual of Mineralogy* (19th–21st eds.); *Manual of Mineral Science* (22nd–23rd eds.); and *Minerals and Rocks: Exercises in Crystal and Mineral Chemistry, Crystallography, X-Ray Powder Diffraction, Mineral and Rock Identification, and Ore Mineralogy* (3rd ed., 2008). He received two awards for excellence in teaching from the University of New Mexico.

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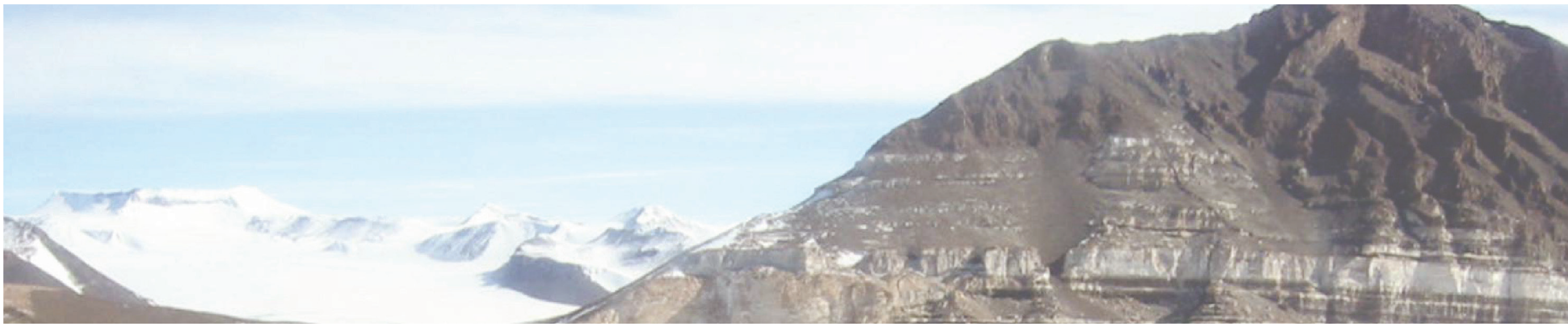
Frontispiece: Eruption of Mount Etna, Sicily, December 2015.
Credit: Andrea Savoca Andrea Savoca / EyeEm, source Getty.



Earth Materials

Introduction to Mineralogy and Petrology

Cornelis Klein
University of New Mexico, Emeritus

Anthony R. Philpotts
University of Connecticut, Emeritus

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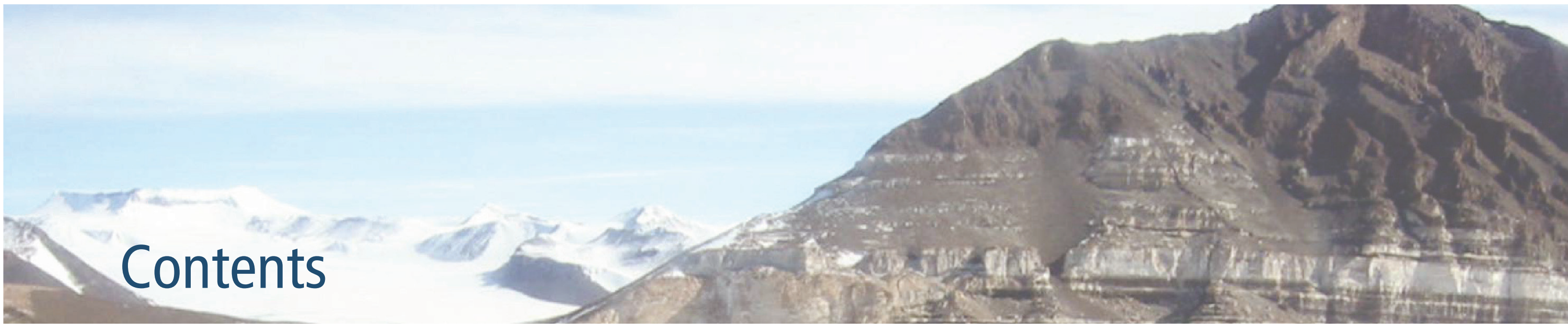
Cover: Polished surface of a deeply weathered breccia with fracture infill of turquoise. Photograph courtesy of David Nufer.

Cornelis Klein *dedicates this book to his two children and their immediate families. His son and daughter-in-law, Marc and Laura Klein, and their two children, Alaxandra and Hugh. And to his daughter and son-in-law, Stephanie and Jack Stahl, and Stephanie's three sons, Max, Miles, and Bo Peponis.*

Anthony R. Philpotts *dedicates this book to his three daughters, Liane, Marlaine, and Alison.*



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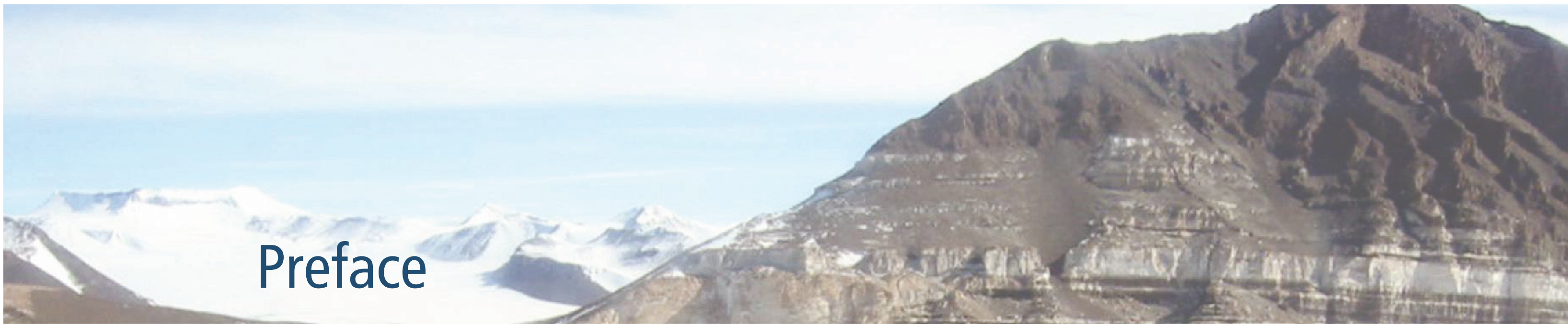

Preface

Over the past two decades, many curriculum changes have occurred in geology, Earth science, and environmental science programs in universities. Many of these have involved the compression of separate one-semester courses in mineralogy, optical mineralogy, and petrology into a single-semester offering that combines mineralogy and petrology, commonly called Earth Materials. Such a course is a challenge to the instructor (or a team of instructors) and the students. This is especially so when few, if any, textbooks for such a one-semester course have been available.

This text, *Earth Materials*, is an introduction to mineralogy and petrology in which both subjects are covered with a roughly even balance. To keep this textbook reasonably short and applicable to a one-semester course, we decided against providing a shallow survey of everything and instead concentrated on what we consider the most fundamental aspects of the various subjects.

In the writing of this text, we assumed that the students who enroll in an Earth materials course would have previously taken an introductory physical geology course, as well as a course in college-level chemistry.

Coverage

Basic aspects of mineralogy must precede the coverage of petrology. This sequence is obvious from the chapter headings. After a brief, general introduction in Chapter 1, minerals and rocks are broadly defined in Chapter 2. That is followed by three chapters that relate to various mineralogical aspects and concepts. Chapter 3 covers the identification techniques that students must become familiar with to recognize unknown minerals in the laboratory and in the field. It also includes discussion of two common instrumental techniques: X-ray powder diffraction and electron beam methods. Chapter 4 covers the most fundamental aspects of crystal chemistry, and Chapter 5 is a short introduction to basic aspects of crystallography. Chapter 6 covers optical mineralogy. This subject is included so that instructors who plan to introduce thin sections of rocks in their course can give their students quick access to the fundamentals of optical mineralogy and the optical properties of rock-forming minerals.

The sequencing of subsequent systematic mineralogy chapters is completely different from that most commonly used in mineralogy textbooks. In these chapters, minerals are discussed in groups based first on chemistry (native elements, oxides, silicates, and so on) and, subsequently, for the silicates, on structural features (layer, chain, and framework silicates, and so on). Here, the decision was made to group systematic mineralogy descriptions as part of the three major rock types: igneous, sedimentary, and metamorphic. This allows for the closest possible integration of mineralogy and petrology.

Chapter 7 gives systematic mineralogical data on 29 of the most common igneous minerals, including, in order of decreasing abundance, silicates, oxides, a few sulfides, and a phosphate.

Before discussing igneous, sedimentary, and metamorphic rocks, the second edition of Earth Materials has a new Chapter 8 that introduces thermodynamics and kinetics. Thermodynamics provides an explanation for the direction of all geologic processes but the rate at which these goals are achieved depends on kinetic factors. Although both of these subjects can be highly mathematical, this chapter introduces them in easily understood mathematical terms. This chapter also discusses one of the most important kinetic processes in unraveling Earth history, radioactive decay.

Chapter 9 presents the most fundamental aspects of the formation of igneous rocks, explaining why the normally solid Earth can, on occasion, partly melt to form magma, whose physical and chemical properties control its rise toward the surface where it eventually solidifies. A new section added at the end of this chapter discusses how evolving isotopic reservoirs in the Earth can reveal the source of magmas. This is followed by Chapter 10, which addresses the occurrence of igneous rock types, their classification, and plate tectonic settings.

Chapter 11 gives systematic mineralogical descriptions of 14 common sedimentary minerals as well as phosphorite and soil. (The siliciclastic components of sedimentary rocks are discussed in Chapter 7, which deals with igneous minerals). Chapter 12 deals with the formation, transport, and lithification of sediment, and Chapter 13 discusses sedimentary rock classification, as well as the occurrence and plate tectonic setting of sedimentary rocks.

Chapter 14 gives the systematic mineralogy of 27 of the most common metamorphic minerals, all of which are silicates, except for two, an oxide and an element. Chapter 15 addresses the causes of metamorphism, gives rock classifications, and relates their occurrence to plate tectonic settings.

CRYSTALVIEWER

The atomic structure illustrations, which are static images in this text, can also be viewed as interactive visualizations in CrystalViewer, a crystal structures visualization program for Mac and Windows. CrystalViewer is designed to provide the missing "third dimension" for crystal structure illustrations in the book. Each structure can be rotated and scaled with the computer mouse, and it is hoped that such interactive exploration will lead to an improved visual understanding of the complex three-dimensional atomic arrangements of minerals. The program contains 105 structure illustrations, which are distributed over two files. The first file, with the title "Learning," contains 24 structures that are referenced with figure numbers from Chapters 2, 4, and 5. These 24 structures illustrate basic aspects of crystal chemistry. The other file, entitled "Reference" with 81 crystal structures, is arranged in alphabetical order, by mineral name. This file contains the structures of the rock-forming minerals discussed in Chapters 5, 7, 10, 13, and 15. These structures complement the structure illustrations in the text that show unit cell outlines, space group notation, and legends with atomic site occupancies. The files and the CrystalViewer download are at www.cambridge.org/earthmaterials.

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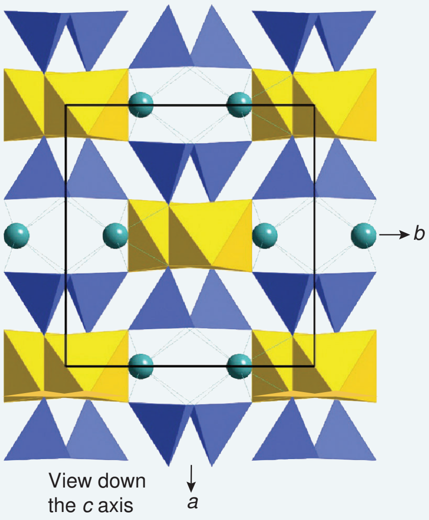

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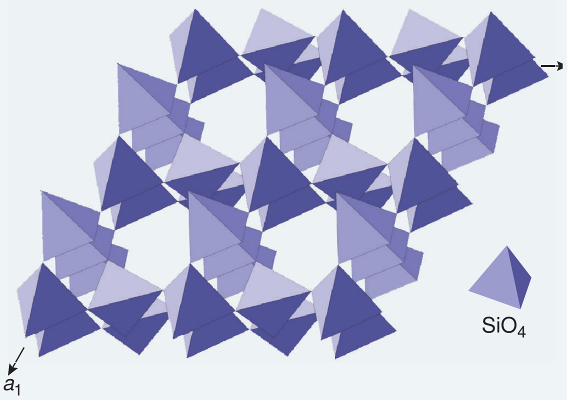


Chapter 16 gives systematic mineralogical descriptions of selected minerals that are of economic importance. Chapter 17 gives a brief overview of some selected resources of Earth materials and has a new section on shale gas, its extraction by hydraulic fracturing (fracking), and its potential environmental impact. Chapter 18 discusses the health effects of several minerals and chemical elements, and the hazards presented by certain rock-forming processes.

In the chapters that deal mainly with systematic mineralogy (Chapters 7, 11, 14, and 16), the main emphasis is on geologic occurrence (paragenesis), chemistry and atomic structure, physical properties that are pertinent to hand specimen identification (in laboratory sessions associated with an Earth materials course), and uses in industry and manufacturing. Hand specimen photographs and atomic structure illustrations are given for each mineral discussed.

This text is meant to be not only a supplement to lectures but also a reference source in the applied laboratory sessions of the course. Basic concepts in crystal chemistry, crystallography, and the origin of various rock types are best presented by the instructor in lectures in the classroom. Mineral and rock identification and classification schemes, however, are best learned in the laboratory with hand specimens and thin sections, using those parts of the book that specifically address the applied aspects.

All chapters begin with a boxed overview of what follows and end with a summary and set of review questions. When a new term is first encountered in the text, it is printed in bold type to signify that its definition is included in the glossary at the end of the text.

Our overall goal was the production of an accessible, highly illustrated and visually attractive, condensed and well-integrated mineralogy-petrology textbook suitable for one-semester Earth materials courses. It is our hope that we have succeeded.

Acknowledgments to First Edition

Cornelis Klein thanks Charles Langmuir, Professor in the Department of Earth and Planetary Sciences at Harvard University, for granting him permission (together with a professional photographer, David Nufer, of David Nufer Photography in Albuquerque, New Mexico) to access and photograph specimens from the Harvard Mineralogy Collections. David and I spent three full days there and with the full-time and very attentive help of Carl Francis (curator of the Harvard Mineralogy Museum and Collections) – whose enormous knowledge of the collections allowed us to locate the most appropriate specimens quickly – we completed all of the necessary hand specimen photography of the minerals for this text. Overnight lodging for our four nights in Cambridge, Massachusetts, was generously provided by Leverett House, one of the college houses of which I had been Allston Burr Senior Tutor between 1966 and 1970. We are most grateful to JoAnn DiSalvo Haas and Lauren Brandt for having provided us with some great student rooms.

Throughout the two-year period devoted to the writing of my sections of this text, many colleagues, be it at the University of New Mexico or elsewhere, have been helpful and generous with their time in reviewing sections of text while still in progress. They appear here in alphabetical order: Adrian Brearley, Jonathan Callender, Brian Davis, Amy Ellwein, Maya Elrick, Dave Gutzler, Rhian Jones, Bruce Loeffler, Matt Nyman, Frans Rietmeijer, Malcolm Ross, Jane Selverstone, and Mary Simmons.

I am grateful to David Palmer of CrystalMaker Software Limited, Yarnton, Oxfordshire, England, for providing expertise and guidance in the design of the crystal structure visualization program that accompanies this textbook.

This book would not have been possible without the support and patient understanding of my wife, Shirley Morrison. The word processing of my part of this text was most efficiently and enthusiastically accomplished by Mabel Chavez of Santo Domingo Pueblo, New Mexico.

Anthony R. Philpotts would like to thank the many reviewers who have painstakingly struggled through what we have written and suggested improvements. We have tried to incorporate as many of these as possible within the limits set by the length of the book. I would particularly like to thank Grant Cawthorn for one of the most thorough reviews I have ever received. His knowledge of igneous rocks and the photographs he provided have greatly benefited the book. Dan Kontak, Tony Morse, Brian Robins, and Jane Selverstone also offered valuable advice, as did numerous anonymous reviewers. I am grateful to all of them.

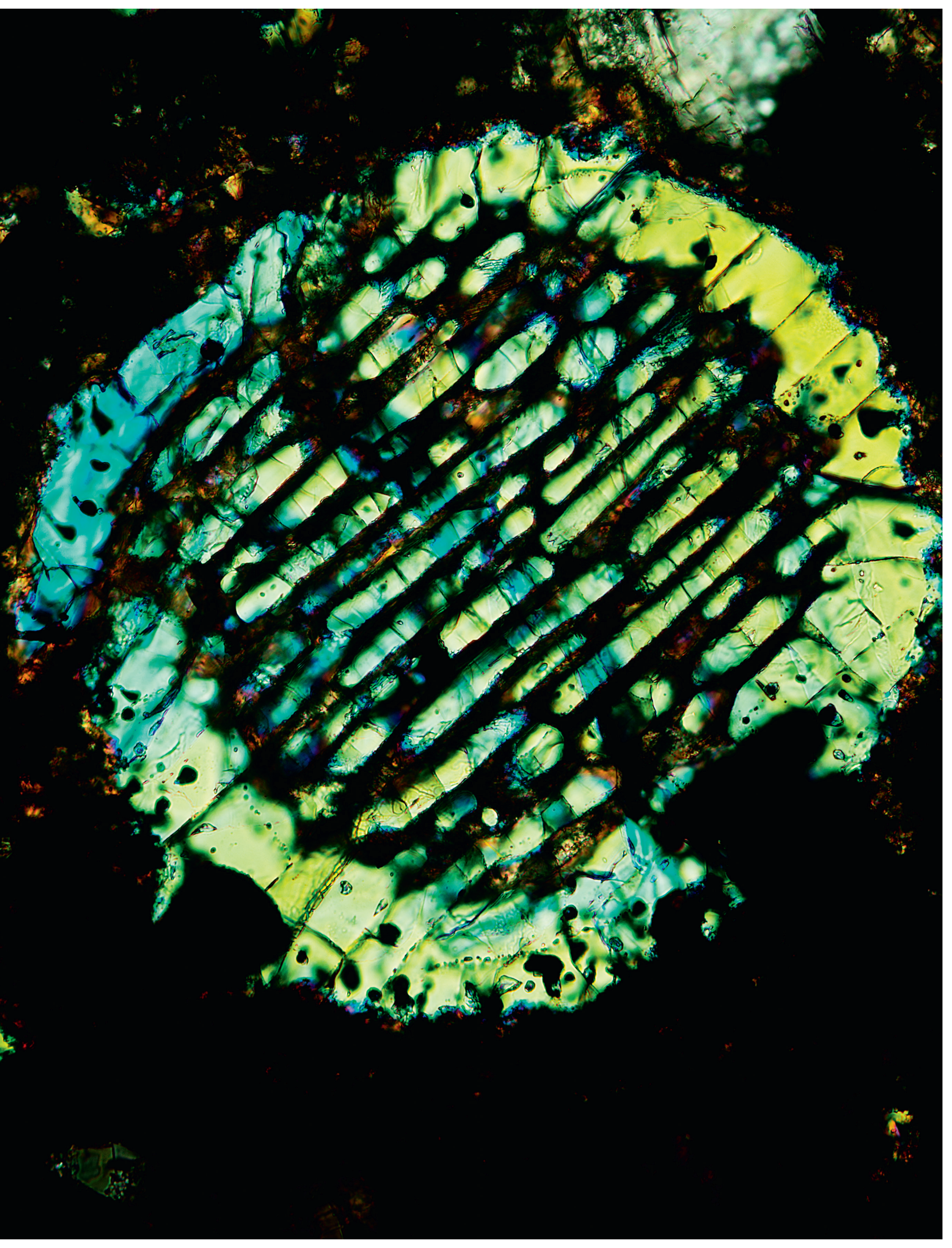
While writing this book, I have greatly appreciated interactions with many colleagues. Jay Ague, Brian Skinner, and Leo Hickey at Yale University, and Sheila Seaman, Mike Rhodes, and Tony Morse at the University of Massachusetts have all provided me with geological insights. I have also learned a considerable amount about sedimentary rocks from Randy Steinen, formerly of the University of Connecticut, and Paul Olsen, of the Lamont-Dougherty Earth Observatory of Columbia University.

I am grateful to the many petrology students I have had over the years. Their many questions and interests played a big role in how I taught the courses and in no small way have determined what, and how, petrology is presented in this book.

Last, none of my part of this book would have been possible without the support of my wife, who allowed me to disappear into my study for fully two years. She is owed an enormous debt of gratitude, especially in view of the fact that when I finished revising my previous book (*Principles of Igneous and Metamorphic Petrology*), I promised her that it was definitely the last one!

Acknowledgments to Second Edition

Anthony Philpotts wants to express his gratitude for having had the opportunity to work with Kase Klein on both the first and second editions of Earth Materials. On June 1, 2016, Kase suddenly, and unexpectedly, passed away. With his passing, the academic world lost one of the great teachers of mineralogy, but I also lost a very dear friend. We were undergraduates together at McGill University in Montreal, taking the same mineralogy and petrology courses and doing all the things that undergraduates typically do. It seemed only natural that toward the end of our careers we should come back together and pool our efforts in writing a book that introduces what we believed were the essentials of mineralogy and petrology that could be covered in the one-semester courses in Earth materials that have recently become so common. Given the vast scope of mineralogy and petrology, deciding on what should be included, or excluded, was a huge task, and I am so grateful to have had the benefit of Kase's wise council. Fortunately, all revisions for the second edition were completed before his untimely death. This book therefore contains his final contribution to the teaching of mineralogy. From its pages, readers will hopefully glean some of Kase's enthusiasm for mineralogy, and with this introduction possibly go on to delve deeper into the subject, as Kase would have hoped.



CHAPTER

1

Introduction

The Earth has had a long history – 4.56 billion years, give or take a few million – but most of its chemical elements were created at a much earlier time. Most of this book is devoted to how atoms (or ions) fit together to form minerals, the basic building blocks of the Earth, and how such minerals became part of what we refer to as rocks. In this introductory chapter, however, we briefly cover the evidence for where Earth's chemical elements came from. Their creation occurred earlier in the history of the universe and was associated with processes taking place in stars and, in particular, those accompanying the death of massive stars. Material from these earlier stars was dispersed into space, and only much later did it come together to form the solar system and planet Earth.

We also review the basic large-scale internal structure of the Earth. Although we never see material from deep in the planet, its composition and movement play important roles in determining processes that create the Earth materials that we see in the crust. Ever since its formation, the planet has been cooling, and a direct consequence of this process has been plate tectonics. We learn in later chapters that almost all new Earth materials are formed in specific plate tectonic settings, and it is, therefore, important to review this material before delving into the details of minerals and rocks.

A cross-section of a spherical chondrule composed mainly of the mineral olivine, $MgSiO_4$, with interstitial glass. It is a piece of the Saratov ordinary chondrite meteorite, recovered north of Saratov, Russia, after a dramatic fireball witnessed on September 6, 1918. The yellow-green and blue of the olivine grains are interference colors created by the interaction of transmitted polarized light with the crystal structure of olivine. Chondritic material such as this is believed to have accreted in the disk surrounding the Sun to form the planet Earth 4.6 billion years ago. This image was produced with a petrographic microscope, using a very thin slice (a "thin section") of the meteorite. The width of the field of view is about 1.2 mm. (Photograph courtesy of Jonathan Lewis, University of New Mexico). A photograph of a hand-specimen-size piece of a different chondritic meteorite is given in Figure 1.4.

This book provides an introduction to the study of the solids that make up planet Earth. These materials consist of naturally occurring chemical compounds, known as **minerals**, and their aggregates, **rocks**. Only through the study of minerals and rocks can we learn about the history of the Earth, and this knowledge is also important because of the extensive use made of Earth materials in everyday life, such as the fabrication of tools; the manufacture of vehicles; and their use as construction materials, sources of energy, and soils for agriculture. This knowledge is clearly important in the search for mineral resources, but the general public needs to know the finite nature of many of our natural resources to make informed decisions.

Many different processes are involved in forming a rock from a group of minerals. These processes are normally divided into three general categories: ones involving molten material, which we call **igneous**; ones involving the weathering of rock and transport of sediment, which we call **sedimentary**; and those that modify rocks through changes in temperature, pressure, and fluids inside the Earth, which we call **metamorphic**. Throughout the book, we first introduce how to identify the minerals that are common in each of these main types of rock, and then we discuss the processes that lead to the formation of those rocks. These processes, many of which are intimately related to plate tectonics, have played important roles in the evolution of the planet.

In the following chapters, we deal with these main types of Earth materials, but in this first chapter we look at where the materials that constitute the Earth came from, and we then review the Earth's major structural units. The wide compositional range of the many minerals and rocks found on Earth must in some way reflect the composition of the Earth as a whole. It is natural, then, to wonder where the chemical elements that constitute the Earth came from and what determined their abundances.

The Earth and solar system were formed 4.56 billion years ago, but none of the original planet has been preserved. The oldest rocks found to date are about 4 billion years old, although individual minerals have been found that are 4.4 billion years old. We are, therefore, missing about half a billion years of history. Fortunately, the study of distant stars provides glimpses into earlier times, and meteorites provide actual samples of material from which our planet is believed to have formed. Therefore, we start our study of Earth materials by briefly examining what astronomical and meteoritic studies tell us about the early history of the Earth.

1.1 Formation of Earth's Chemical Elements in Supernovae

Earth materials are formed from chemical elements that have had a long history and whose origins we can explain through studies of distant stars and meteorites. Stars are born from the condensation mainly of hydrogen, and they spend most of their life fusing the hydrogen to form helium. Their lives can end in various ways depending on the mass of the star, with the more massive ones ending in cataclysmic explosions known as **supernovae**, during which elements heavier than iron are created. These explosions disperse material throughout space and form the raw material from which new stars and solar systems are formed. The Earth and other terrestrial planets in the solar system were formed from the chemical elements left over from these early supernovae and other evolved stars that collected together to form the Sun and solar system 4.6 billion years ago.

When the universe began with the **Big Bang** ~14 billion years ago, only light elements such as hydrogen and helium and trace amounts of lithium, beryllium, and boron were formed. Subsequently, processes in stars formed heavier elements through nuclear fusion. Small stars, such as the Sun, fuse hydrogen atoms together to form helium, and late in their life, the helium atoms may fuse together to form carbon, but none of the heavier elements is formed. Stars that are more than eight times the mass of the Sun have greater gravitational attraction and can generate higher pressures and temperatures in their cores, which lead to additional nuclear reactions that create elements as heavy as iron. Once a star reaches the iron stage, it implodes under its own gravitational attraction and then explodes to form a supernova (Fig. 1.1). In these cataclysmic explosions, all the elements heavier than iron are formed.

Although supernovae occur in our part of the galaxy only once every few hundred years, they are relatively common in the center of the galaxy and in other galaxies. They have consequently been well documented. For example, NASA's **Hubble space telescope** has provided spectacular photographs of these exploding stars, and the orbiting Chandra X-ray observatory allows us to identify the actual elements that are produced in a supernova (Fig. 1.1).

The debris from a supernova initially forms clouds and jets of gas that are hurled out at enormous speeds from the exploding star (Fig. 1.1). These expanding clouds can remain visible for thousands of years. For example, the Crab Nebula is a supernova remnant from an explosion witnessed by Chinese astronomers in 1054 CE (common era). Today, this cloud is still expanding at the incredible velocity of 1800 km s^{-1}. Eventually, the material ejected from a supernova is dispersed throughout space, and it is from such material that our solar system was formed.

1.2 Birth of the Solar System and Earth

Most of the dispersed matter in the universe consists of hydrogen, with the heavier elements formed in stars constituting only a very small fraction. If the dispersed matter becomes clustered, it develops a gravitational field, which causes more

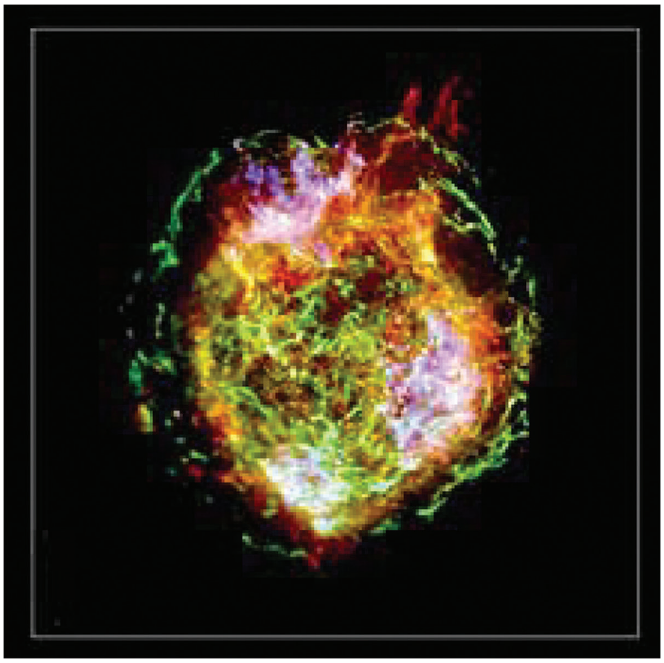


Figure 1.1 Cassiopeia A is a supernova remnant. This image, taken with NASA's Chandra X-ray Observatory, allows us to identify the elements being created in the exploding star by the characteristic wavelengths of X-rays emitted by each element, which have been converted in this image to false colors. (Photograph courtesy of NASA.)

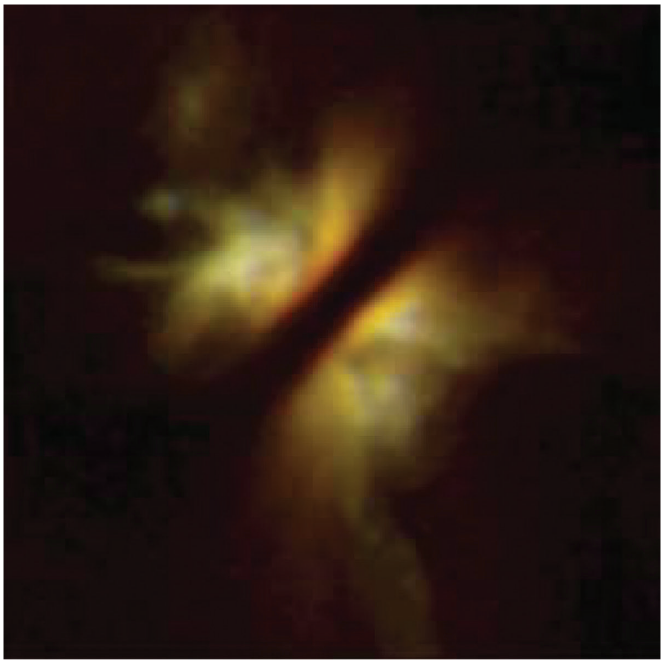


Figure 1.2 Hubble space telescope image obtained by the Near-Infrared Camera and Multi-Object Spectrometer (NICMOS) shows a star (IRAS 04302+2247) that is hidden by a nebular disc of material (diagonal dark region) similar in mass and size to the one that formed our solar system. Light from the star illuminates gas and dust that is still being pulled into the nebular disk. (NASA HST image.)

material to be attracted to it. These gas and dust clouds contract under gravitational forces and form what is known as a **nebula**, which eventually collapses into a flattened rotating disk (Fig. 1.2). If the nebula is sufficiently large, pressures and temperatures in its core are raised by gravitational collapse to a point at which nuclear fusion begins (10 000 000 Kelvin-degrees absolute), and a star is born. The critical mass required for fusion is ~80 times the mass of the planet Jupiter.

The nebula that would become our solar system was formed slightly more than 4.56 billion years ago. Most of the material in that nebula collapsed inward to form the Sun, but some remained in the solar disc to form planets, moons, asteroids, meteorites, and comets. In the inner part of the disc, where temperatures were higher, elements like carbon, nitrogen, and hydrogen were present as gases, and solid material was composed of rock-forming elements such as silicon, magnesium, iron, and oxygen. Because silicon, magnesium, and iron are much less abundant than carbon, nitrogen, and hydrogen, the **terrestrial planets** (Mercury, Venus, Earth, Mars) and the asteroids, which formed in the inner solar system, are small. Farther out in the solar disc where temperatures were lower, ices of water, carbon dioxide, ammonia, and methane could also form, and because these involved the more abundant elements in the solar nebula, they formed the much larger outer **gas giant planets** (Jupiter, Saturn, Uranus, and Neptune).

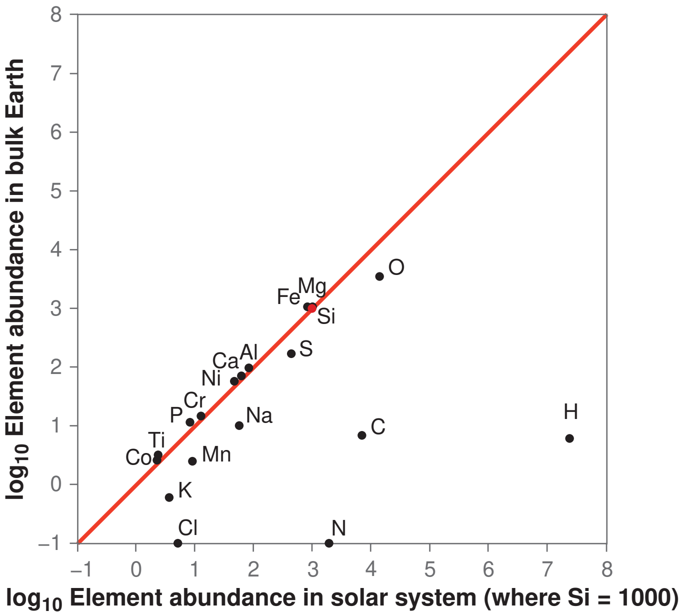
Because the Sun constitutes 99.9% of the mass of the solar system, its composition must be essentially the same as that of the nebula from which it formed. We can determine the composition of the outer part of the Sun from the strength of absorption lines in the electromagnetic spectrum that are characteristic of the elements. The Sun vigorously convects, so analyses of the **photosphere**, the light-emitting part of the Sun, are believed to represent a large part of the Sun. However, heavier elements are concentrated toward its core, so estimates of the solar system's bulk composition from analyses of the photosphere take into account this distribution (Fig. 1.3(A)).

The Sun is composed largely of hydrogen (74%) and helium (24%), with oxygen and carbon being the next most abundant elements, and all other elements being extremely minor. The planets, asteroids, meteorites, and comets were formed from particles in the solar nebula that accreted to form larger bodies. In the inner part of the solar disc, only the less volatile solids were available to form the terrestrial planets. Their compositions will differ from solar abundances in that they are depleted in the more volatile elements (Fig. 1.3(B)).

Meteorites are natural objects from space that impact the Earth's surface. During the early part of Earth's history, these impacts led to the accretion of the planet. With time, the frequency of meteorite impacts decreased. Meteorites still impact the Earth and provide us with samples of the primordial material from which the Earth was most likely formed.

Element	Bulk solar system	Bulk Earth
H	2.431 x 10^7	6
He	2.343 x 10^6	-
O	14130	3494
C	7079	7
Ne	2148	-
N	1950	0.1
Mg	1020	1061
Si	1000	1000
Fe	838	1066
S	445	169
Ar	103	-
Al	84	97
Ca	63	71
Na	58	10
Ni	48	58
Cr	13	15
Mn	9.2	2.5
P	8.4	11.5
Cl	5.2	0.1
K	3.7	0.6
Ti	2.4	3.2
Co	2.3	2.6

(A)



(B)

Figure 1.3 **(A)** Estimated abundances of elements in the bulk solar system (after Lodders, 2003) and the bulk Earth (after Newsom, 1995) based on the abundance of silicon in the solar system being 1000. **(B)** Logarithmic plot of element abundances in bulk solar system versus those in the bulk Earth. The less volatile elements have the same abundances in both bodies and hence plot near the red line (slope = 1), whereas the more volatile elements are depleted in the Earth.

Most come from the asteroid belt that lies between the orbits of Mars and Jupiter, but a very small number are composed of material that was blasted from the surface of the Moon and Mars by large meteorite impacts. Some meteorites are clearly fragments of planetary bodies that grew large enough to partially melt and undergo differentiation to produce iron-rich cores and silicate mantles, whereas others never grew large enough to differentiate.

The most common type of meteorite is called a **chondrite**, because it contains small (millimeter-size) spheres known as chondrules, which consist of minerals composed mainly of silicon, oxygen, magnesium, and iron (Fig. 1.4 and chapter-opening photograph). Chondrules are never found in terrestrial rocks. They are thought to have formed by flash heating and melting of primordial dust particles in the solar disc at temperatures near 2000°C. What caused the heating is uncertain, but we know that the melting and subsequent cooling must have been rapid, over a period of hours, because of the form of the crystals, as, for example, the barred texture of the olivine in the chapter-opening photograph.

Chondrules are among the first pieces of rock that formed in the solar system. The oldest objects in chondrites are so-called refractory inclusions (Fig. 1.4). These are made of exotic minerals rich in low volatility elements such as calcium, aluminum, and titanium. They are about 2 million years older than chondrules, and their formation ages are taken to be the age of the solar system itself, 4.567 billion years. Chondrites also contain rare, tiny mineral grains that are the debris from supernovae that took place before the solar system formed. The Earth is believed to have formed from accretion of material similar to that found in chondrites. Their composition is, therefore, used along with constraints set by the mass of the Earth, its moment of inertia, and known seismic discontinuities (see the following section) to estimate the Earth's bulk composition (Fig. 1.3(A)). This estimate shows the Earth to be depleted in volatile constituents (e.g., H, C, N, O) compared with the bulk solar system, but the relative abundances of the less volatile elements are similar (Fig. 1.3(B)). For example, the abundances of

Figure 1.4 A piece of the Axtell carbonaceous chondrite, which was found in Texas in 1943. The chondrite contains many small (millimeter-size), light-gray chondrules and a dark-gray matrix. The large white object in the center is an example of an inclusion, one of the oldest pieces of rock that formed in the solar system, 4.567 billion years ago. (Photograph courtesy of the Institute of Meteoritics, University of New Mexico.)

magnesium, silicon, and iron are all about the same in the solar system (Sun) and the Earth. These three elements, along with oxygen, make up most of the Earth, with other elements being minor constituents. Therefore, it should not come as a surprise that many rock-forming minerals are compounds that include these four elements.

1.3 Accretion and Early History of the Earth

Planet Earth is believed to have formed by the accretion of primordial solar material similar in composition to chondrites. As the planet grew larger, the kinetic energy of accreting material was converted to heat in the planet. Some of these early bombardments were so large that they actually knocked material off the planet. One such collision with a Mars-size body before 4.45 billion years ago removed material from Earth to form the Moon.

During this early accretionary stage, the Earth was hot. Not only did accretion generate enormous amounts of heat, but also radioactive decay provided additional heat. Another important source of heat was the formation of the molten iron-nickel core. The oldest rocks on Earth indicate that a strong magnetic field already existed 4 billion years ago. The magnetic field is generated by convection in the molten metallic outer core, which must, therefore, have been present at that time. The energy released by sinking iron and nickel to form the core generated sufficient heat to melt a large fraction of the Earth. Arguments based on the abundance of radioisotopes of hafnium and tungsten indicate that the Earth accreted in about 10 million years and that **core formation** was completed by about 30 million years after accretion of the planet. The combined effects of accretion, radioactive decay, and core formation guaranteed that the Earth had an extremely hot birth, and early in its history the surface would have been completely molten. Since that time, the Earth has been cooling, and the dissipation of heat has been the most important planetary process, which has made the Earth a dynamic planet.

The planet began to cool and solidify, and because of chemical variations and changes due to increased pressure with depth, a zoned planet was produced (Fig. 1.5). We have already seen that iron and nickel sank to form the core in the first 30 million years. As they sank, an equivalent volume of lower-density hot material would have risen toward the surface, which would have allowed its heat to be radiated into space and helped cool the planet. This cooling by transfer of hot material to cooler regions is known as convective cooling, and even though the outer part of the planet is now solid, convective cooling still remains the most effective way the planet has of getting rid of heat. The solidification of the planet has been a long, slow process, and it continues today, with the outer part of the core still molten. During this convective cooling of the planet, igneous processes redistributed elements, and the result is a compositionally layered planet.

1.4 Internal Structure of the Earth

The main evidence for layering in the planet comes from the study of the paths and velocities of seismic compressional (P) and shear (S) waves passing through the Earth. This evidence is discussed in all introductory geology texts and is not repeated here. Instead, we simply review the main findings of these studies as they relate to the Earth's internal structure (Fig. 1.5).

The Earth's radius is 6371 km, almost half of which (3483 km) is occupied by the metallic core, which is composed predominantly of iron and nickel but must also contain small amounts of light elements, such as silicon, oxygen, sulfur, and hydrogen. The core is slowly crystallizing from the bottom up, with the solid **inner core** having a radius of 1220 km. The temperature in the inner core is estimated to be above 5000 K, which is considerably hotter than the outer part of the core, which is about 4000 K. The inner core is solid not because of temperature but because of the extremely high pressure at the center of the Earth (364 GPa [billion pascal]; see Sec. 9.3.1). As the liquid in the **outer core** crystallizes onto the inner core, it liberates the **latent heat of crystallization** of iron and nickel, which helps drive the convection cells in the outer core, where the Earth's magnetic field is generated.

Above the core lies the largest unit in the Earth, the **mantle**. Although the mantle is solid, it behaves as a plastic material that slowly convects. What is not clear is whether convection currents pass all the way through the mantle or convect in two separate layers, the lower and upper mantle. The division between these two parts of the mantle is the prominent seismic discontinuity at a depth of ~660 km. The subduction of lithospheric plates into the mantle generates earthquakes that can be traced to a depth of 660 km but no deeper. Does this mean that material from the upper mantle cannot penetrate into the lower mantle, or does it simply mean that rocks below this depth are not sufficiently brittle to generate earthquakes? These two possible explanations have led to the two-layer mantle convection model and the whole-mantle convection model, which are illustrated in the left and right halves of Figure 1.5(C), respectively.

Recent studies of seismic velocities in the mantle favor at least some subducted slabs penetrating to the depth of the core–mantle boundary, where they may correlate with depressions on that boundary (Fig. 1.5(C)). Immediately above the core–mantle boundary is the 100 km to 300 km-thick **D″** (**D double prime**) **layer**, which may be the graveyard of subducted slabs. This is a complex layer, but toward its base is a 5 km to 40 km-thick zone with ultralow seismic velocities, which undoubtedly indicate the presence of

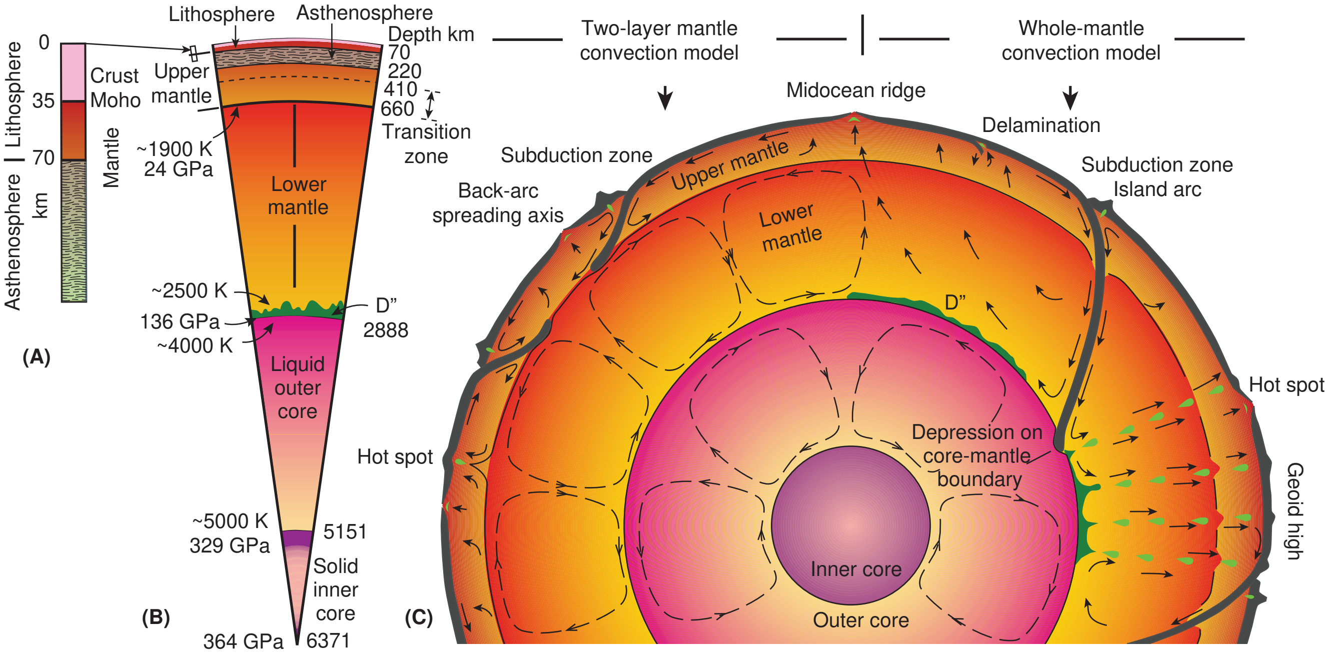


Figure 1.5 Major structural units of the Earth. **(A)** Cross-section through the lithosphere. **(B)** Section through the Earth showing the depth, pressure, and temperature at major seismic discontinuities. **(C)** Cross-section through the Earth showing the two-layer and whole-mantle convection models (left and right, respectively). Bright green indicates parts of the mantle undergoing partial melting as it rises toward Earth's surface.

partially melted rock. It is possible that magmas that rise at hot spots such as Hawaii have their source in this zone.

The upper mantle is bounded on its lower side by the 660 km seismic discontinuity. The region between this depth and another prominent discontinuity at 410 km is called the **transition zone** (Fig. 1.5(B)). Above this is the uppermost mantle, which terminates at the base of the **crust** at the prominent **Mohorovičić discontinuity** (or **Moho**). An extremely important zone marked by low seismic velocities occurs in the uppermost mantle between depths of 20 to 50 km beneath oceans and 70 to 220 km beneath continents. This zone is known as the **asthenosphere**, from the Greek word *asthenēs*, meaning "weak." Its low velocities are attributed to the presence of very small amounts of melt, which weakens the rock. Above the asthenosphere, the uppermost mantle and overlying crust form the relatively strong **lithosphere** (Fig. 1.5(A)). The asthenosphere is of importance because it is on this weak layer that the lithospheric plates move around the surface of the Earth to give us **plate tectonics**.

Finally, the crust is the outermost layer of the Earth. It is from 25 to 70 km thick beneath continents and 7 to 10 km thick beneath oceans. The rocks in the continental crust are less dense than those in the oceanic crust, and as a result of **isostasy** (buoyancy), continents stand higher than ocean floors.

1.5 Cooling of the Planet and Plate Tectonics

We know that the Earth's interior is hot and that the planet is still cooling. Deep drill holes indicate that the temperature in the Earth increases by about 25°C per kilometer but can range from 10 to 60°C km^{-1}. This is known as the **geothermal gradient**. We also know that heat flows from high to low temperature and must, therefore, be escaping from the Earth.

Knowing the **thermal conductivity** of rocks (0.005 cal cm^{-1} s^{-1} °C^{-1}), we can calculate that a geothermal gradient of 25°C would result in 1.25×10^{-6} calories escaping from 1 square centimeter of the Earth's surface every second (see Sec. 8.10.1). By expressing this value as 394 kilocalories per square meter per year, we can better appreciate how small a quantity of heat this is. Recall that a **calorie** is the quantity of heat required to raise 1 gram of water 1 degree centigrade. We are perhaps more familiar with the calorie when used for the energy content of food, but the food calorie is actually a kilocalorie (kcal = 1000 cal). For example, when we see that a McDonald's Quarter Pounder hamburger contains 410 calories, this is actually 410 kcal, which is almost the same as the amount of heat flowing from a square meter of the Earth's surface in an entire year. Despite its low value, this heat flow is sufficient to make the Earth a dynamic planet. It drives convection in the mantle and the movement of lithospheric plates, which results in plate tectonics and the processes that create and destroy rocks.

Calculations of the heat flow from the Earth have been performed on more than 24 000 drill holes over all of the continents and the ocean floor. These data have been synthesized by the **International Heat Flow Commission** to create the map shown in Figure 1.6 (see "Online Resources" at end of chapter). It uses SI rather than cgs units of heat flow; that is, milliwatts per square meter (mW m^{-2}). If we convert the heat flow discussed in the previous paragraph (1.25×10^{-6} cal cm^{-2} s^{-1}) to SI units, it becomes 50.2 mW m^{-2}. On the map, this value can be seen to be at the high end of the pale blue regions and is typical of most continental areas.

The heat-flow map shows that heat is not lost evenly from the planet. Indeed, most escapes from new ocean floor formed along divergent tectonic plate boundaries. These regions, which constitute only 30% of the Earth's surface, account for 50% of all heat lost from the planet. This shows that plate tectonics is intimately related to the planet's cooling. Near the Earth's surface, heat is transferred through rocks by **conduction**; that is, thermal vibrations of atoms are transferred to adjoining atoms down the temperature gradient. This is a slow process because rocks have such low thermal conductivity. In the Earth's mantle, however, solid rocks are plastic and capable of moving, albeit very slowly. In this region, heat can be transferred by moving hot low-density rock from depth toward the surface to replace cooler higher-density rock that sinks. This sets up **convection**, which more efficiently transfers heat in the mantle than does conduction. The thermally driven mantle convection creates stresses in the lithosphere that result in plate tectonics. The motion of tectonic plates, in turn, controls processes that ultimately are responsible for the formation of igneous, metamorphic, and sedimentary rocks.

1.6 Plate Tectonics and the Formation of Rocks

The lithosphere, which consists of the crust and upper mantle, is about 100 km thick. It is broken into eight major plates and numerous smaller ones. The major plates, which are indicated in Figure 1.6 by letters, include, in alphabetical order, the African (AF), Antarctic (AA), Australian (AU), Eurasian (EA), Indian (I), North American (NA), South American (SA), and Pacific (PA) plates. Some of the more important smaller plates include the Arabian (AR), Caribbean (CB), Cocos (CC), Juan de Fuca (JF), Nazca (N), Philippine Sea (PS), and Scotia (S) plates.

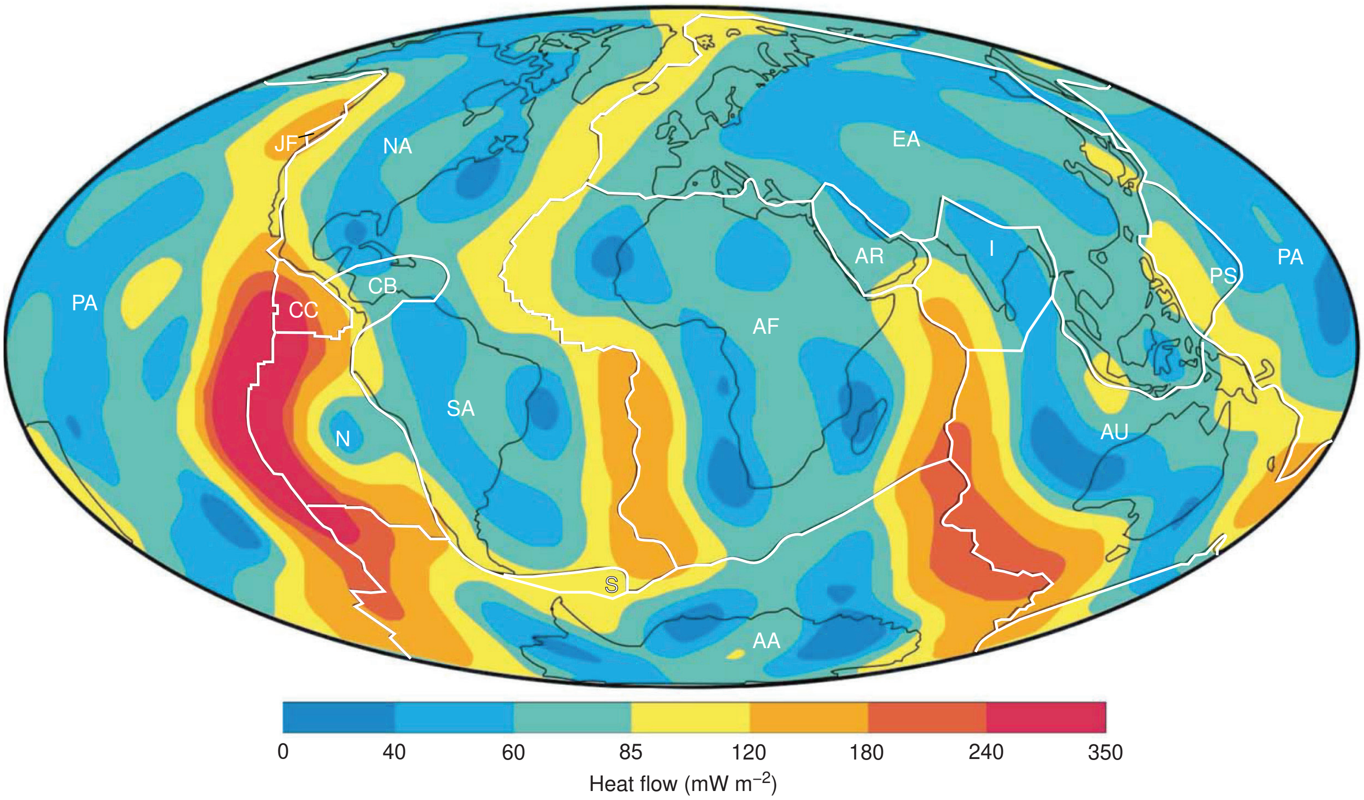


Figure 1.6 Global heat flow as synthesized by the International Heat Flow Commission (www.geophysik.rwth-aachen.de/IHFC/heatflow.html). For discussion of the synthesis, see Pollack *et al.* (1993). Tectonic plate boundaries are shown by white lines, and the names of the plates are shown by letters, the full names of which are given in the text.

Plate boundaries are of three types. At **divergent plate boundaries**, plates move apart and new crust is created by molten material rising from the mantle and solidifying to form new ocean floor, as occurs along the Mid-Atlantic Ridge and East Pacific Rise. At convergent plate boundaries, plates converge and crust is destroyed as it is subducted into the mantle, as happens to the Pacific plate, where it is subducted beneath the Aleutian Islands and Japan. Along **transform plate boundaries**, plates grind past each other along major faults, such as the San Andreas. Useful animations of these plate motions and reconstructions of past plate positions are given on the U.S. Geological Survey's Web site referred to in "Online Resources" at the end of the chapter.

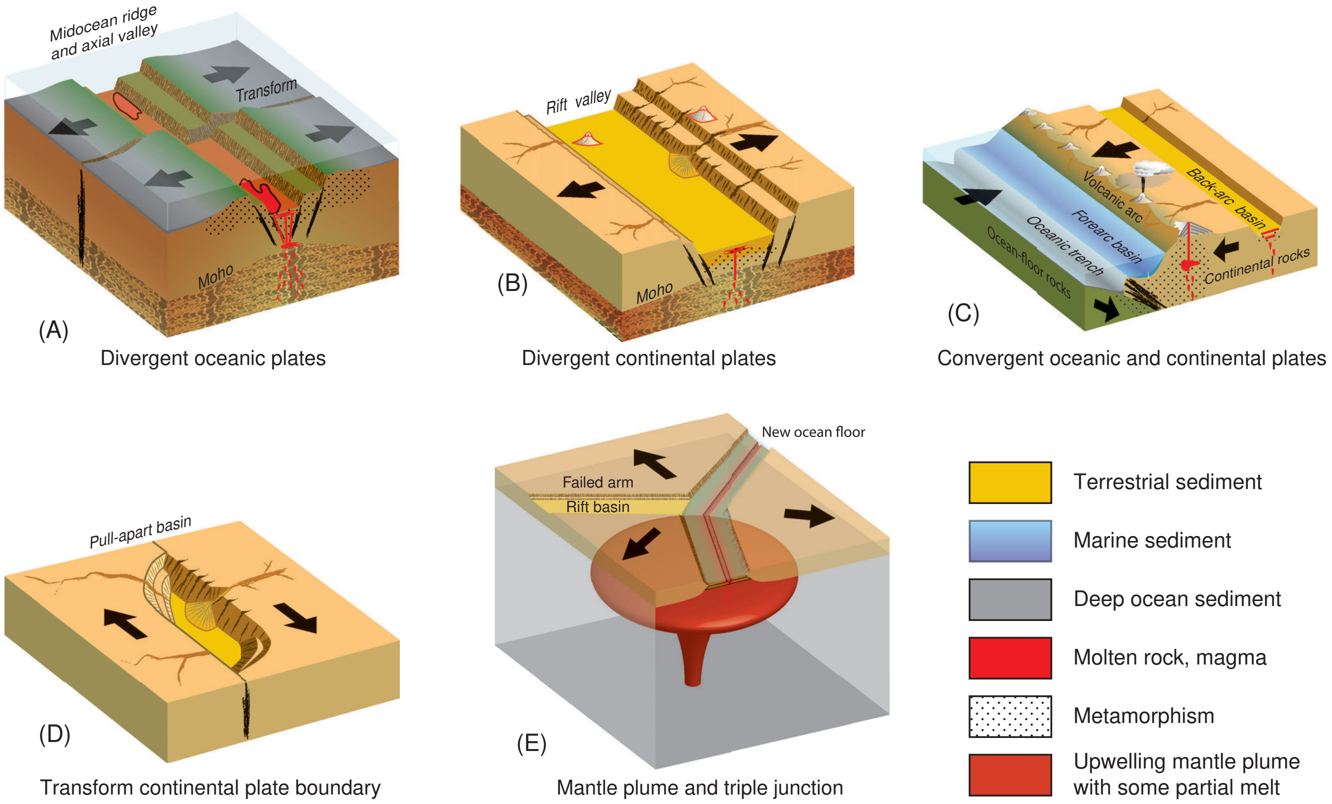
The rates at which plates diverge from each other can be measured from magnetic anomalies on the ocean floor (see USGS animations). New crust formed at midocean ridges develops magnetic anomalies due to periodic reversals in the Earth's magnetic field. As plates diverge, these anomalies are split apart, and by correlating similar age anomalies on either side of the spreading axis, the rate of divergence can be determined. These **relative plate velocities** can be as much as 160 mm/year but are typically about 40 mm yr^{-1}, which is of the same order of magnitude as the rate at which your fingernails grow.

Absolute plate velocities are not as easily determined but can be determined if we assume that **hot spots**, such as Hawaii or Yellowstone, have sources deep in the mantle that do not move relative to each other, which appears to be a good first approximation. As a lithospheric plate moves across a stationary hot spot, a string of volcanoes results that produce a **hot-spot track**. For example, the Hawaiian Island chain was created by the Pacific plate moving across the Hawaiian hot spot (Fig. 10.41). By dating the volcanoes along this track, the Pacific plate is shown to be moving at 95 mm yr^{-1} in a direction N 59° W.

Most rocks are formed by processes related to plate tectonics, and many are formed near plate boundaries. We can think of the location in which a rock is formed as a rock factory, and as we will see in later chapters, most of these factories are intimately related to specific plate tectonic settings. By way of introduction, we briefly describe these main plate tectonic settings.

1.6.1 Divergent Plate Boundaries

The world's most productive rock factories occur at divergent plate boundaries in oceanic regions, where molten material rises from the mantle and cools and solidifies to form new oceanic crust (Fig. 1.7(A)). The cooling gives these regions high heat flow (Fig. 1.6). While still hot, the new crust has lower density than older, colder crust, so it isostatically stands high and forms a **midocean ridge**. These ridges typically have a median



Divergent oceanic plates

Divergent continental plates

Convergent oceanic and continental plates

Transform continental plate boundary

Mantle plume and triple junction

Figure 1.7 Types of tectonic plate boundaries and sites of formation of igneous, sedimentary, and metamorphic rocks.

valley, which slowly widens as the plates diverge and is the locus of much of the lava that erupts along these ridges. Much of the cooling of the new crust results from circulation of seawater through the rocks, which changes their minerals and results in metamorphism. As the plates diverge and cool, they become denser, and the ocean floor deepens. The new ocean floor receives a constant flux of sediment, which consists mainly of the bodies of **pelagic organisms** that sink to the bottom on dying. Because the ocean floor gets older away from a spreading axis, the thickness of this layer of sediment gradually thickens.

If divergence occurs in a continental plate, the stretched lithosphere fails in the crust along **normal faults** to form a **rift valley**, whereas the asthenosphere rises from below (Fig. 1.7(B)). Sediment eroded from the highlands is washed into these basins, and magma formed in the rising asthenosphere forms igneous rocks. The sedimentary rocks are usually slightly metamorphosed.

1.6.2 Convergent Plate Boundaries

The world's second most productive rock factory occurs at convergent plate boundaries, where one plate is subducted beneath another. If both plates involve oceanic lithosphere, the older, and hence denser, ocean crust is subducted beneath the younger ocean crust. If one plate is continental and the other oceanic, the oceanic plate, being denser, is subducted beneath the continent, as illustrated in Figure 1.7(C). When continental plates collide, the less dense crustal rocks resist sinking into the mantle and are crumpled to form major orogenic belts. Convergent plate boundaries have the greatest relief on the planet, ranging from the highest mountains to the deepest oceanic trenches.

When oceanic rocks are subducted, the increased pressure causes metamorphism and release of water, which rises into the overriding plate, where it results in partial melting. The melt, being less dense than the solid rocks, rises toward the surface and forms the volcanoes that characterize most convergent plate boundaries. Radioactive decay in the thickened crust and the passage of magma through the crust raises its temperature and, along with the stresses caused by convergence, causes metamorphism in the orogenic belt. Erosion of mountains produces large amounts of sediment, much of which is rapidly transported to **forearc basins**. Behind many convergent plate boundaries, the lithosphere may be stretched, with formation of **back-arc basins**, which become sites of sediment deposition. If back-arc spreading continues, the lithosphere may rift apart and form new ocean floor. In oceanic trenches, deep ocean sediment may accumulate and, along with sediment spilling over from forearc basins, become intensely deformed and metamorphosed at the convergent plate boundary.

1.6.3 Transform Boundaries

Very few new rocks are formed at transform plate boundaries, but existing rocks become highly deformed by the shearing action of one plate grinding past the other. Irregularities along transform boundaries can result in formation of pull-apart basins, which become sites of sediment deposition (Fig. 1.7(D)).

1.6.4 Mantle Plumes and Hot Spots

Regions of long-lasting volcanism at relatively stationary positions on the planet are known as hot spots. As lithospheric plates pass over them, they leave a hot-spot track. The Hawaiian hot spot is one of the most prominent, but many others occur around the world. It has been postulated that hot spots form above **mantle plumes** that rise from deep in the mantle, possibly from as deep as the D″ layer near the core–mantle boundary. On approaching the base of the lithosphere, these plumes are supposed to flatten out to form a large mushroom-shaped head (Fig. 1.7(E)).

Considerable controversy surrounds the existence of mantle plumes. Early attempts to identify them seismically failed but did show that, if they exist, they must have small diameters at depth. Recent seismic studies, however, have been able to image the plume beneath Hawaii. The enormous amounts of heat released at hot spots, such as Hawaii and Yellowstone, necessitate a deep source in the planet.

Large mantle plumes in the geologic past are believed to have caused periods of extensive volcanism, during which huge volumes of new volcanic rocks were created in what are known as **large igneous provinces** (LIPs). The lithosphere above these plumes would have been heated and become less dense and hence risen to form large domes. As a plume head spreads, the lithosphere would have been rifted apart to form a **triple junction** (Fig. 1.7(E)). Commonly at these triple junctions, two of the rifts remain active and create new ocean floor, whereas the other rift becomes inactive or widens only slowly and is known as a failed rift. A mantle plume forming such a triple junction may be present beneath the Afar region of Ethiopia, with the Red Sea and Gulf of Aden being the active rifts and the East African Rift being the failed arm (Box 9.3).

1.7 Outline of Subsequent Chapters

In the following chapters, we discuss the mineralogical makeup of all the major rock types and discuss how and where they are formed and what uses we make of them. We start by learning about the physical properties of minerals, which are used to identify them in hand specimens. Next we learn about the chemical makeup of minerals and the way atoms fit together to form crystalline structures, as well as their external crystal form and internal atomic arrangement. Another chapter provides instruction on how to use the polarizing petrographic microscope, one of the most useful tools for studying minerals and rocks.

Armed with these tools on how to identify minerals, we proceed through the following chapters by first studying the common rock-forming minerals that occur in a particular rock type, which is followed by chapters dealing with the formation and classification of that rock type. We begin by discussing igneous minerals and rocks, because these would have been the first Earth materials formed and constitute the most abundant material in the crust. This is followed by sedimentary minerals and rocks, and finally we deal with metamorphic minerals and rocks.

Throughout the book, we make reference to uses that are made of minerals and rocks, but in the penultimate chapter, we focus on some of the most important Earth materials that we make use of on a daily basis. This includes construction materials, clays for ceramics, metals from ore minerals, and energy sources.

In the final chapter, we discuss the effects of Earth materials on human health, which can be positive or negative. This is a huge topic that we can only briefly touch on. Through food, we obtain nutrients from the Earth that are essential to our well-being. Feeding the ever-growing world population is an agricultural challenge that requires the use of fertilizers that come from the Earth. Some minerals are hazardous to our health. In some cases, these hazardous materials are part of the natural environment, but in others they are the result of human activity.

After reading this book, we hope that the reader will have an appreciation of how Earth materials came into existence and how we make use of them. A basic understanding of Earth materials is essential not only to the professional working with such materials but also to every human, because we interact with these materials every day, through tools we use, materials with which we construct, energy we use, and food we eat. Hopefully, this book will provide a basic understanding of Earth materials that will be useful to a wide spectrum of readers.

Summary

This introductory chapter briefly summarizes where the chemical elements that form the Earth came from, the planet's main structural units, and the plate tectonic settings in which new rocks are generated.

- Most of the elements in the Earth, especially those denser than helium, were formed by processes occurring in stars and during explosion of massive stars (supernovae) early in the history of the universe.
- A solar system forms from the dispersed matter in space when a cloud of gas and dust collapses gravitationally into a rotating disc, with a star forming at the center of the cloud and the planets forming from the material in the disc.
- The Earth and solar system were formed 4.56 billion years ago from the debris left over from an earlier supernova, but none of the earliest-formed material in the planet has survived in its original form, so we turn to meteorites to learn about the material that probably accreted to form the planet.
- The terrestrial planets are small because they are formed from the least abundant elements in the solar system, whereas the outer gaseous giant planets also include the more abundant elements.
- Chondritic meteorites, which contain small spheres of minerals composed of oxygen, silicon, magnesium, and iron, are thought to be composed of the same material that accreted to form the planet Earth. These four elements are the most abundant elements in the Earth.
- Heat from the accretion of the planet, radioactive decay, and core formation would have been sufficient to melt the outer part of the Earth early in its history. Since then, cooling has been the most important planetary process.
- The major divisions of the Earth are its core, mantle, and crust. The core, which is composed predominantly of iron and nickel, consists of an inner solid and an outer liquid core. The mantle is divided into upper and lower by a prominent seismic discontinuity at a depth of 660 km. The Mohorovičić discontinuity marks the boundary between the mantle and crust, at a depth of 7 to 10 km beneath oceans and 25 to 70 km beneath continents.
- The outer ~100 km of the Earth forms the relatively strong lithosphere, which moves in a number of plates over the much weaker asthenosphere creating plate tectonics.

- The Earth is slowly ridding itself of internal heat at a rate of about 394 kcal m^{-2} yr^{-1}. As a result of plate tectonics, most of the internal heat is released from new ocean floor formed at divergent plate boundaries.
- Eight major and numerous smaller lithospheric plates have boundaries that are either divergent, convergent, or transform.
- Relative velocities of plate divergence are on the order of 40 mm yr^{-1}.
- The largest volumes of new crust are formed at divergent plate boundaries, most along midocean ridges.
- At convergent boundaries, oceanic crust is subducted into the mantle, but new crust is formed by the eruption of many volcanoes.
- Sediments eroded from continents are deposited in basins that are formed at convergent plate boundaries, rift valleys at divergent plate boundaries and back-arc spreading axes, and pull-apart basins along transform boundaries.
- Mantle plumes are hypothesized to bring hot rocks up from deep in the mantle. Hot spots are believed to form from melts that rise from these plumes toward the surface.
- The spreading head of a mantle plume may be responsible for rifting of the lithosphere at triple junctions.

Review Questions

1. Where were most of Earth's chemical elements formed?
2. Why are the terrestrial inner planets small compared with the outer gas giant planets?
3. What is a chondrule, and why do we use the composition of chondritic meteorites to determine the composition of the Earth?
4. What caused the Earth to be so hot early in its history that its outer part would have been molten?
5. What are the major divisions of the Earth?
6. What two important layers in the Earth are responsible for plate tectonics?
7. What are the main types of plate boundaries, and what types of rock might be formed there?

ONLINE RESOURCES

www.geophysik.rwth-aachen.de/IHFC/heatflow.html – This is the Web site of the International Heat Flow Commission, where you can download the heat-flow map of the world and see other information relating to the Earth's internal heat.

http://geomaps.wr.usgs.gov/parks/animate/ – This U.S. Geological Survey Web site provides useful animations of many aspects of plate tectonics.

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Pollack, H. N., Hurter, S. J., and Johnson, J. R. (1993). Heat flow from the Earth's interior: Analysis of the global data set. *Reviews of Geophysics*, 31, 267–280.

The following issues of *Elements* provide excellent surveys of topics addressed in this chapter:

Asteroids (2014). *Elements*, 10, no. 1, 11–52.
Cosmochemistry (2011). *Elements*, 7, no. 1, 11–48.
Mineralogy of Mars (2015). *Elements*, 11, no. 1, 19–56.

CHAPTER

2

Materials of the Solid Earth

This chapter introduces minerals and rocks, the solid building materials of planet Earth. We define minerals and rocks and give examples of each from common daily uses. The main purpose of this chapter is to explain what minerals and rocks are with minor reference to specific names. Although we use several rock and mineral names in giving examples, these need not be memorized, because we encounter them in later chapters. In this chapter, it is important to understand what minerals and rocks are and to appreciate their differences. The examples of minerals and rocks that we encounter on a daily basis are given simply to emphasize the importance of Earth materials to our daily lives. Indeed, human cultural evolution is normally classified on the basis of the Earth materials used for making tools (e.g., Stone Age, Bronze Age, Iron Age). Although we have benefited from the use of Earth materials, some materials pose potential health hazards (e.g., asbestos). Rocks have provided the main source of construction material for large buildings throughout history, and even though modern buildings are mostly made of concrete and steel, the concrete is made from limestone. We end the chapter with a brief discussion of where rocks are formed. Rocks are the direct product of plate tectonic processes, and characteristic sets of igneous, sedimentary, and metamorphic rocks form in specific plate tectonic settings.

A deeply eroded bedrock sequence of river-transported volcanic debris with laminar and cross-bedding, and volcanic cobble conglomerates. The pillars with rounded and elongate (pillow-like) tops are known as “hoodoos” and are the result of differential weathering; the rounded tops being more resistant than the lower support pillars. The outcrops are part of the Abiquiu Formation of Oligocene–lower Miocene age (about 24 million years old). The area is known as Plaza Blanca, or White Place, and is located about 4 miles (6.4 kilometers) east of Abiquiu, New Mexico. These cliffs have been made famous by a series of paintings in the early 1940s by the world-renowned American abstract painter Georgia O’Keefe (1887–1986).

This text has the title *Earth Materials*. An inclusive definition of Earth materials encompasses the following: **minerals** and **rocks**, which are the solid parts; **soils**, the unconsolidated materials above bedrock; **fossil fuels**, which include all the hydrocarbons used for fuel and energy – petroleum, natural gas, and coal; the various forms of H_2O, in salt water and freshwater, in glaciers and ice caps; and the atmosphere, the mixture of gases that surrounds the Earth.

This book is an introduction to the solid materials that compose the Earth, but short discussions of soils (Chapter 11), coal (Chapter 13), and fossil fuels (Chapter 17) are included.

Solid materials are found abundantly underfoot on hiking trails in mountainous regions, but they are also present on beaches all around the globe. The solid materials in mountain chains, most commonly seen as outcrops in highway cuts, are rocks. Some common rock types are granite, basalt, limestone, and sandstone. The loose, solid materials on beaches consist mostly of the mineral quartz (with some minor components such as feldspar and mica grains mixed in) or calcite. Almost all beach sands are quartz rich, but some in the Caribbean consist mainly of granular calcite.

This book deals extensively with various aspects of minerals and rocks, and our main objective is to understand their origin and identification. Therefore, we are concerned with the questions of why and how chemical matter (**elements** and **ions**) is organized into particular minerals and rocks, and how minerals and rocks react to physical changes (e.g., in temperature and/or pressure) in the Earth's interior and to chemical changes in those exposed to the atmosphere. Parts of the text are also devoted to mineral and rock descriptions, because they are essential as basic knowledge for further discussion and for their identification in the laboratory or in the field.

2.1 Definition of a Mineral

A mineral is a naturally occurring solid, with an ordered atomic arrangement and a definite (but commonly not fixed) chemical composition. Almost all minerals are formed by inorganic chemical processes.

This definition is most easily understood if we assess each of its clauses in sequence.

Naturally occurring means that minerals are formed by processes that occur in nature and are not produced by laboratory processes. Many gemstones that occur naturally are today routinely manufactured in the laboratory. These are referred to as **synthetic** gems. Almost all reputable jewelers exhibit and sell naturally occurring gems such as emerald, sapphire, and so on. Specialty stores, however, might sell their synthetic counterparts. Such laboratory-produced materials should be identified with the prefix *synthetic,* as in synthetic emerald.

The word *solid* excludes liquids and gases. In solids, chemical elements (generally as ions, that is, electrically charged atoms) occur in fixed and regular patterns, which is not the case for liquids and gases. One very rare mineral that does occur as a liquid is mercury, Hg, in its elemental form. Mercury occurs in liquid spheres and globules and is a unique exception to the definition of a mineral as a solid.

An *ordered atomic arrangement* requires that the internal structure of minerals consists of regularly repeated three-dimensional patterns of atoms, ions, or ionic groups that are held together by various chemical bonds. Solids that lack such a regular internal repeated pattern are referred to as **amorphous**.

A *definite (but commonly not fixed) chemical composition*. The word *definite* means that all minerals have fixed ratios of cations (positive charge) to anions (negative charge). For example, in the simple mineral composition of quartz, SiO_2, the cation (Si^{4+}) to anion (O^{2-}) ratio is 1:2. This is referred to as *fixed* because all quartz has this specific cation–anion ratio. A slightly more complex composition is shown by the mineral olivine, which is normally represented by the formula $(Mg,Fe)_2SiO_4$. The cation–anion ratios in this formula are *fixed* as follows: $(Mg^{2+}, Fe^{2+}) = 2$, $Si^{4+} = 1$, and $O^{2-} = 4$, which results in the ratio 2:1:4. Given that in the atomic structure of olivine the Si^{4+} occurs as $(SiO_4)^{4-}$ anionic complexes with a tetrahedral outline, these ratios can be rewritten for $(Mg, Fe)_2SiO_4$ as 2:1. In olivine, the Mg^{2+} and Fe^{2+} ions (which have the same electrical charge and similar ionic sizes and can, therefore, be housed in the same atomic site in the olivine structure) can substitute for each other freely, which leads to the clause *but commonly not fixed*. Most mineral compositions have such chemical substitutions in their formulas; therefore, the majority of mineral compositions show considerable chemical variability, although the overall cation–anion ratios remain fixed.

Formed by inorganic processes reflects the fact that all common rock-forming minerals are the result of inorganic chemical processes. This does not mean that there are no exceptions to this statement. The mineral calcite, $CaCO_3$, which is the constituent of mollusk shells, has been deposited by the organic soft parts inside the shell, and as such it is of organic origin. Bones and teeth in the human body consist of a form of the mineral apatite, $Ca_5(PO_4,CO_3)_3(OH,O,F)$, which in this instance is of organic origin. Those two examples are exceptions to the statement that minerals are formed by inorganic processes. These organically formed species are normally included in any listing, or catalog, of minerals.

An example of an organic material that is definitely excluded, although commonly sold as a gem in jewelry stores, is amber. This is because amber does not fit most of the criteria outlined in the preceding mineral definition. It not only is always of organic origin but also is a hard, brittle, fossil resin that lacks an ordered atomic internal structure and has a highly variable (not fixed) chemical composition. Because it is a very attractive solid material, especially when polished, with an appealing yellow to brown color, it is sold among other gems, most of which are inorganic in origin and fit the definition of a mineral, as given already.

2.1.1 Examples of Some Familiar Minerals

At this stage, let us review a few minerals that you may have some familiarity with: halite, quartz, talc, chrysotile (one of several "asbestos" minerals), and garnet. This brief overview of the five minerals will aid in your understanding of the definition of a mineral given in the prior section.

All five minerals are naturally occurring inorganic solids. They also have regular atomic internal structures, and their composition (or range of composition) is a function of the internal structure as well as the chemical composition of the source from which each mineral crystallized.

Halite, also known as table salt, has the composition NaCl (Fig. 2.1(A)). Halite is a member of a group of minerals known as **halides** in which the anion is Cl^-, Br^-, F^-, or I^-. Halite has a simple, highly symmetric structure (see Fig. 2.1(B)) that leads to a cubic external shape (the grains in saltshakers, when observed with magnification, are all little cubic fragments, known as cleavage fragments, not little cubic crystals; Fig. 2.1(C)). Naturally occurring halite has a composition very close to NaCl, because K^+, which occurs in the mineral sylvite, KCl, with the same structure as NaCl, has an ionic radius much larger than that of Na^+. The two cations, therefore, have difficulty substituting for each other in the same structural space. Halite is extracted from sedimentary rocks known as evaporite deposits. It is also extracted from large evaporative ponds (created by the diking of shallow seas) along the coast of countries with arid, desertlike climates, through evaporation of seawater. This type of halite is produced by natural processes in a manmade system. However, it is still referred to by its mineral name.

The other four minerals in our list are all silicates. In these the $(SiO_4)^{4+}$ ionic group is the basic building block, in the form of a tetrahedron (a four-sided geometrical body), which occurs in the structure of almost all silicates (Fig. 2.2(A)). The manner in which these tetrahedra are linked to one another and to cations in the silicate structure is what creates the large variety of silicates.

Quartz, SiO_2, is familiar in many ways (Fig. 2.2(B)). It forms the rounded sand grains on beaches (Fig. 2.2(C)); it is the loose granular material used in sandboxes; and as crushed, angular grains, it is the abrasive component of many standard sandpapers. Its structure consists of a close linking of $(SiO_4)^{4-}$ tetrahedra (Fig. 2.2(D)) that is devoid of any other chemical elements. It is so consistently of constant SiO_2 composition that it is commonly referred to as a pure substance. This is in contrast to the compositional variability of many other silicates.

Quartz sand is an important component of cement in the construction industry, and it is a source of material for making silica glass. The manufacture of synthetic quartz crystals is also an important industry. Because perfect quartz crystals (*perfect* meaning "no defects" of any sort in clear quartz; i.e., no cracks, no bubbles, no inclusions of fluids or of other minerals) are difficult to obtain consistently from natural occurrences, synthetic quartz is routinely manufactured (Fig. 2.2(E)). This quartz is used for highly specialized electronic applications, such as the timing mechanism in quartz watches.

Talc, $Mg_3Si_4O_{10}(OH)_2$, is a chemically more complex mineral than quartz (Fig. 2.3(A)). This mineral, packaged and sold

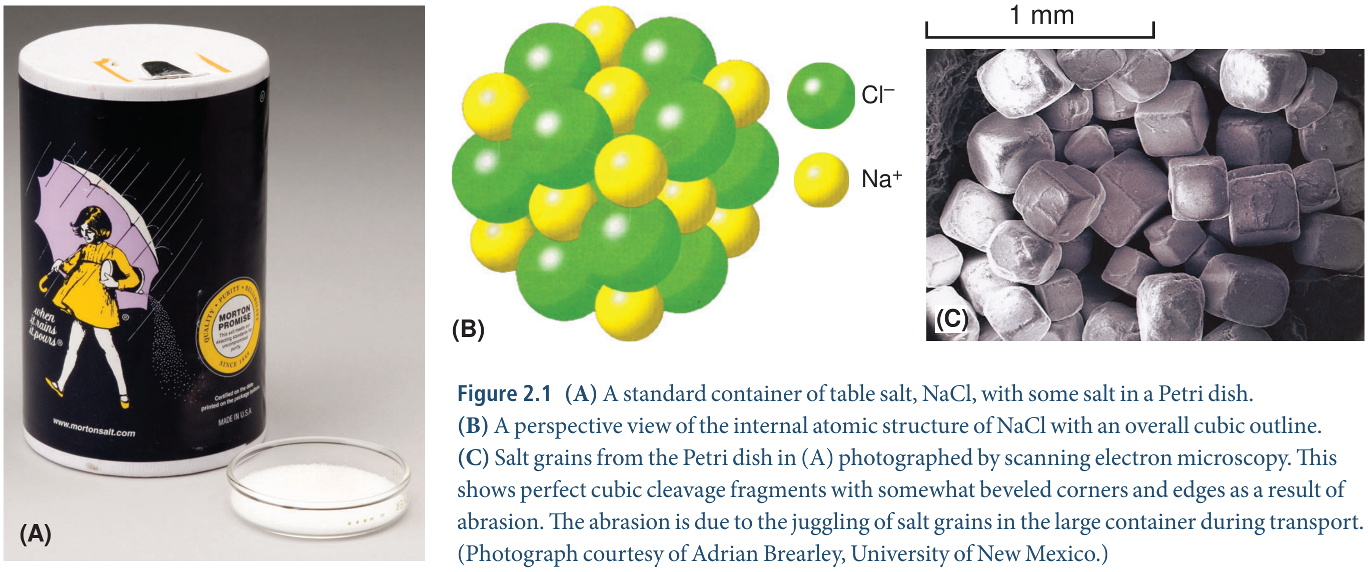


Figure 2.1 **(A)** A standard container of table salt, NaCl, with some salt in a Petri dish. **(B)** A perspective view of the internal atomic structure of NaCl with an overall cubic outline. **(C)** Salt grains from the Petri dish in (A) photographed by scanning electron microscopy. This shows perfect cubic cleavage fragments with somewhat beveled corners and edges as a result of abrasion. The abrasion is due to the juggling of salt grains in the large container during transport. (Photograph courtesy of Adrian Brearley, University of New Mexico.)

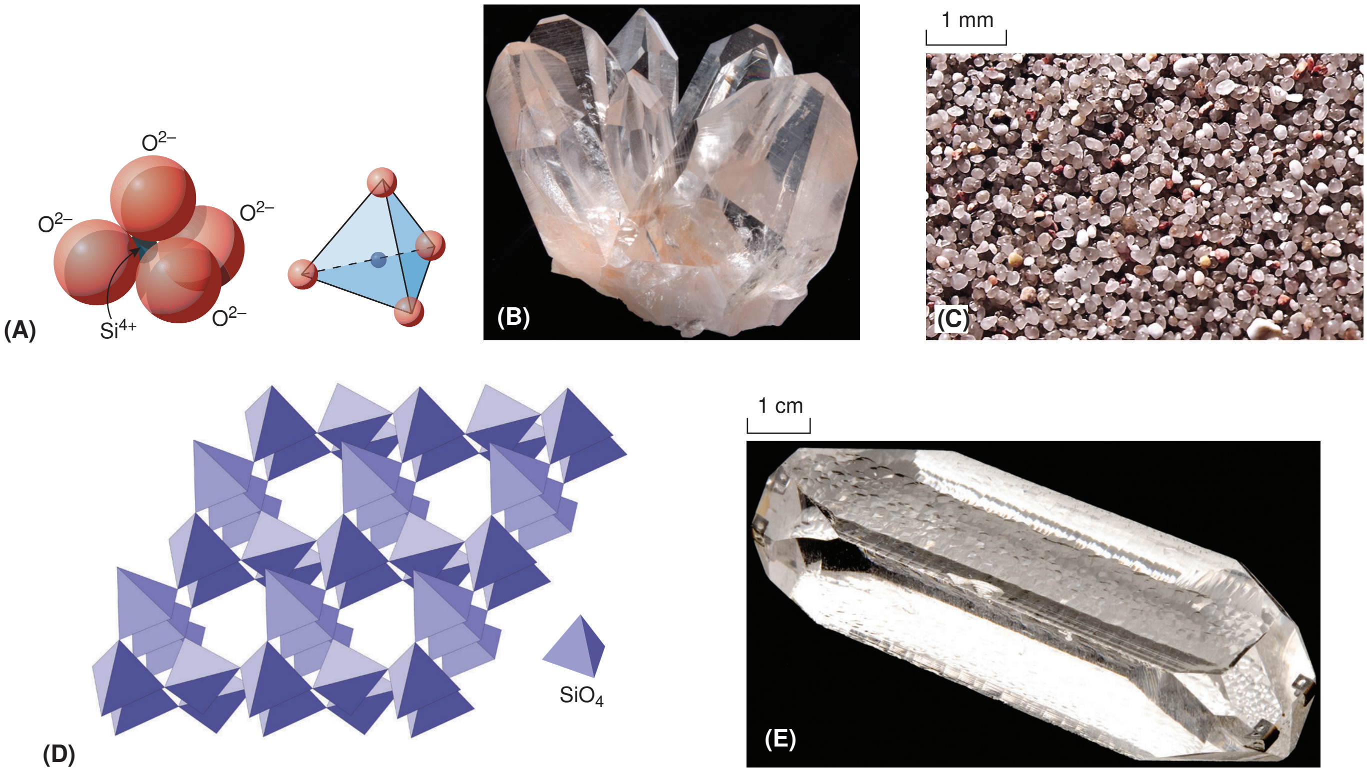
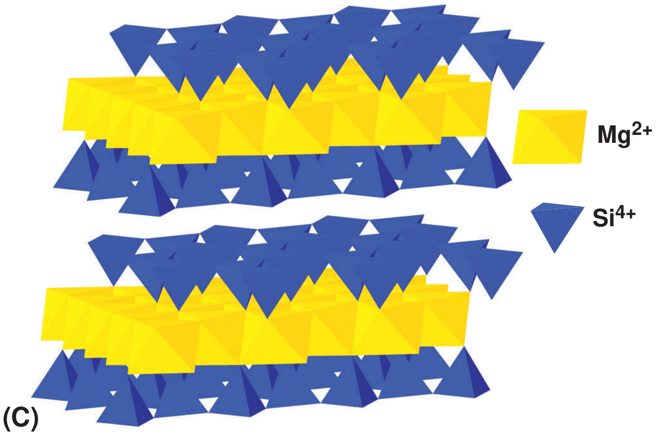


Figure 2.2 **(A)** On the left, a drawing of a central Si^{4+} ion surrounded by four O^{2-} ions; on the right, a schematic representation of the same, showing the outline of a tetrahedron (from the Greek *tetra*, meaning "four," and *hedron*, meaning "plane"), a four-sided geometric shape. **(B)** Euhedral (meaning "well formed") crystals of quartz, SiO_2. **(C)** Beach sand consisting mainly of well-rounded translucent and milky quartz grains. Several of the colored grains are quartz with colored inclusions and/or feldspar. **(D)** A perspective view of the internal, atomic structure of quartz, consisting of a network of linked $(SiO_4)^{4-}$ tetrahedra. **(E)** A synthetic crystal of quartz, which, due to the conditions of growth in high-temperature vessels in the laboratory, has a very different external shape from crystals that occur in nature (see Fig. 2.2(B)). Long dimension of crystal is 8 cm.

as talcum powder, is a material that has likely been part of your life since birth (Fig. 2.3(B)). Talc is a versatile mineral used in cosmetic products, in ceramics, in the paper industry, in vulcanizing rubber, and in paint production. The atomic structure of talc consists of sheets of $(SiO_4)^{4-}$ tetrahedra (cross-linked by Mg^{2+} ions in between), producing a flat sandwichlike arrangement (Fig. 2.3(C)). These structural layers are responsible for the thin, somewhat flexible folia that pure talc exhibits in nature. In the manufacture of cosmetic products, the original talc is ground very finely in roller mills to preserve the original platy structure of the mineral during milling (Fig. 2.3(D)). In most cosmetic products made mainly of talc, some minor other materials are added, such as coloring agents and scent. Talc has very little variation in its chemical composition; as such, the formula $Mg_3Si_4O_{10}(OH)_2$ applies to most of its occurrences.

Chrysotile, $Mg_3Si_2O_5(OH)_4$, is a mineral that you may not have heard of. Instead, you may have read articles, or seen programs on television, on the health issues associated with asbestos. The word *asbestos* is a commercial term that includes six naturally occurring minerals, of which chrysotile is by far the most common. About 95% of asbestos that was used commercially was chrysotile (Fig. 2.4(A)). The other 5% consisted of a very different structure type, known as an amphibole (with the mineral crocidolite being the most common constituent). The chrysotile structure consists of atomic layers that are coiled to form hollow tubes like a drinking straw (Fig. 2.4(B)–(D)). These flexible fibers can occur naturally as bundles, similar to yarn (Fig. 2.4(A)) and can, therefore, be woven into cloth, which was used in suits and gloves for firefighters (Fig. 2.4(E)) before it was banned in the United States. The main use of chrysotile was as insulation of the internal steel structures of skyscrapers (to protect against meltdown in case of fires) and in many building materials. It has long been shown that chrysotile is rather harmless, and it is clear that banning this material from many products has been unwise. The health controversy about asbestos is discussed in Chapter 18. The chemical composition of chrysotile is rather constant and is well represented by the formula $Mg_3Si_2O_5(OH)_4$.

Garnet is the birthstone for January and has been commonly used as a red gemstone, especially in jewelry of the Victorian Era (1837–1901). Garnet often shows up in antique and estate jewelry (Fig. 2.5(A)). This common association of the red color



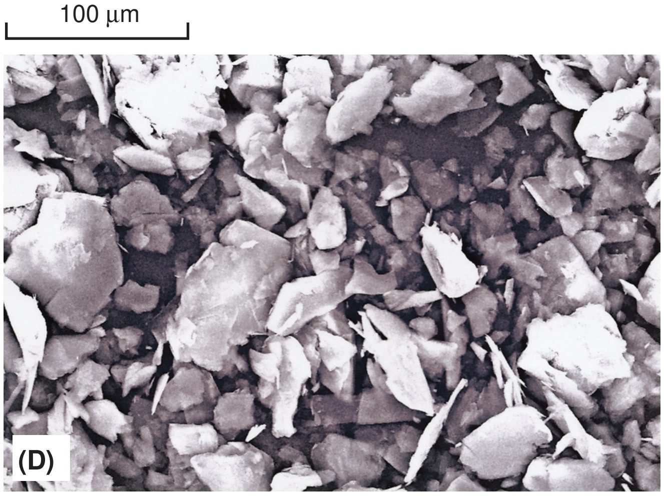


Figure 2.3 **(A)** Hand specimens of talc, $Mg_3Si_4O_{10}(OH)_2$. **(B)** Commercial containers of baby (talcum) powder and cosmetic facial powder. Two dishes, with talc and facial powder, respectively. **(C)** A perspective view of the layered internal atomic structure of talc. The Mg^{2+} ions are sandwiched between two opposing sheets of $(SiO_4)^{4-}$ tetrahedra. **(D)** Talcum powder from the Petri dish in **(B)** photographed by scanning electron microscope. This shows the somewhat variable grain size of the tiny (very soft) flakes at about 400× magnification. (Photograph courtesy of Adrian Brearley, University of New Mexico.)

in garnet jewelry gives the impression that garnet as a gem is generally of a reddish color. In reality, garnet includes a closely related group of rock-forming minerals of a wide range of colors, from pink to brown, yellow, green, orange, and black. Garnet commonly occurs in good crystal forms, one of which is known as a dodecahedron, consisting of twelve parallelogram, diamond-shaped faces (*dodeca*, from the Greek meaning "twelve"; Fig. 2.5(B)). Garnet is also familiar because it is used in a variety of abrasive applications (because of its high hardness and sharp broken edges) as in garnet paper (used in specialized applications in the finishing of leather, hard rubber, and plastics).

The internal, atomic structure of garnet is a compact and complex arrangement of independent $(SiO_4)^{4-}$ tetrahedra (Fig. 2.5(C)) bonded to cations such as Ca^{2+}, Fe^{2+}, Mn^{2+}, Mg^{2+}, as well as Al^{3+}, Fe^{3+}, or Cr^{3+}. The compactness of its structure is reflected in its density (or specific gravity), which is considerably higher than that of other silicates. As seen from the foregoing listing of ions that may occur in its structure, the chemical composition of garnet is highly variable. Six specific garnet compositions include the following:

- $Mg_3Al_2(SiO_4)$ – pyrope
- $Fe_3Al_2(SiO_4)_3$ – almandine
- $Mn_3Al_2(SiO_4)_3$ – spessartine
- $Ca_3Al_2(SiO_4)_3$ – grossular

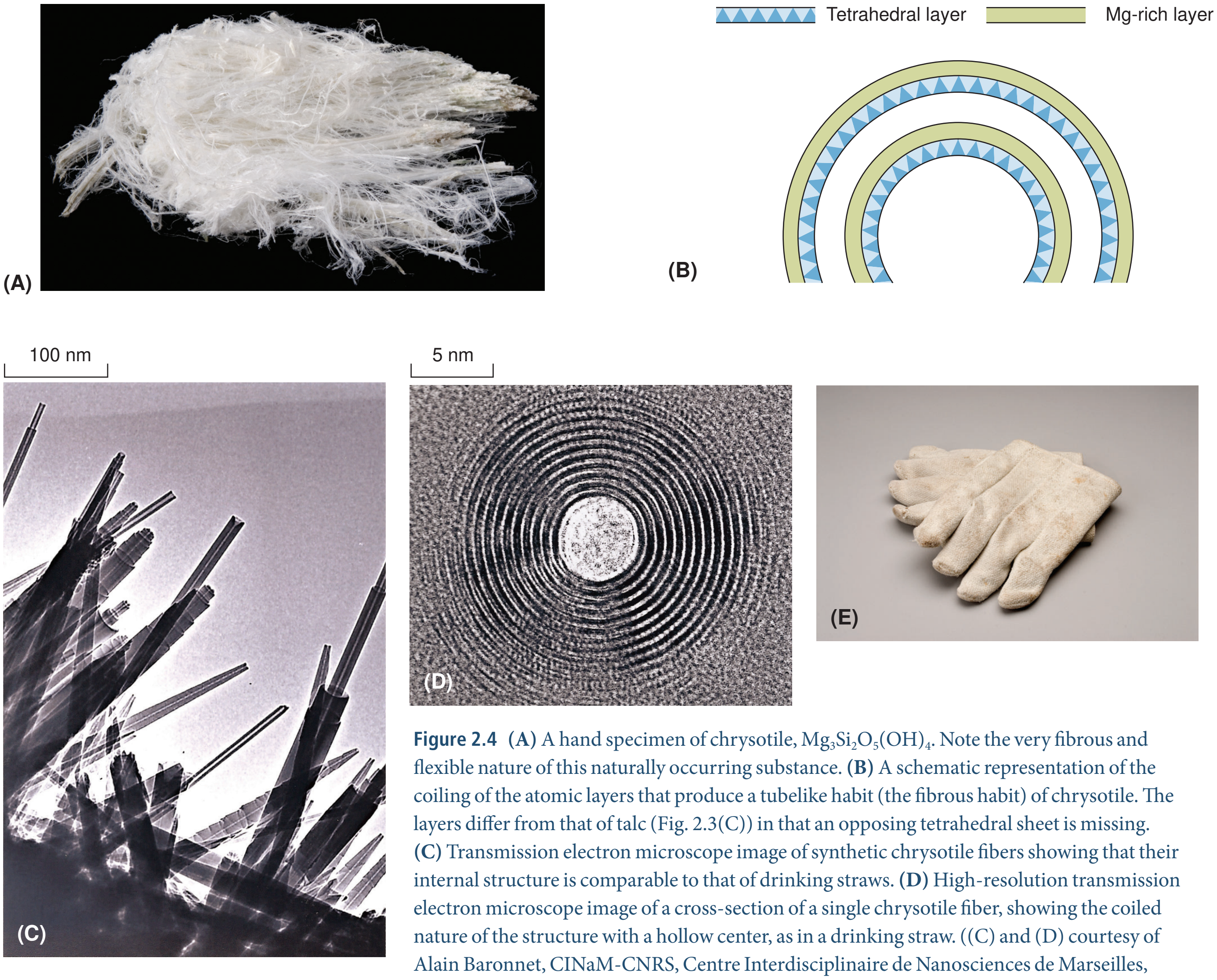


Figure 2.4 **(A)** A hand specimen of chrysotile, $Mg_3Si_2O_5(OH)_4$. Note the very fibrous and flexible nature of this naturally occurring substance. **(B)** A schematic representation of the coiling of the atomic layers that produce a tubelike habit (the fibrous habit) of chrysotile. The layers differ from that of talc (Fig. 2.3(C)) in that an opposing tetrahedral sheet is missing. **(C)** Transmission electron microscope image of synthetic chrysotile fibers showing that their internal structure is comparable to that of drinking straws. **(D)** High-resolution transmission electron microscope image of a cross-section of a single chrysotile fiber, showing the coiled nature of the structure with a hollow center, as in a drinking straw. ((C) and (D) courtesy of Alain Baronnet, CINaM-CNRS, Centre Interdisciplinaire de Nanosciences de Marseilles, France.) **(E)** Laboratory gloves, used in high-temperature experiments, woven from very flexible and strongly insulating, naturally occurring chrysotile fibers.

- $Ca_3Fe_2^{3+}(SiO_4)_3$ – andradite
- $Ca_3Cr_2(SiO_4)_3$ – uvarovite

In other words, garnets are a good example of a mineral group in which the cation-to-anion proportions are fixed, at 3:2:3, but the amounts of a specific cation, in a specific atomic (structural) site, are highly variable.

Garnets have also been synthesized in the laboratory. The reason for such synthetic production was that some garnets with very unusual compositions (that do not occur in nature) were found to be fairly good imitations of diamond. These synthetic garnets (with an internal structure identical to that of natural garnet) have extremely unusual compositions that include elements such as yttrium (to produce YAG, an abbreviation for yttrium aluminum garnet) and gadolinium and gallium (GGG, a gadolinium gallium garnet). These synthetic simulants of diamond have been surpassed in popularity since the synthesis of cubic zirconia, ZrO_2, in 1976, as an almost perfect inexpensive simulant for natural diamond, with the composition of carbon, C.

The name garnet is very dear to one of the authors, Anthony R. Philpotts, because the maiden name of his wife, Doreen, is Garnet, and they now live in Connecticut, whose state mineral is garnet.

2.2 How Are Minerals Classified?

Since the mid-nineteenth century, minerals have been systematically grouped into different chemical classes on the basis of their chemical composition. Such groupings are based on

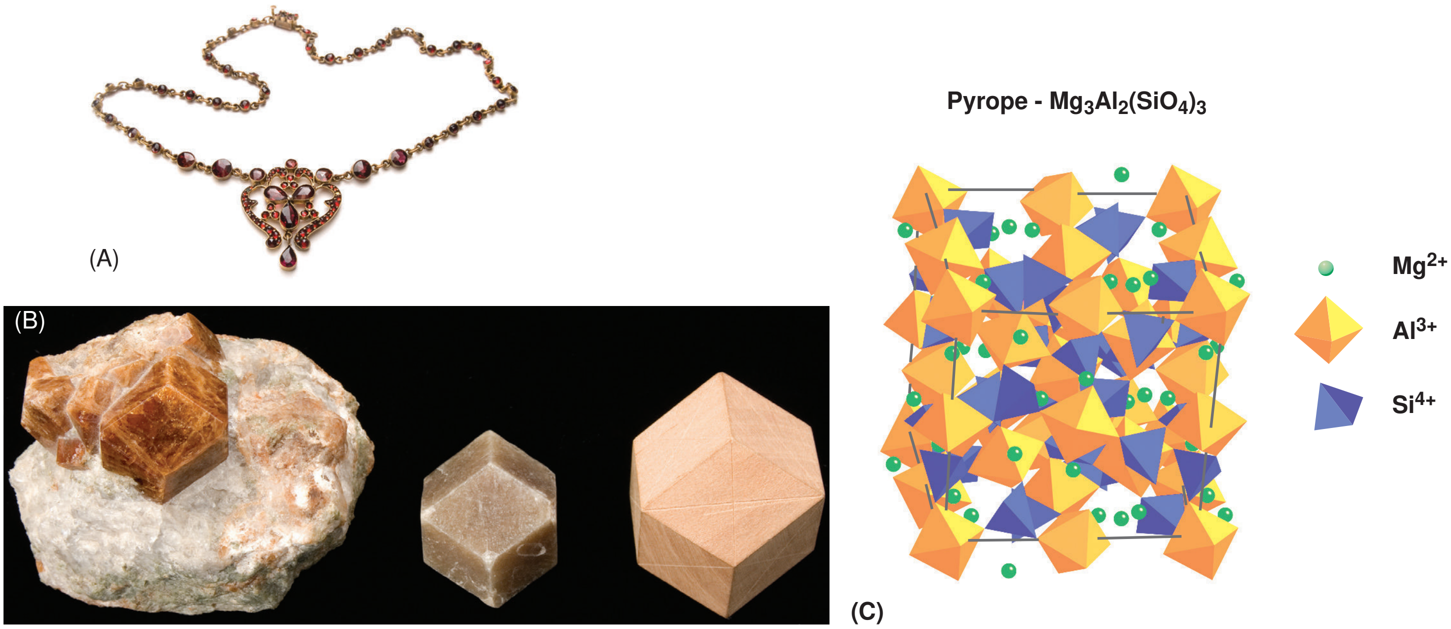


Figure 2.5 **(A)** A garnet necklace of Victorian design. This type of red garnet is referred to as Bohemian garnet in the trade. It is a red garnet of pyrope composition. (Courtesy of Ron Beauchamp, Beauchamp Jewelers, Albuquerque, NM.) **(B)** Examples of the relatively common occurrence of garnet in well-formed (euhedral) dodecahedrons. Two almost perfect crystals, as well as a small wooden model of the same dodecahedron, used in laboratory teaching of crystal forms. **(C)** A perspective view of the complex and densely packed atomic structure of a garnet of composition $Mg_3Al_2(SiO_4)_3$, known as pyrope. The overall outline of the structure is that of a cube.

the composition of the dominant anion or anion complex. For example, minerals with sulfur, S^{2-}, as an anion are grouped under sulfides; those with $(SiO_4)^{4-}$, as an anionic group, are silicates. The broadest classification subdivisions used in all mineralogical literature are based on the anionic unit in the chemical formula as indicated in the following:

• Native elements	Au, Cu, Pt
• Sulfides	ZnS, FeS_2, $CuFeS_2$
• Sulfosalts	Cu_3AsS_4, $Cu_{12}Sb_4S_{13}$
• Oxides	Al_2O_3, Fe_3O_4, TiO_2
• Hydroxides	$Mg(OH)_2$, FeO(OH)
• Halides	NaCl, KCl, CaF_2
• Carbonates	$CaCO_3$, $CaMg(CO_3)_2$
• Phosphates	$Ca_5(PO_4)_3$(F,Cl,OH)
• Sulfates	$CaSO_4{\cdot}2\,H_2O$
• Tungstates	$CaWO_4$
• Silicates	Mg_2SiO_4, Al_2SiO_5

Approximately 4150 minerals are known, of which 1140 are silicates; 624, sulfides and sulfosalts; 458, phosphates; 411, oxides and hydroxides; 234, carbonates; and 90, native elements.[1]

In this text, we provide systematic descriptions of 87 minerals and briefly mention a few more in Section 16.18, which deals with gem minerals. Most of these are silicates. The remaining minerals are members of the carbonate, oxide, hydroxide, phosphate, sulfide, and native element classes. The reason for this small number is that these 87 represent the most common minerals that enter into the composition of the most abundant rock types. This small number of minerals is, therefore, referred to as the **rock-forming minerals**. Combinations of these minerals reflect the composition of the most common rock types, and they are the basis for rock classifications.

2.3 How Are Minerals Named?

The naming of minerals is an interesting but not a scientific process. Many common mineral names date from times when there were essentially no scientific tools to classify, define, or describe a mineral quantitatively.

The name *quartz* is of obscure origin but dates back to the Middle Ages, when it was first applied to describe waste material produced during mining (such waste is now referred to as gangue). The name *feldspar* is derived from the word *feldtspat*, given in 1740 to the presence of spar (spath) in tilled fields overlying granite bedrock in Sweden. The name *garnet* is very likely derived from the Latin *granatum*, for "pomegranate," because of its similarity in color to that of the fruit pulp. Since

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[1] These data were provided by J. A. Mandarino, Toronto, Ontario, Canada in March 2006. A complete listing of all chemical classes is given in Klein and Dutrow, 2008, p. 333.

these early days, when quartz, feldspar, garnet, and other common mineral names were chosen, the process by which a new mineral species must be uniquely defined has become a very demanding, quantitative scientific process, but the naming of a new mineral is still left to the investigator who discovered the new mineral species.

In the twentieth century, there has always been a clear set of regulations that mineralogists have had to follow in the characterization of a newly discovered mineral. Since 1959, the Commission on New Minerals and New Mineral Names of the International Mineralogical Association (IMA) has been internationally recognized for the purpose of controlling the introduction of new minerals and new mineral names and of rationalizing mineral nomenclature. This commission maintains a Web site (http://pubsites.uws.edu.au/ima-cnmnc/). The abbreviation CNMNC stands for its new name: Commission on New Minerals, Nomenclature, and Classification. If an investigator thinks that he or she has discovered a new mineral, a scientifically complete report on all aspects of the new mineral's chemical and physical properties must be submitted for review to the commission. An international committee of mineralogists reviews the report.

The naming of the mineral by the original investigator is by far the easiest and most fun part. Minerals can be named after the original locality of the find (e.g., aragonite, $CaCO_3$, – with an internal structure that is distinctly different from that of calcite, also $CaCO_3$ – after a locality in the Aragon region of Spain); after some major chemical constituent (as in molybdenite, MoS_2, because molybdenum is the only cation in the structure); after all of the cations, K^+, Al^{3+}, and Si^{4+}, in a mineral (as in kalsilite, $KAlSiO_4$); or after a famous personality (as in sillimanite, Al_2SiO_5, after Benjamin Silliman, 1779–1864, professor of chemistry and mineralogy at Yale University). If you are so lucky as to discover a new mineral, the choice of the name is pretty much up to you.

2.4 What Is a Crystal, and What Is the Crystalline State?

The majority of minerals occur as relatively small, irregular grains in an interlocking pattern with other minerals as the constituents of various rock types. These grains are generally less than 1 cm in diameter and are irregular in shape. So, where do the beautifully shaped large crystals come from that are commonly exhibited in natural history museums and high-quality rock shops (Fig. 2.6)? These have most commonly been carefully extracted (mined) from unique geologic occurrences known as **veins** (most desirable with open spaces known as **vugs**) and as **pegmatites**.

Veins are lenticular or tabular bodies, commonly with some coarse-grained minerals, which may cut across the structure seen in the bedrock. Veins are mostly the result of mineral deposition in free spaces in a fracture (fissure) that either was opened or was gradually opening during the period of mineralization. Open spaces (or vugs) are commonly the sites from which prospectors and mineral collectors retrieve beautifully crystallized mineral specimens, with large crystals that grew in these open spaces (Fig. 2.7). Pegmatites are exceptionally coarse-grained igneous rocks, usually found as irregular dikes, lenses, or veins. In general, their mineral grain size is well over 1 cm in diameter (see Fig. 9.15). All three – veins, vugs, and pegmatites – are the main source of well-formed large crystals.

What is a crystal? A **crystal** can be defined as a mineral, or other crystalline chemical compound (a solid with a specific chemical composition), with an external shape bounded by smooth plane surfaces (Fig. 2.8). Such a crystal shape is the outward expression of its ordered internal, atomic arrangement. Crystals can be described as perfect, good, or malformed, depending on how well the external shape reflects the overall symmetry inherent in the internal atomic arrangement. Perfect crystals or crystal groupings are what museum curators collect for mineral exhibits open to the public.

Three other terms that are commonly applied to crystals to describe the perfection (or lack thereof) of their external shape are **euhedral**, **subhedral**, and **anhedral**.

Euhedral, interchangeable with *perfect*, describes a crystal with excellent crystal shape (*eu*, from the Greek, meaning "good," and *hedron*, meaning "plane").

Subhedral describes mineral grains (and crystals) that are partly bounded by good crystal faces, as well as faces that may have been crowded by adjacent mineral grains (*sub*, from the Latin, meaning "less than").

Anhedral is applied to mineral grains that lack well-formed crystal faces as a result of having grown against adjacent minerals during their crystallization (*an*, from the Greek, meaning "without"). The majority of mineral grains that compose various rock types are anhedral to subhedral because such grains were generally in contact with neighboring grains (without open spaces) during their growth.

The term **crystalline** is applicable to all solid materials that exhibit an internal, ordered arrangement of the constituent atoms (or ions) forming a repetitive three-dimensional pattern. This crystalline state may be expressed in esthetically pleasing large, euhedral crystals (Fig. 2.8). Most rock-forming minerals that are part of various rock types occur as anhedral to subhedral grains, lacking any outwardly observable symmetry that might reflect their internal structure. Even these anhedral grains, however, have internal ordered atomic structures with specific chemical compositions that reflect their temperature or pressure of formation. In other words, all minerals (not just well-formed crystals) are part of the crystalline state. The

Figure 2.6 A hand specimen of beautifully crystallized green microcline feldspar (known as amazonite) and smoky quartz crystals. The crystals in this museum-quality specimen grew freely in an open space (a vug) without interference from adjoining minerals.

crystallinity of small-grained, anhedral minerals can be proved by optical techniques, by X-ray diffraction methods, electron beam methods, and others (see Chapter 3). Minerals (and other materials) that lack the ordered internal arrangement are referred to as amorphous.

2.5 What Is a Rock?

A rock is simply a naturally occurring consolidated mixture of minerals. In rare cases it may include amorphous material such as volcanic glass or coal, which do not fit the definition of a mineral. It is the solid material that makes up the Earth. We saw in Chapter 1 that the Earth's composition reflects the abundance of elements formed in a supernova and later modified by accretionary process during formation of the solar system. We have also seen that a mineral has a restricted compositional range. It is unlikely, therefore, that in any given part of the Earth, this bulk composition can be incorporated into a single mineral. Instead, a number of minerals must form to accommodate all of the elements present, and this mixture is a rock.

What do we mean when we say that rock is consolidated? In general, rocks are harder, and in many cases, much harder, than the soils that blanket the Earth's surface. Where highways cut through rock, drilling and blasting are often required to remove the material. Some rocks are quite soft but are still more competent than loose surficial materials. It is the strength of rocks that allows high mountain ranges to stand tall or quarry walls or road cuts to stand at steep angles (Fig. 2.9).

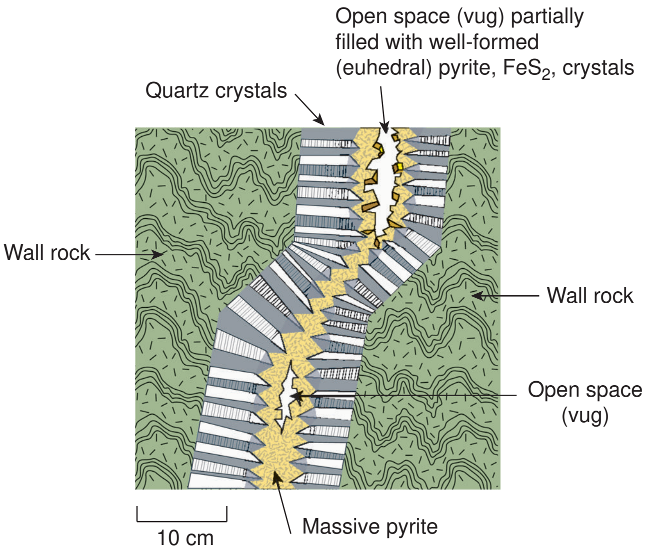


Figure 2.7 A schematic cross-section of a vein that is the result of open space filling. Well-formed quartz crystals grew perpendicular to the walls of the host rock. Some open spaces (vugs) still remain. One is empty, and the other is partially filled with well-formed cubic crystals of pyrite.

A rock's strength is determined by the way the individual mineral grains are intergrown with one another and the strength of the individual minerals. For example, the grains of quartz in Figure 6.14(A) have sutured boundaries, so they fit together like the pieces in a jigsaw puzzle. The rock shown in Figure 6.5, from the Giant's Causeway, in Northern Ireland, consists of an interlocking network of feldspar and pyroxene crystals. Because of the even distribution and random orientation of the crystals, this rock has no planes of weakness and, as a result, is one of the toughest rocks known. Quarrying of this rock type, which is popularly known as **trap rock** (from the Dutch word *trap*, meaning "stairs," which often describes the topography on these bodies of rock) is a major worldwide industry because, when crushed, the rock forms the most durable aggregate to mix with asphalt for paving roads (Fig. 2.9).

The way in which individual mineral grains are intergrown in a rock is referred to as **texture** (Fig. 2.10(A)). Larger-scale features, which commonly reflect uneven distributions of minerals such as compositional layering, are referred to as **structure** (Fig. 2.10(B)). Textures and structures develop when rocks are formed, and hence they reveal much about their origin. The texture and structure of rocks, along with

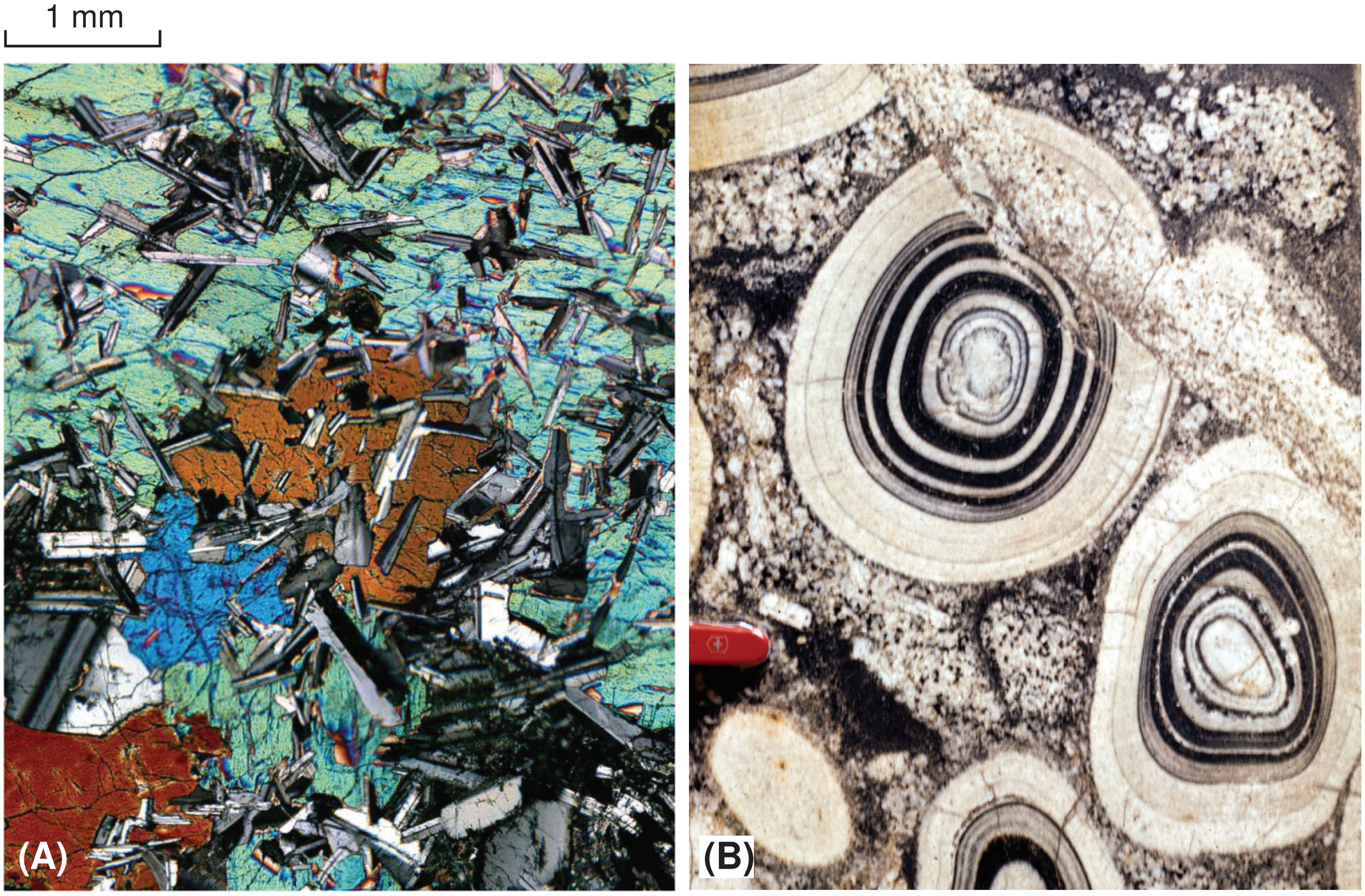
Figure 2.8 Examples of some very well-formed (euhedral) crystals. From left to right: a milky, translucent crystal of gypsum; a red crystal of tourmaline; a transparent, light blue crystal of aquamarine (a gem variety of the mineral beryl); and a red crystal of ruby (a gem variety of the mineral corundum).

their composition and absolute age, preserve the record from which Earth's history is revealed. Being able to correctly read the textures and structures in rocks is, therefore, of paramount importance. We discuss here only a few of the most important points about rocks and how they are formed.

Figure 2.9 The active north face of Tilcon's North Branford quarry, Connecticut, where a thick basaltic lava flow is quarried for its extremely durable rock that is used as aggregate and mixed with asphalt to pave roads. This quarry produces 20 000 tons of crushed trap-rock aggregate per day.

2.6 How Do Rocks Form? Classification into Igneous, Sedimentary, and Metamorphic

Although the solid Earth is made of rocks and rocks are found everywhere, the formation of a rock is a rare event. In all likelihood, if you look at a geological map of the region where you live, you will find rocks that formed a long time ago, and there may have been only a couple of times in all of Earth's history that rocks were formed in your region. Rock formation is a rare occurrence because the conditions required for their formation occur only in a few places on Earth at any given time.



Texture

Structure

Figure 2.10 **(A)** *Texture* refers to the way individual mineral grains are intergrown. It is seen best in thin sections of the rock under a polarizing microscope, as seen here in this photomicrograph of a basaltic rock from the Bird River Sill, South Africa. This texture is described as ophitic, meaning that small plagioclase feldspar crystals (gray) are completely embedded in larger crystals of pyroxene (brightly colored grains). Photograph taken under crossed polarized light (see Chapter 6 for explanation of polarized light). **(B)** *Structure* refers to larger-scale features that are commonly evident at the hand specimen or outcrop scale. This sample of granite from Kangasala, Finland, exhibits an orbicular structure, where concentrations of light and dark minerals form concentric rhythmic layers around a central inclusion. Swiss army knife for scale.

Many rocks form in response to the Earth's continuous attempt to cool down from its fiery beginning. We saw in Chapter 1 that early in Earth's history the planet was almost totally molten. Its surface would have been covered by molten rock, a **magma ocean**. Since then, enormous amounts of heat have been lost into space, and almost all of the Earth's crust and mantle have solidified. The cooling still causes the solid mantle to convect, which in turn moves lithospheric plates across the surface of the planet. This plate motion sets up conditions necessary for the formation of rocks.

Throughout Earth's history, the largest production of rocks has involved the partial melting of the mantle, followed by the buoyant rise of the melt into the crust, and the eventual solidification of the melt. Molten rock is known as **magma**, and rocks that form from the solidification of magma are known as **igneous rocks**. Most of the crust is made of rocks that were initially igneous. The formation of igneous rocks transfers heat from within the Earth to near the surface, where it can be more easily released into space.

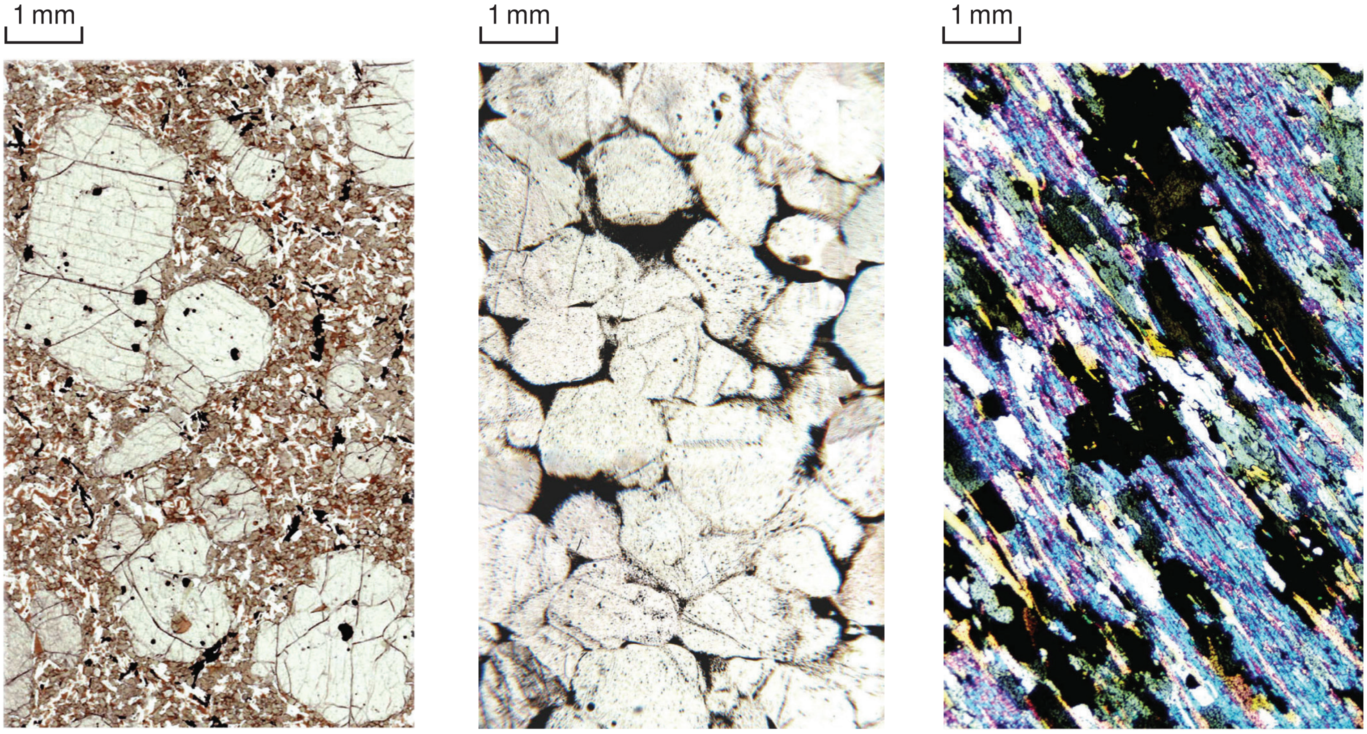
Although igneous rocks are the most abundant rocks in the crust as a whole, most shallow crustal rocks are formed from the consolidation of sediment and are known as **sedimentary rocks**. Energy from the sun drives the hydrologic cycle, which causes weathering and transport of sediment. A sedimentary rock forms if this sediment finds a basin in which to accumulate. Most sediment accumulates in the sea, but some can be trapped in continental basins that develop in response to plate tectonics.

Tectonic plates continuously move across the surface of the Earth at rates of centimeters per year. When rocks, whether of igneous or sedimentary origin, find themselves in new environments where pressures and temperatures are different from where they formed, minerals change to equilibrate with their new environment, and a new rock is formed. Rocks that are formed in response to changes in environmental factors, such as pressure, temperature, or fluid composition, are described as **metamorphic rocks**. Most of the reactions involved in metamorphism consume heat and, therefore, help cool the Earth. Although we began by saying that most rocks in the crust are of igneous origin, many of these have subsequently been metamorphosed and, along with metamorphosed sedimentary rocks, constitute ~60% of the crust.

Distinguishing between igneous, sedimentary, and metamorphic rocks is usually simple at both the outcrop and microscopic scales. Most igneous rocks form relatively homogeneous massive bodies, which if crystallized in the crust may be relatively coarse grained. If the magma erupts onto the surface, the grain size is much finer, but the rock forms characteristic volcanic structures. Most sedimentary rocks are layered, with the layering generally paralleling the surface on which deposition occurs; this is usually close to horizontal, especially when the sediment is fine grained. Metamorphic rocks have textures that indicate recrystallization of minerals. If only heating is involved, the recrystallized grains form equidimensional polyhedra. If directed pressures are involved, as would occur, for example, at convergent plate boundaries, the metamorphic rocks commonly produce a prominent **foliation**, such as that found in **slate**, which is used for roofing tiles.

Under the microscope, the three types of rock are usually easily distinguished. Igneous rocks typically consist of minerals that show a sequence of crystallization. The earliest crystallizing minerals tend to be well formed (euhedral), and because they start growing first, they tend to be larger than other crystals in the rock. These early formed crystals are known as **phenocrysts**. They are surrounded by other later crystallizing minerals that form a **groundmass** (Fig. 2.11(A)). In contrast, the grains of many sedimentary rocks show evidence of transport and rounding through abrasion (compare Figs. 2.2(C) and 2.11(B)). These grains are the most resistant minerals to abrasion, with quartz being by far the most common. The sedimentary grains are commonly cemented together by quartz or a carbonate mineral. Transport also tends to separate grains on the basis of size and density. As a result, most sedimentary rocks are layered, with material in individual layers sharing similar transport properties. The largest volumes of metamorphic rock are formed near convergent plate boundaries, where subducting slabs are raised to such high pressures that they release fluids that rise into the overriding slab, where they promote metamorphism. Because these rocks develop on a regional scale, they are described as regional metamorphic rocks. This is in contrast to metamorphic rocks developed on a local scale near igneous intrusions where heat and fluids escaping from the cooling body produce contact metamorphic rocks. Regional metamorphic rocks formed near convergent plate boundaries undergo recrystallization in a directed stress field, which causes elongate and platy minerals to align perpendicular to the maximum compressive stress. Regionally metamorphosed rocks are, therefore, typically foliated (Fig. 2.11(C)), in contrast to contact metamorphic rocks, which typically exhibit no foliation whatsoever (Fig. 2.12).

All three major rock types are illustrated in the sample shown in Figure 2.12 from Montreal, Quebec. The main rock type in this sample is a sedimentary rock formed by the accumulation of calcium carbonate ($CaCO_3$) mud near the shore of North America during the Ordovician Period (450 Ma). Because it is composed of calcium carbonate, it is called a **limestone** (lime being CaO). It is dark gray because it contains hydrocarbons, which were formed from the remains of animal and plant matter that accumulated with the mud. During the Cretaceous Period (110 Ma), magma from the Earth's mantle intruded this gray limestone along numerous fractures to form small black **dikes**. As the magma cooled and



(A) Igneous (B) Sedimentary (C) Metamorphic

Figure 2.11 Typical igneous, sedimentary, and metamorphic rocks as seen in photomicrographs of thin sections under low magnification. **(A)** Basalt from the 1959, Kilauea Iki, Hawaii, lava lake, containing phenocrysts of olivine (clear) in a groundmass of brown pyroxene and opaque ilmenite. The olivine phenocrysts have inclusions of a still earlier opaque chromium-rich spinel. Plane polarized light. **(B)** Photomicrograph of a thin section of sandstone showing subrounded grains of quartz surrounded by dark clay particles and quartz cement. Plane polarized light. **(C)** When Avalon and North America collided to form the Appalachian Mountains in southern New England, metamorphism of muddy sedimentary rocks resulted in the growth of mica crystals (bright blue and red) that were preferentially oriented perpendicular to the maximum compressive stress. The result was a strongly foliated rock that we call schist. Crossed polarized light.

crystallized to form the black basaltic igneous rock, the liberated heat expelled the hydrocarbons from the limestone, converting it to a white contact metamorphic rock called **marble**. The relation between the three main rock types in this sample leads to a clear relative chronology; that is, the limestone is the oldest rock because it was intruded by the basalt, and the metamorphism is clearly a consequence of the intrusion of the basaltic magma. Although not evident in the photograph, the limestone contains fossils that are indicative of the Ordovician Period, and the igneous rock has been dated as Cretaceous by absolute methods based on the radioactive decay of uranium to lead. In this way, we piece together Earth's history from the record preserved in rocks.

2.7 Examples of Some Familiar Rocks

Most people are familiar with a number of common rocks and their uses. The most familiar rocks are those used for building materials, but rocks have many other important uses in everyday life, such as supplying us with a variety of raw materials, including fossil fuels, or acting as reservoirs for water and oil. In this section, we consider just a few familiar rock types.

Perhaps the most familiar rock of all is **granite**. It has been used as a building stone since Egyptian times, and, because of its great durability, it has been popular for tombstones and other memorial structures. Even today when large buildings are made of steel and reinforced concrete, granite is still used as a decorative facing stone. One of the most common of these stones is **rapakivi granite**, which is shipped from southern Finland all over the world. It has a characteristic appearance with large round phenocrysts of pink alkali feldspar surrounded by narrow rims of greenish-gray plagioclase feldspar in a ground-mass of pink alkali feldspar and quartz (Fig. 2.13). In the polished stone business, the word *granite* has come to mean any hard homogeneous igneous rock and includes rocks that are very different in composition from granite. In geological usage, granite refers to a coarse-grained igneous rock composed of approximately two-thirds alkali feldspar and one-third quartz. The continental crust has a composition very similar to granite. Most large bodies of granite have formed by melting of the lower crust.

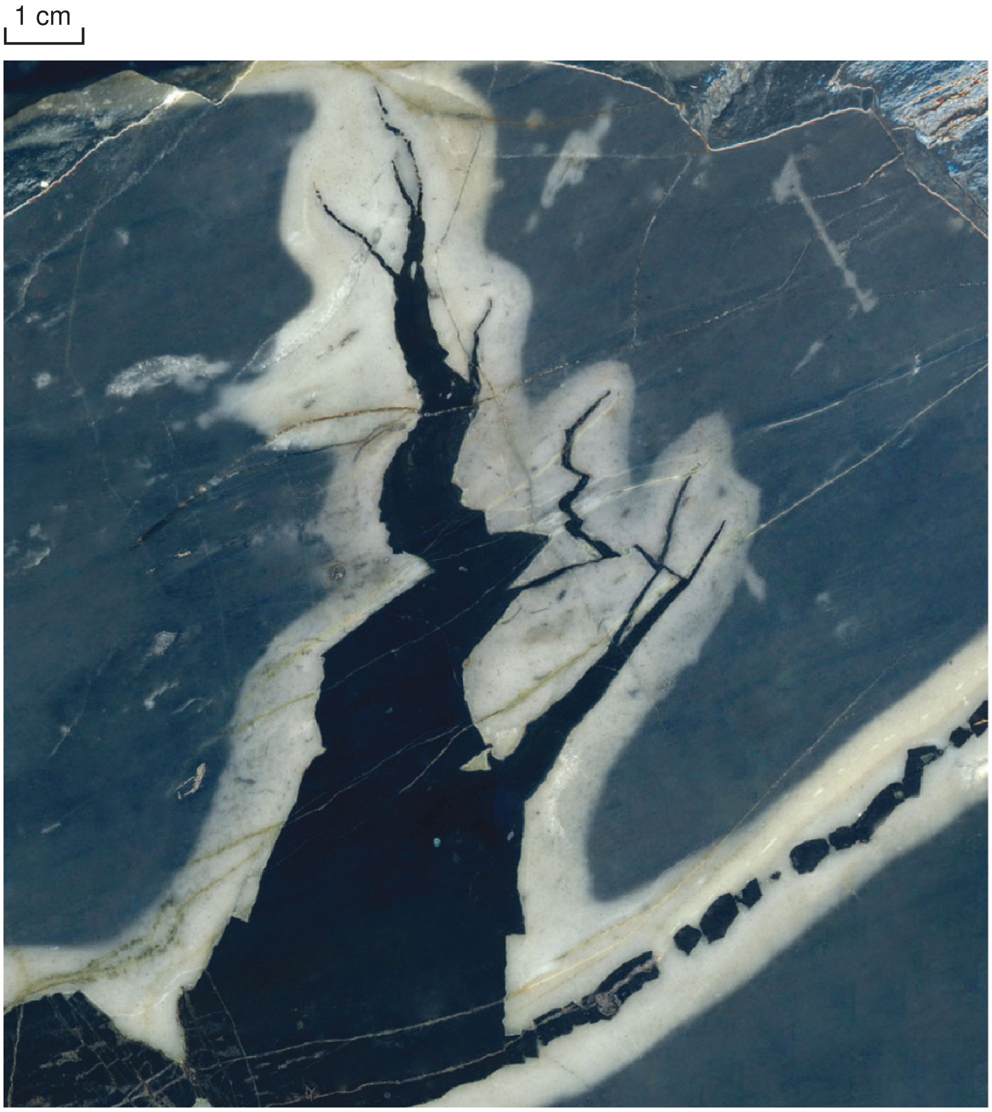


Figure 2.12 Sedimentary, igneous, and metamorphic rocks from Montreal, Quebec. The gray rock is Ordovician limestone, formed from the accumulation of calcium carbonate mud on the ancient continental shelf of North America. In the Cretaceous Period, this rock was intruded by hot mantle-derived basaltic magma, which solidified to form black igneous rock. Heat from the intrusion drove hydrocarbons out of the limestone at the contacts with the igneous rock to produce a white metamorphic rock, marble.

Figure 2.13 Rapakivi granite is one of the most common decorative building stones. It is shipped from quarries in southern Finland all over the world. Its characteristic texture is created by large rounded pink crystals of alkali feldspar rimmed by grayish-green plagioclase feldspar.

Although granite may be the most familiar igneous rock, by far the most abundant rock on the surface of the planet is the volcanic rock known as **basalt**. Most of the ocean floors and large parts of continents are underlain by basaltic lava flows. Because the lava cools quickly under water and on land, the rock is fine grained, and because it contains ~50% iron-bearing minerals, it is a dark color (see Sec. 3.3), in contrast to the light color of granite, which contains only small amounts of iron-bearing minerals. We see basalt erupted from volcanoes such as those in Hawaii (Fig. 2.14), but the largest volumes of basalt, especially those on the ocean floor, have erupted from long fissures rather than central vents. Although basalt may not be as familiar a rock as granite, the chances are that you come in contact with it far more than any other rock type. Worldwide, basalt is the preferred rock for aggregate to be mixed with asphalt for paving roads (see trap-rock quarry, Fig. 2.9). It is by far the most durable rock for this purpose and is always used as long as a source is not too distant to make transportation costs

Figure 2.14 Basaltic lava erupting from Pu‘u ‘Ō‘ō in the east rift zone of Kilauea on the Big Island of Hawaii in March 2004. **(A)** Aerial view of the summit crater with steam rising from several small active vents. The crater rim was breached in the foreground and lava poured down the slope to produce the patchy light and dark colored rock. Once a crust had formed the lava continued to flow beneath the surface and extrude on the lower slopes of the volcano. **(B)** Molten lava that has traveled from the summit of Pu‘u ‘O‘o, which is seen in the background, extrudes from beneath the bulbous crust of the flow. By traveling beneath a surface crust, lava retains its heat and is able to flow greater distances.

Figure 2.15 **(A)** Rainwater percolating through fractures in limestone causes solution and the development of karst topography. In this scene from the Cirque de Mourèze, Languedoc-Roussillon, France, pillars of dolomitic ($CaMg(CO_3)_2$) limestone have been left standing between the joints along which solution occurred. **(B)** Beneath the surface, solution of limestone forms caves. At times when the water becomes supersaturated with calcium carbonate, calcite is precipitated to form stalactites, where water drips from the roof, and stalagmites, where drips land on the floor of the cave. Large open channels, such as the one seen here in Harrison's Cave, Barbados, make many limestones important aquifers.

prohibitive. It is also a dense rock, and hence the aggregate is commonly used for railway beds and to stabilize freshly excavated slopes along, for example, highway cuts through surficial material that may be prone to slump.

A number of sedimentary rocks play important roles in modern life. Limestone is perhaps the most familiar sedimentary rock. Massive varieties have long been a popular building stone, because it is soft and easily quarried, yet is remarkably strong. Unlike most other rocks, limestone slowly dissolves in rainwater – only rock salt is more soluble. When limestone is exposed to weathering, it rapidly develops solution features, which characterize what is known as **karst** topography (Fig. 2.15(A)). Beneath the surface, solution leads to the development of caves (Fig. 2.15(B)). Solution plays an important role in converting beds of limestone into important aquifers and reservoirs for oil. For example, the Cretaceous Edwards limestone in Texas was exposed to a period of weathering shortly after its deposition and developed extensive solution channels. The limestone was later covered by clay, which was formed from the weathering of volcanic ash. The clay was subsequently converted into an impervious rock known as **shale**. The shale now caps and confines the water in the Edwards limestone, making it one of the world's largest aquifers, supplying water to more than 2 million people in south-central Texas. Caves, with their stalactites and stalagmites (Fig. 2.15(B)), attest to how easily $CaCO_3$ can be moved around by solutions. In some regions

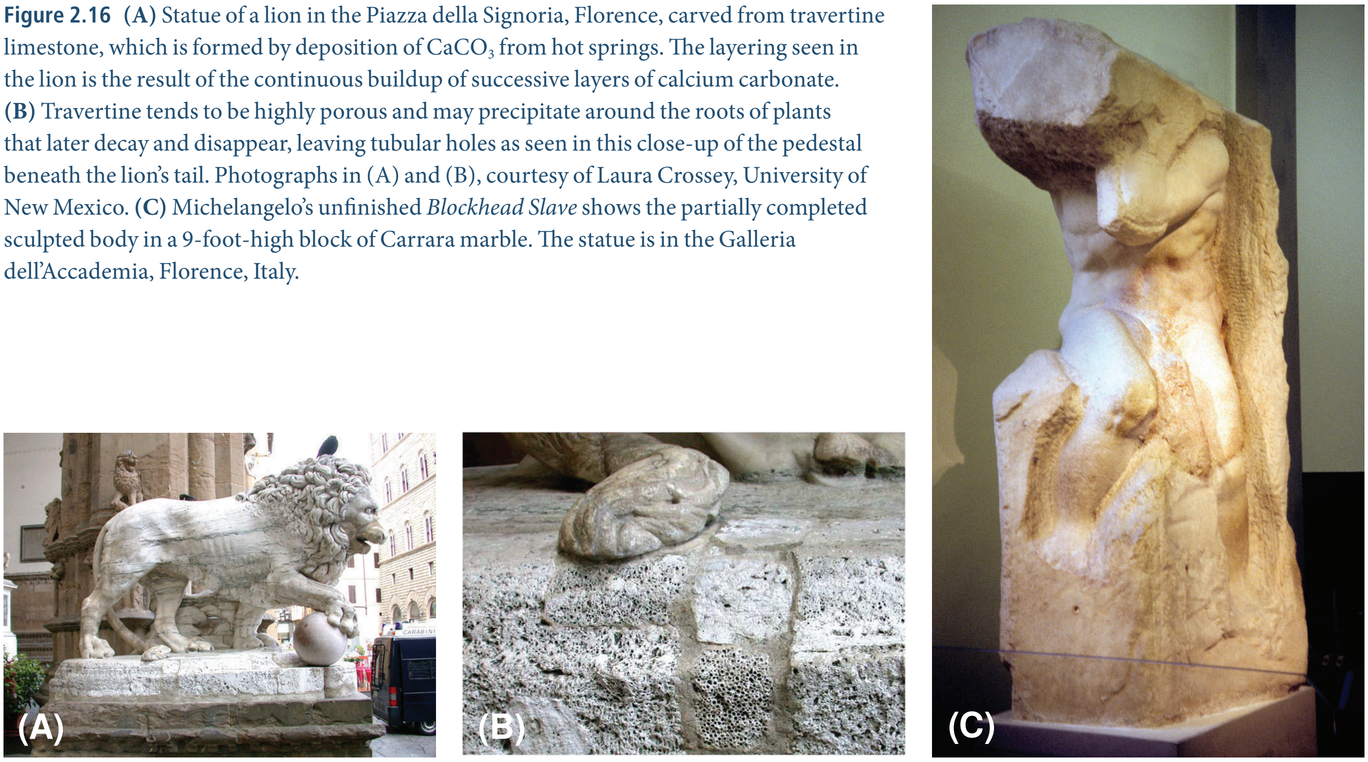


Figure 2.16 **(A)** Statue of a lion in the Piazza della Signoria, Florence, carved from travertine limestone, which is formed by deposition of $CaCO_3$ from hot springs. The layering seen in the lion is the result of the continuous buildup of successive layers of calcium carbonate. **(B)** Travertine tends to be highly porous and may precipitate around the roots of plants that later decay and disappear, leaving tubular holes as seen in this close-up of the pedestal beneath the lion's tail. Photographs in (A) and (B), courtesy of Laura Crossey, University of New Mexico. **(C)** Michelangelo's unfinished *Blockhead Slave* shows the partially completed sculpted body in a 9-foot-high block of Carrara marble. The statue is in the Galleria dell'Accademia, Florence, Italy.

where there is a source of heat, large convecting groundwater systems can be set up, and when the hot water comes out on the surface, it forms a geyser. If the circulating water passes through carbonate-bearing rocks, it is typically supersaturated in $CaCO_3$ when it pours out on the surface and cools. The result is precipitation of layers of calcite to form a rock known as **travertine**. Travertine is commonly rather porous and, being made of the soft mineral calcite, is easily cut into blocks for building purposes or flooring tiles. It has also been used for statues, as seen in the example of the lion in Figure 2.16(A). Limestone is also the raw material from which cement is made. Cement, in turn, is mixed with sand and gravel in roughly 30:70 proportions to form concrete. Today, the construction industry uses, worldwide, a staggering 8 billion tons of concrete per year; that is, more than 1 ton of concrete for every person on the planet each year. This enormous production is accompanied by the release of carbon dioxide into the atmosphere, which is of concern because of its greenhouse effect on the climate. **Sandstone** is another familiar sedimentary rock. Most sandstone is composed of quartz (Fig. 2.11(B)), a mineral that is almost chemically inert. Sandstone is, therefore, a very resistant rock, commonly forming prominent cliffs (Fig. 2.17) and providing a source of building stone. When the grains of quartz in sandstone are not completely cemented, the rock can have a high porosity, which makes it a good aquifer or reservoir rock for oil. Another important sedimentary rock is **coal**, one of the main sources of fossil fuel. Coal beds occur in sequences of sedimentary rocks that were formed when the vegetation in

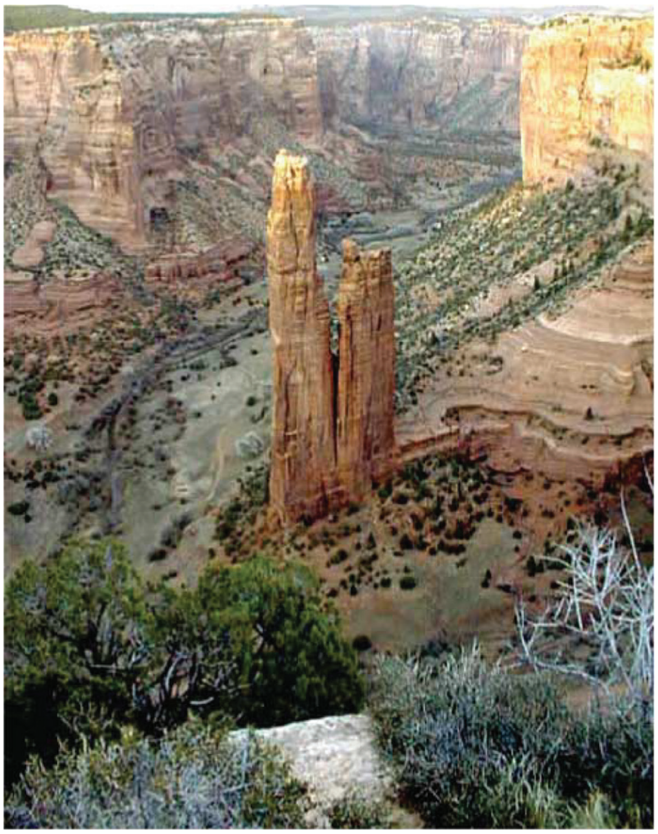


Figure 2.17 Spider rock, in Canyon de Chelly (pronounced "Shay"), Arizona, consists of hard cross-bedded sandstone that was formed from sand dunes that drifted across a desert on the western side of the Pangaea supercontinent during the Permian.

coastal swamps and deltas was buried beneath layers of sand and pebbles to form a rock sequence consisting of coal, sandstone, and **conglomerate**, respectively (Fig. 2.18).

One of the most common metamorphic rocks is **slate**, which is a fine-grained rock that can be split into extremely thin but large sheets. It is composed largely of small crystals of mica, whose parallel alignment (see Fig. 2.11(C)) gives the rock its ability to cleave. It is also chemically resistant to weathering but is soft and can be easily cut into desired shapes. Before the relatively recent introduction of asphalt roofing tiles, slate was one of the most widely used materials for covering roofs. Huge quarries, such as those in Wales (Fig. 2.19), attest to the amount of material removed for this purpose. Perhaps the largest sheets of slate are used in the manufacture of high-quality pool (billiard) tables, where it is important to have an absolutely flat surface that will not warp. Blackboards in classrooms were also originally made from slate, but these are now usually made of green frosted glass. As the temperature of metamorphism increases, mica crystals grow larger and become visible in the hand specimen to form a rock known as **schist**. With further increases in temperature, mica reacts with other minerals and contributes to the formation of garnet (Sec. 2.1.1), which is one of the most common high-temperature metamorphic minerals. The appearance of garnet and other granular minerals at the expense of mica converts foliated schist into a hard layered rock known as **gneiss**, and if the temperature is high enough, the rock can actually begin to melt and form a mixed metamorphic-igneous rock known as **migmatite**. Migmatites commonly exhibit interesting structures that make them popular in the stone industry for use as decorative kitchen countertops. For example, the countertop illustrated in Figure 2.20 is of a garnet-rich migmatite from Brazil. The wispy white patches are composed of granite that segregated as a liquid from the solid garnet-rich part of the rock. The patches pinch and swell as a result of deformation that occurred at the time of melting. In contrast, a later dike of granite that cuts the rock can be seen to be undeformed. The quarrying of high-grade metamorphic and igneous rocks for the manufacture of countertops has become a big business, with Brazil, India, and China being some of the major producers. Another common metamorphic

Figure 2.18 Coal bed in a syncline exposed in a road cut near McAdoo, Pennsylvania. At the far end of the road cut, alternating green and red sandstone and shale are overlain by a thin bed of coal, which in turn is overlain by lighter colored sandstone that coarsens upward and, at the top of the road cut, contains small pebbles of quartz (a rock known as conglomerate). Nearby, thicker beds of coal have been mined for the much-prized slightly metamorphosed coal known as anthracite. The syncline is cut by at least two thrust faults.

Figure 2.19 One of the many quarries in northern Wales from which slate has been extracted for roofing tiles.

Figure 2.20 Kitchen countertop made from high-grade metamorphic rock from Espirito Santo, Brazil. The rock contains abundant red garnet (see Fig. 2.5). It also contains irregular light-colored streaks of granite, which were formed when this rock reached a high enough temperature to begin melting. Much of the deformation that can be seen in this rock probably took place while it was partly molten. A straight, undeformed granite dike cutting the metamorphic rock must have intruded at a later date. (Photograph courtesy of Tim Wawrzyniec and Amy Ellwein, University of New Mexico.)

rock is marble, which is formed from the metamorphism of limestone (Fig. 2.12). It is used both as a construction material and as a decorative facing stone. It also is the favorite material of sculptors, because it is soft enough to carve easily, yet has considerable strength. One of the most famous sources of marble is from Carrara, ~100 km west-northwest of Florence, Italy. This is where Michelangelo spent considerable time looking for just the right piece of marble for his next statue (Fig. 2.16(C)).

2.8 Plate Tectonics and the Generation of Rocks

Plate tectonics, which is driven by the cooling of the planet, sets up the conditions necessary for the formation of igneous, sedimentary, and metamorphic rocks. Most rocks are formed at specific plate tectonic locations, which we can think of as **rock factories** – the places where rocks are made in response to plate tectonic-related processes. At each factory, suites of rocks are formed that are characteristic of the particular plate tectonic setting. In later chapters, we see specifically what these rock associations are, but in this section we outline where these rock factories are located with respect to plate tectonics and mention only briefly the rocks they produce.

Figure 2.21(A) shows a schematic cross-section through the outer part of the Earth at a **convergent plate boundary** where an oceanic lithospheric plate is being subducted beneath a continental plate. At the left side of the diagram, the **midocean ridge** is **a divergent plate boundary**. Although the figure is static, it is important to keep in mind that the plates are moving (yellow arrows) at rates of centimeters per year. This motion develops relief on the surface of the planet and disturbs the temperature and pressure distributions in the rocks beneath. These disturbances are the primary causes for rock formation; rocks form in an attempt to eliminate the perturbations caused by plate motion. The main plate tectonic settings where rocks are formed are listed across the top of the cross-section in larger print, and the actual rock types formed are given below in smaller print. Photographs of particular rock types associated with particular settings are keyed to the cross-section by bold letters (B–G).

2.8.1 Midocean-ridge Rock Factory

By far the largest rock factories on Earth occur along midocean ridges, where tectonic plates move apart (Fig. 2.21(B)). The divergence makes room for magma to rise along fractures to form steeply dipping sheetlike bodies of igneous rock known as dikes and to erupt on the ocean floor along the rift valleys located on the crest of the oceanic ridges. As much as 20 km^3 of new rock are formed per year along the 65 000-km-long midocean ridge system. This is an order of magnitude more than is erupted subaerially. The igneous rock formed here is always of basaltic composition, and because it is formed at a midocean ridge, it is commonly called a **midocean ridge basalt** (or MORB for short). This is the most abundant rock on the surface of the planet, covering most of the ocean floor. Because it erupts beneath water, its surface cools rapidly and commonly develops meter-sized blobs of lava known as **pillows** (Fig. 2.21(B)). Almost no sedimentary rocks are formed in this environment. Midocean ridges are typically far from any continental source of sediment. The sediment that does eventually accumulate on this newly formed ocean floor consists of silica-rich mud formed from the skeletons of **radiolaria**, minute pelagic organisms that build their bodies from silica. This radiolarian ooze accumulates slowly, so only as the ocean floor gets older away from the divergent plate boundary does it attain significant thickness.

Another important rock-forming process takes place in the vicinity of midocean ridges. The ridges stand high relative to older ocean floor because they are still hot and, thus, float higher than does older denser oceanic crust. Seawater circulates through the newly formed crust and helps cool it. As much as 34% of the total amount of heat lost through the ocean floor is estimated to be removed by this circulation, and the entire volume of water in the world's oceans circulates through oceanic ridges every 8 million years. This enormous circulation of hot water through the rock leads to **hydrothermal alteration**, with many of the original igneous minerals being converted to hydrous and carbonate minerals. These newly formed minerals play an all-important role in triggering rock-forming processes when the oceanic plate is subducted at a convergent plate boundary.

2.8.2 Convergent-plate-boundary Rock Factory

Although midocean ridges are the most productive rock factories on Earth, most rocks they produce are subducted back into the mantle at convergent plate boundaries (Fig. 2.21(A)). As slabs subduct, the increased pressure causes the hydrothermal alteration minerals that were formed in the basalt as it cooled at the midocean ridge to react and liberate water and carbon dioxide, which rise into the overlying mantle wedge. These volatile constituents, especially water, lower the melting points of rocks, and magma is formed. The magma rises toward the surface and forms a chain of conical-shaped volcanoes, which are built of lava and ash ejected during volcanic explosions. The main rock type is known as **andesite**, which contains a little more silica than does basalt but otherwise looks very similar (Fig. 2.21(C)). The higher silica content makes the magma more viscous than basaltic magma, which accounts for the steep slope on the volcanoes, but it also prevents gas escaping

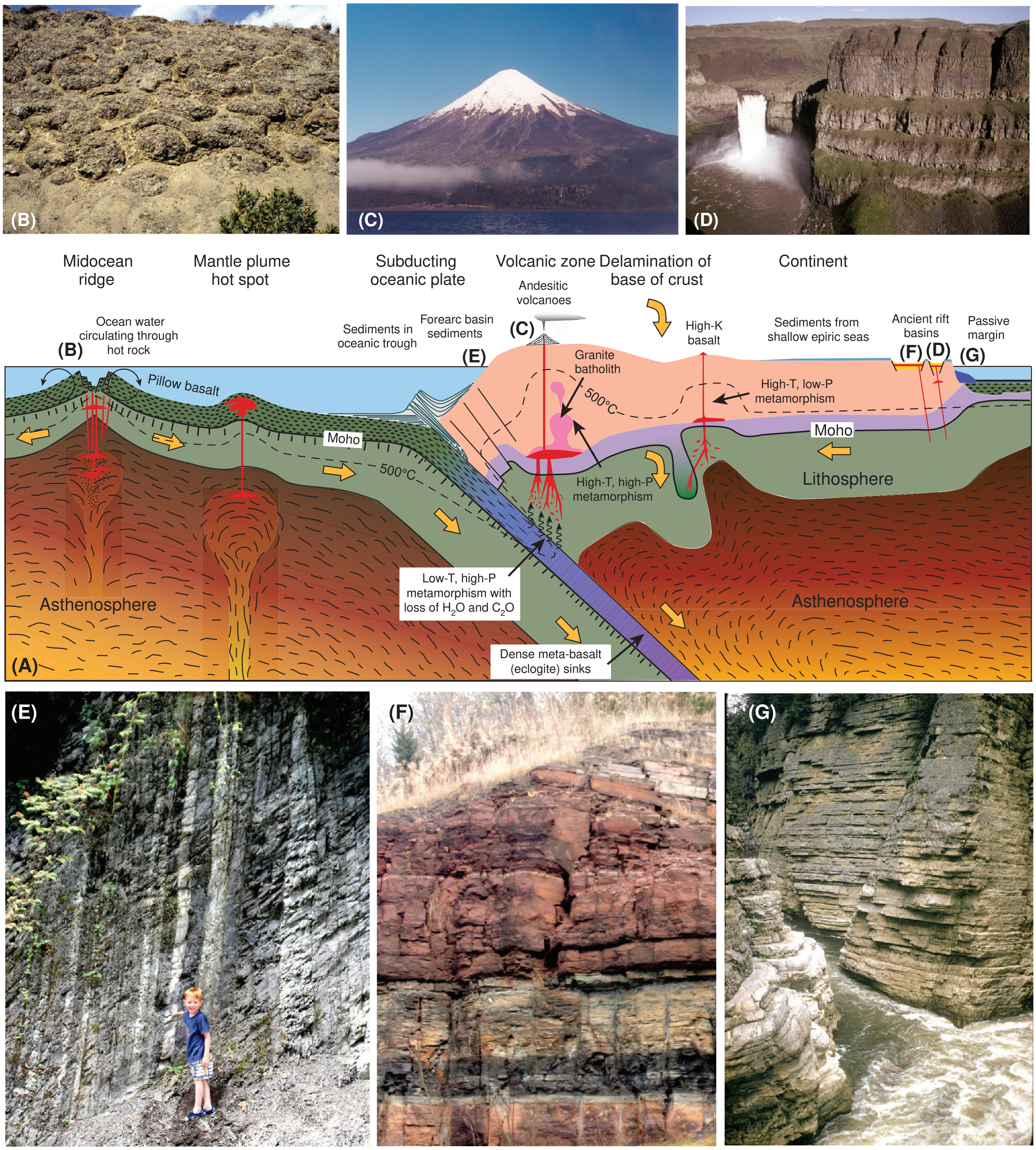


Figure 2.21 **(A)** Cross-section of the lithosphere extending from a midocean ridge (left) through a convergent plate boundary (center) to a passive continental margin (right). Letters in the cross-section (B–G) refer to the photographs of rocks formed at specific plate tectonic settings. **(B)** Pillows of basaltic lava erupted on the ocean floor in an outcrop on the island of Cyprus, where part of the Mediterranean ocean floor is exposed. **(C)** When a subducting plate reaches a depth of about 100 km, water is released that rises into the overlying wedge and causes melting. This magma rises to form conical andesitic volcanoes, such as Osorno in Chile. **(D)** Volcanic rocks associated with rift basins are commonly erupted from long fissures to form thick basaltic lava flows, known as flood basalts, as seen here at Palouse Falls, in eastern Washington. **(E)** Steeply dipping beds of Ordovician Martinsburg shale and sandstone near Shippensburg, Pennsylvania. These sedimentary rocks were tipped on end during the Appalachian orogeny, which also began to convert the shale into a metamorphic rock with a slaty cleavage dipping to the left in the photograph. **(F)** Red arkosic sandstone and black shale in the Mesozoic Hartford Rift Basin in Connecticut. **(G)** Potsdam Sandstone in Ausable Chasm, New York, was deposited as a quartz-rich sand on the Cambrian shore of North America.

easily from the magma. These magmas typically contain a considerable amount of water, which was derived from the subducting oceanic plate, and when they approach the surface, exsolving gas can cause violent volcanic explosions, which deposit layers of ash over large areas. Not all magma rises to the surface to form volcanoes. Some may pond near the base of the continental crust, where it causes melting of crustal rocks to produce granitic magma, which may solidify at depth to form large bodies known as **batholiths** (Fig. 2.21(A)). Granitic batholiths form the core of many mountain chains developed at convergent plate boundaries.

The relief created in the overriding plate at convergent boundaries, both through folding and thrusting of existing rocks and through the growth of new volcanoes, creates ideal conditions for the generation of sediment. Rivers transport the sediment rapidly to the ocean, with the finest sediment making it out into the deep waters of the **forearc basin** formed above the subducting slab. The rapid accumulation of coarser sediment near the shore leads to unstable conditions, with the sediment slumping and moving to deeper water in the form of **mudflows** and **turbidity currents**. These dense suspensions are able to transport coarser sediment great distances out into the forearc basin. Deposition from turbidity currents results in **graded layers** that vary from coarse at the base to fine at the top. These sediments are converted to shales and sandstones that become highly deformed as they are scraped off the subducting plate and accreted to the orogenic wedge. Figure 2.21(E) shows steeply dipping shales and sandstones of the Ordovician Martinsburg formation in Pennsylvania, which were deposited in a forearc basin that developed during the closing of the Iapetus Ocean.

2.8.3 Continental Divergent-plate-boundary Rock Factory (Rift Valley)

Divergent plate boundaries can occur within continental plates, with formation of **rift valleys**. The East African Rift is a modern example of such a boundary. Figure 2.21(A) shows paleo-rift basins, such as those that developed in eastern North America and Morocco when Pangaea rifted apart to form the Atlantic Ocean. The relief along rift valleys results in rapid transport of sediment into the rift, and as these depositional basins are on continents, the oxygen in the atmosphere keeps iron in the sediment in its ferric state, which stains many of these rocks red. Some sediment containing organic matter, however, is black because it accumulates under anaerobic (no oxygen) conditions in deep lakes that develop along rift valleys (Fig. 2.21(F)). Because the transport distance from highland to basin is commonly short, the harder minerals, such as quartz, have insufficient time to abrade and eliminate the softer minerals such as feldspar. Consequently, the sandstones contain considerable amounts of feldspar and are known as feldspathic sandstone. As sedimentary basins form on the Earth's surface in response to rifting, the mantle beneath rises, decompresses, and partially melts to form basaltic magma, which erupts from long fissures paralleling the rifts. This develops outpourings of basaltic magma that form large flat lava flows known as **flood basalts** (Fig. 2.21(D)).

2.8.4 Mantle Plume Hot-spot Rock Factory

Other important igneous rock factories occur at **hot spots**, which form above what are believed to be **mantle plumes** that rise from possibly as deep as the core–mantle boundary (Fig. 2.21(A)). Hot spots remain relatively stationary on the planet while tectonic plates move independently above them. This independence might suggest that hot spots are not part of the plate tectonic cycle, but they undoubtedly play a major role in the convective transfer of heat through the mantle and crust. The best-known hot spot is located beneath the island of Hawaii (Fig. 2.14), with its trail of islands and seamounts bearing witness to the motion of the Pacific plate across the hot spot (Fig. 10.41(A)). Basaltic rocks are the primary igneous rock formed above hot spots, but if the hot spot rises beneath a continental crust, as it does beneath Yellowstone National Park, for example, a wide range of igneous rocks can form, including granite (Fig. 10.20).

2.8.5 Passive-margin Rock Factories

When continents rift apart to form an ocean, **passive margins** form; that is, the edge of the continent simply abuts the new ocean floor that was formed along the rift. The relief along such margins is typically low, and the supply of sediment to the newly formed continental margin is slow. Wave action along the shoreline has ample time to abrade soft minerals and to sort the sediment on the basis of grain size. The result is a sequence of flat-lying or gently dipping sedimentary rocks that range from quartz-rich sandstone to shale (Fig. 2.21(G)). Limestone may also be part of the sequence if the sediments accumulate where the climate is warm enough to promote abundant growth of organisms with carbonate skeletons or shells. The Bahamas is a modern-day example of such an environment. As passive margins migrate away from spreading axes, the oceanic crust cools and subsides, making room for deposition of considerable thicknesses of sediment.

2.8.6 Epeiric-sea Rock Factories

The rate of tectonic plate motion is not constant and at times is significantly greater than at others, as indicated by variations in the width of magnetic anomalies on the ocean floor. For example, the Atlantic Ocean is opening at a couple of centimeters per year. In contrast, India split away from Madagascar at the end of the Cretaceous at ~10 cm yr^{-1} toward Asia. During periods of rapid plate motion, midocean ridges become more active and more new hot ocean crust is created. As a result, ocean ridges become larger and displace ocean water onto the continents to form shallow **epeiric seas**. Deposition in these shallow seas can result in extensive beds of flat-lying sedimentary rocks that do not owe their present location to a specific plate tectonic setting but nonetheless are formed in response to plate tectonic processes. Much of the central part of North America is covered with sedimentary rocks formed in these shallow seas. Minor flooding of the continent can also occur as a result of the meltback of continental ice sheets and local tectonic conditions.

2.8.7 Metamorphic Rock Factories

In a static Earth, the temperature everywhere would increase at the same rate with depth, so that a given temperature would always be found at the same depth. The Earth, however, is dynamic and the temperature variation with depth changes dramatically with plate tectonic setting. For example, if we were to drill a deep hole in a stable continental region, we would find that a temperature of 500°C would be reached at a depth of ~20 km (based on a common geothermal gradient of 25°C km^{-1}). The dashed line in Figure 2.21(A), which represents the location of this temperature, is known as an **isotherm** (equal temperature). If we trace the isotherm across the figure, we see that its depth changes considerably. Beneath the midocean ridge, it is much shallower because of the presence of all the new hot igneous rock. Where the oceanic plate is subducted beneath the continental plate, the isotherm is transported to considerable depth. In the overlying plate, the production and rise of magma into the crust causes the isotherm to move to shallower depths. The isotherm can also be perturbed if parts of the lower continental crust delaminate and sink into the mantle. The hot mantle that rises to replace the delaminated slab causes isotherms to be raised in that region. The result is that the 500°C isotherm occurs at very different depths, and consequently pressures, depending on the plate tectonic setting. Changes in temperature, pressure, and fluid composition produce metamorphic rocks.

The main plate tectonic settings for the development of regional metamorphic rocks are shown in Figure 2.21(A). Ocean floor rocks, on being subducted, experience a rapid increase in pressure with little increase in temperature. This produces metamorphic rocks that are characterized by minerals that are stable at low temperature and high pressure. One such mineral is the blue amphibole glaucophane, which makes many of these rocks blue. Water and carbon dioxide released from these metamorphic rocks rise into the overriding mantle wedge, where they help promote metamorphic reactions in the overlying rocks. The water is also essential in causing melting, and as magma rises into the overlying crust, it transports heat with it. This, in turn, brings about metamorphism at high temperatures and pressures. Above zones of delamination, the temperatures of rocks at relatively shallow depths (low pressure) can be raised to elevated temperatures to bring about metamorphism at high temperatures and low pressures. The rise of the mantle beneath rift valleys produces a slightly elevated temperature gradient, which can cause low-temperature metamorphism.

In later chapters, we see what specific rock types are developed in these various plate tectonic settings. In the meantime, it is important to keep in mind the role that plate tectonic processes play in the formation of rocks.

Summary

This chapter introduces the solid materials that constitute the Earth, that is, minerals and rocks. We distinguish between minerals and rocks and give some common examples of both that are encountered on a daily basis. We discuss how minerals and rocks are classified, and how their origin is closely related to plate tectonic processes. The following are the main points discussed in this chapter:

- Minerals are the basic building blocks of the Earth. A mineral is a naturally occurring solid, with a definite (but commonly not fixed) chemical composition and an ordered atomic arrangement. All minerals have a definite crystalline structure; that is, they have an ordered three-dimensional arrangement of the constituent atoms, which imposes the chemical restrictions on their composition.
- Minerals are classified into a number of chemical groups, with the silicates being by far the largest. Despite the large number of minerals on Earth, only 87 occur as essential constituents of rocks. These are known as the rock-forming minerals.
- Because of the restricted chemical composition of minerals, several minerals must normally be present to account for the composition of the Earth at any given locality. This assemblage of minerals is what we refer to as a rock. The

assemblage is normally restricted to consolidated masses to distinguish it from loose surficial materials. The solid Earth is made of rock.

- Rocks can form by crystallization of molten rock known as magma, in which case they are known as igneous. They can form through the cementing and consolidation of sediment, in which case they are known as sedimentary. Rocks that undergo mineralogical and textural changes in response to changes in environmental factors such as temperature, pressure, and fluid composition create new rocks known as metamorphic.
- Rocks are formed in response to plate tectonic processes. As a result, common associations of igneous, sedimentary, and metamorphic rocks develop that are characteristic of specific plate tectonic settings.
- The largest quantities of new rock are formed at midocean ridges, where divergent plates cause basaltic magma to rise from the mantle.
- The second-largest production of new rocks occurs at convergent plate boundaries, where andesitic volcanoes are the surface expression of intense igneous activity at depth, with granite batholiths being emplaced into the core of orogenic belts. Sediment eroded from these belts and transported into forearc basins is accreted onto continents as it is scraped off the subducting slab.
- Hot spots, rift basins, passive continental margins, and flooded parts of continents are other important settings for rock formation.
- All rocks, when exposed to changes in temperature, pressure, or fluid composition, can undergo mineralogical changes to produce metamorphic rocks. Changes in environmental factors are caused mainly by plate tectonic motion, but local changes can occur near igneous intrusions.

Review Questions

1. What is a mineral, and why is it important to specify naturally occurring?
2. Why does table salt (NaCl) break into cubelike cleavage fragments?
3. What is the composition, shape, and electrical charge on the basic building unit of all silicate minerals?
4. What are some common uses for the mineral quartz (SiO_2)?
5. How does the arrangement of silica tetrahedra in the crystal structures of quartz and talc differ?
6. Although the cation-to-anion ratio in garnet is fixed, what allows it to have a wide compositional range, and why are such widely different compositions still classified as the same mineral?
7. Can minerals be synthesized in the laboratory?
8. On what basis are minerals classified into different chemical groups, and of these, which forms the largest group?
9. What is a crystal, and does the crystalline state require that crystal faces be present?
10. What is a rock, and how does it differ from a mineral?
11. What is the difference between a rock's texture and structure?
12. From a geological map of the area where you live, determine how many rock-forming periods your home area has experienced and approximately what fraction of geologic time these periods represent.
13. What single process has been operating continuously since the beginning of the Earth and has been responsible for the formation of most rocks and drives plate tectonics?