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

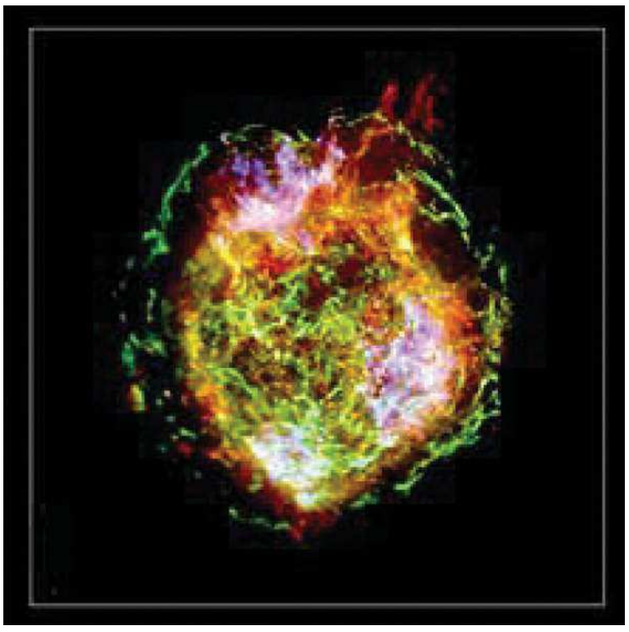


Figure 1.1 Cassiopeia A is a supernova remnant. This image, taken with NASA's Chandra X-ray Observatory, allows us to identify the elements being created in the exploding star by the characteristic wavelengths of X-rays emitted by each element, which have been converted in this image to false colors.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

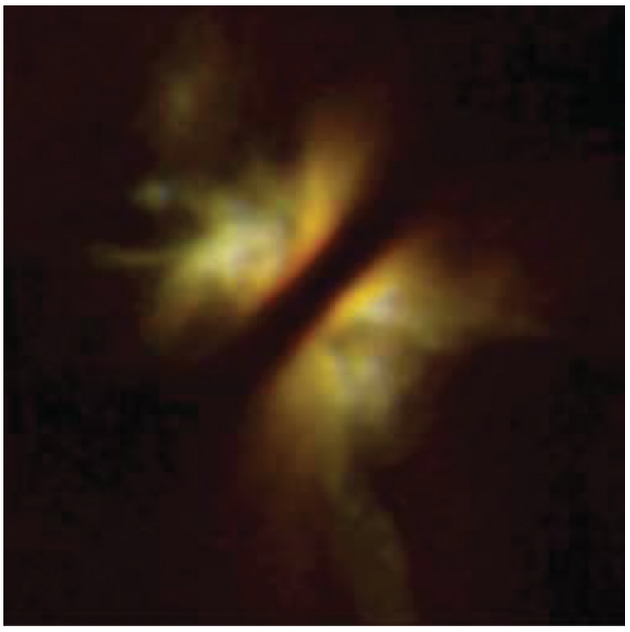


Figure 1.2 Hubble space telescope image obtained by the Near-Infrared Camera and Multi-Object Spectrometer (NICMOS) shows a star (IRAS 04302+2247) that is hidden by a nebular disc of material (diagonal dark region) similar in mass and size to the one that formed our solar system. Light from the star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

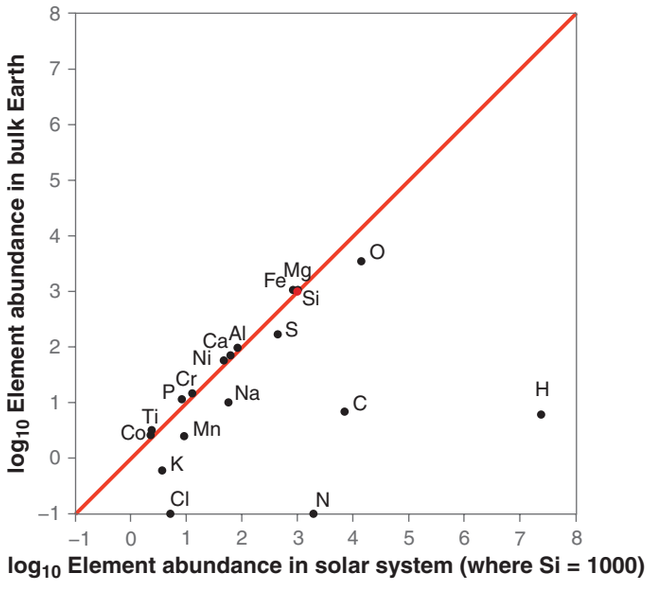
Because the Sun constitutes 99.9% of the mass of the solar system, its composition must be essentially the same as that of the nebula from which it formed. We can determine the composition of the outer part of the Sun from the strength of absorption lines in the electromagnetic spectrum that are characteristic 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	2.431×10^7	6
He	2.343×10^6	-
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

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.)

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

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

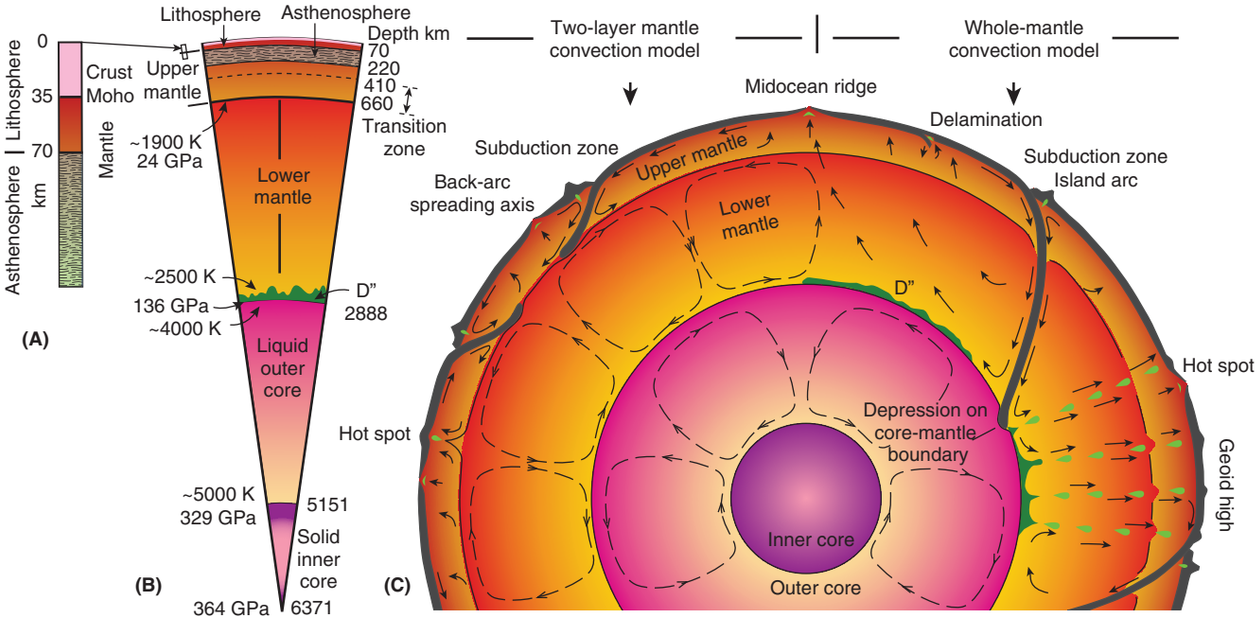


Figure 1.5 Major structural units of the Earth. **(A)** Cross-section through the lithosphere. **(B)** Section through the Earth showing the depth, pressure, and temperature at major seismic discontinuities. **(C)** Cross-section through the Earth showing the two-layer and whole-mantle convection models (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.

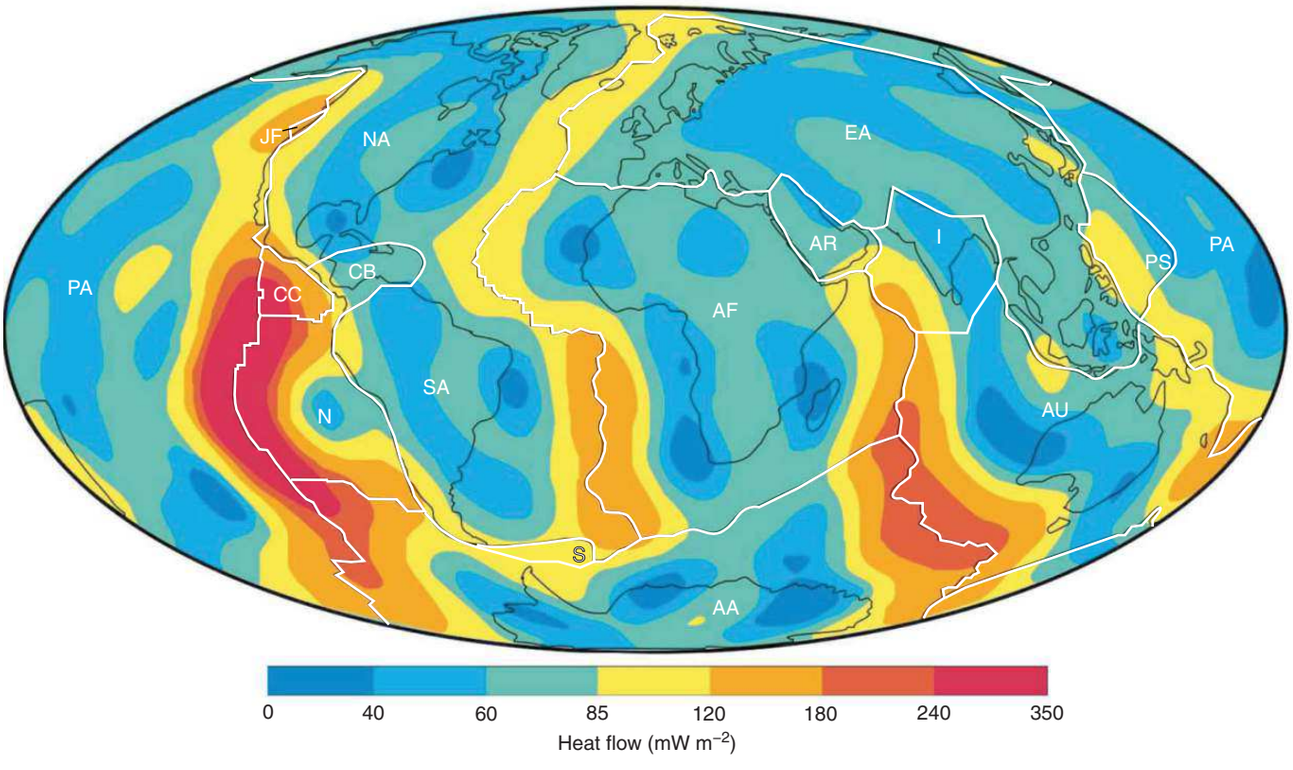


Figure 1.6 Global heat flow as synthesized by the International Heat Flow Commission (www.geophysik.rwth-aachen.de/IHFC/heatflow.html). For discussion of the synthesis, see Pollack *et al.* (1993). Tectonic plate boundaries are shown by white lines, and the names of the plates are shown by letters, the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

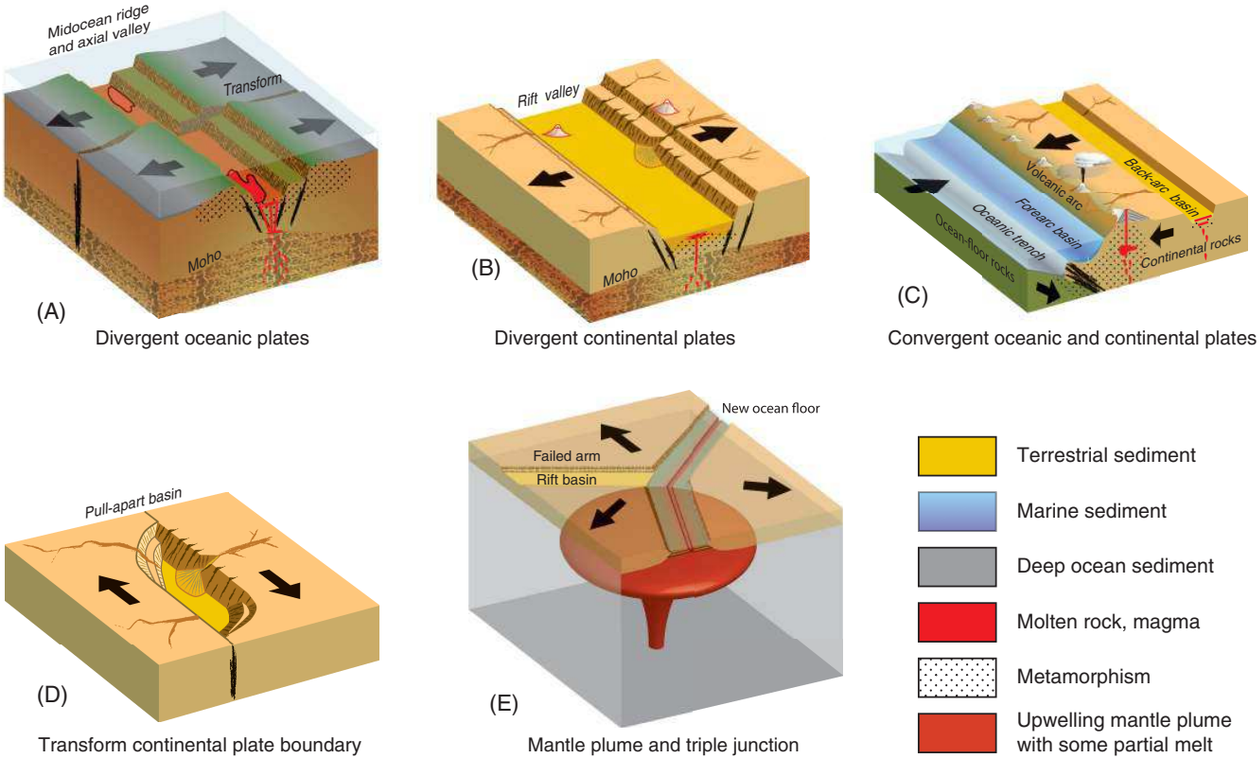


Figure 1.7 Types of tectonic plate boundaries and sites of formation of igneous, sedimentary, and metamorphic rocks.

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.