CHAPTER

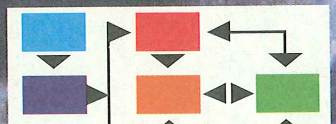
4

THE EARTH'S INTERIOR

OBJECTIVES:

By the end of this chapter, you will be able to:

- appreciate the difficulty of learning about the interior of the earth;
- recognize that the interior of the earth is divided into layers of different materials and densities;
- identify important sources of information that have been used to create an understanding about the earth's interior;
- relate the nature and composition of the earth to conditions on the surface of the earth.



Introduction

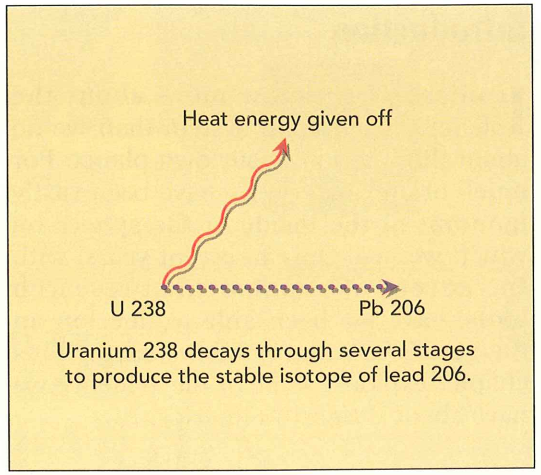
Ironically, we know more about the planets of our solar system than we do about the interior of our own planet. For much of our history, we have been vastly ignorant of the inside of the sphere on which we live. Only in recent years, with the advent of sophisticated research tools, have we been able to develop an image of the interior of the earth. This chapter explores some of the evidence we have about the earth's interior.

4·1 The Earth's Internal Heat Sources

It is thought that the earth formed about 4.6 billion years ago when a vast cloud of gases and dust was gradually pulled inward by the force of gravity to form the sun and the planets of the solar system. The earth continued to grow because its gravitational attraction acted like a magnet to small planetesimals (early planets) and meteorites. The additional materials must have been solid since the earth's gravity was not strong enough to pull in liquids or gases. This explanation of the origin of the earth is called the cold accretion theory. The term **accretion** refers to a gradual increase in size resulting from the addition of materials from beyond the earth.

2•4

Today, it is known that the earth's interior is so hot that it should be in a liquid state. However, the enormous pressures of overlying materials make much of it behave as though it were solid. If the pressures were released, this material would quickly turn into liquid or gaseous states, as volcanic eruptions show.



Uranium 238 decays through several stages to produce the stable isotope of lead 206.

Figure 4.1a **Radioactive Decay: A Major Source of Energy From Below**

The key long-term radioactive elements:

Uranium (U) 238
Uranium (U) 235
Thorium (Th) 232
Potassium (K) 40

The key shorter-term radioactive elements:

Aluminum (Al) 26
Uranium (U) 236
Samarium (Sm) 146
Plutonium (Pu) 244
Curium (Cm) 247

Figure 4.1b **Radioactive Elements in the Earth's Interior**

To move from the idea of cold accretion to an understanding of the earth's molten interior, we must address several questions. The first is how the internal temperature of the earth reaches temperatures between 4000°C and 6600°C. A second question is how these temperatures brought about the formation of layers in the interior of the earth. Thirdly, what other effects have these high temperatures had on the earth?

The melting of the materials of the earth would require unthinkable amounts of energy. One source of heat is the kinetic energy of moving bodies striking the earth. A second source is the compression of rock materials inside the earth due to the enormous pressures of the material above. However, the major source of heat was, and continues to be, the decay of unstable, radioactive elements within the rocks of the earth. Figure 4.1b shows the most common radioactive elements that created this internal "heat engine". The short-term elements were present in the rocks of the early earth, but have completely decayed. The longer-term elements are still decaying and heating the rocks of the earth's interior.

It's a Fact . . .

- Meteorites were scientifically recognized only in the early 1800s. Before that time, people describing stones falling from the sky were thought to be hallucinating or observing fallout from a volcanic eruption.
- It is estimated that about 100 t of dust from burned-up meteorites falls into earth's atmosphere each day.

QUESTIONS

1. List several ways in which your life might be different if the gravitational attraction of the earth were greater, or less, than it is today.
2. a) Use the information in this section to explain why the earth's interior will eventually cool and become solid, like the interior of the moon.
   b) Suggest what general effects a cold, solid interior might have on the surface of the earth.
3. a) Draw a diagram to show how accretion worked to bring about the formation of the earth.
   b) Draw a second diagram to illustrate the three major sources of energy that led to the earth's hot interior.
4. Although much less frequently than in the earth's early period, meteorites still strike the earth. How might this fact be important in your life?

4·2 A Layered Earth

Figure 4.2 lists the proportions of the various elements that make up the earth and their atomic masses. The higher the atomic mass, the greater the density of the element. Studies have shown that the centre of the earth is composed of materials of high density and atomic weight, while the outer layers are made up of less dense materials. How did this "layering" take place?

In a solid body, there is no way elements can separate into layers of different density. But, in a molten and/or semi-molten state, heavier elements begin to differentiate from the surrounding lighter elements and settle towards the centre of the earth under the effects of gravity. This is how the core of the earth was formed in the first billion or so years of the earth's existence (Figure 4.3). Lighter elements

Element	Symbol	Percentage by Mass	Atomic Mass
Iron	Fe	35	55.85
Oxygen	O	30	16.00
Silicon	Si	15	28.09
Magnesium	Mg	13	24.31
Nickel	Ni	2.4	58.69
Sulphur	S	1.9	32.06
Calcium	Ca	1.1	40.08
Aluminum	Al	1.1	26.98
Sodium	Na	0.57	22.99
Chromium	Cr	0.26	52.00
Manganese	Mn	0.22	54.94
Cobalt	Co	0.13	58.93
Phosphorus	P	0.10	30.97
Potassium	K	0.08	39.10
Titanium	Ti	0.05	47.88

Figure 4.2
The Major Elements Making Up Planet Earth

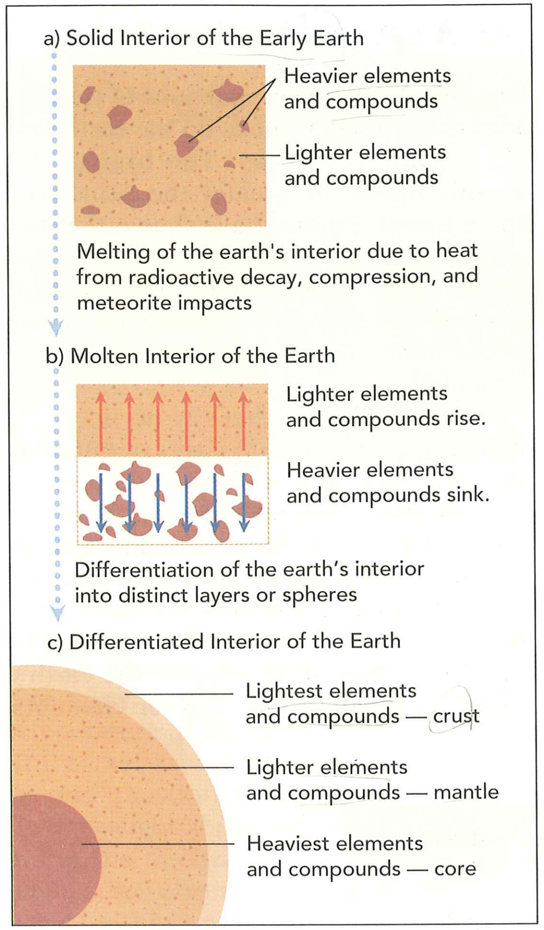


Figure 4.3 Differentiation of the Earth's Interior Into Layers

and compounds, on the other hand, rose towards the surface to form the crust and the upper layers of the **mantle**.

Many scientists believe this layering process was a quick one, taking only a few hundred million years. The result was the formation of a dense core of iron and nickel surrounded by a thick mantle of lighter rocks made up largely of various **silicates**. The silicates are minerals that combine the two most abundant elements in the earth's crust, oxygen (O) and silicon (Si). As time passed, the lightest materials of the mantle rose to the surface and began to form the earth's crust.

The process of differentiation first occurred billions of years ago, but the elements and compounds found within the interior of the earth have slowly continued to separate into the various layers shown in Figure 4.4. As this diagram shows, the internal layers of the earth can be determined in two ways: by their chemical composition or by their physical properties. It is important to note the differences in the number, names, and depths of these layers, depending on which criterion is used. For example, the term **"crust"** is used to identify the thin outer layer of rocks that are less dense than those of the mantle. The term **"lithosphere"** refers to the solid outer layer of the earth where the rocks are harder and more rigid than those of the plastic asthenosphere layer below. These layers are now differentiated by only slight differences in density. As a result of this ongoing process, scientists believe that the lighter materials are still being added to the crust of the earth, increasing the size and mass of the continents.

Chemically, the **core** of the earth is believed to be composed of a mixture of iron, nickel, and traces of other heavy metals. The pressures in the core are tremendous. Because of this, and despite extremely high temperatures, physically, the inner core is in a solid state. The outer core, being under less pressure but at a similar high temperature, is in a liquid state.

Chemically, both the upper and lower mantle are composed of silicates of magnesium and iron. These are much lower in density than the materials that make up the core. Physically, the **mesosphere** is largely solid in nature. Even so, it is very hot and will flow slowly under pressure.

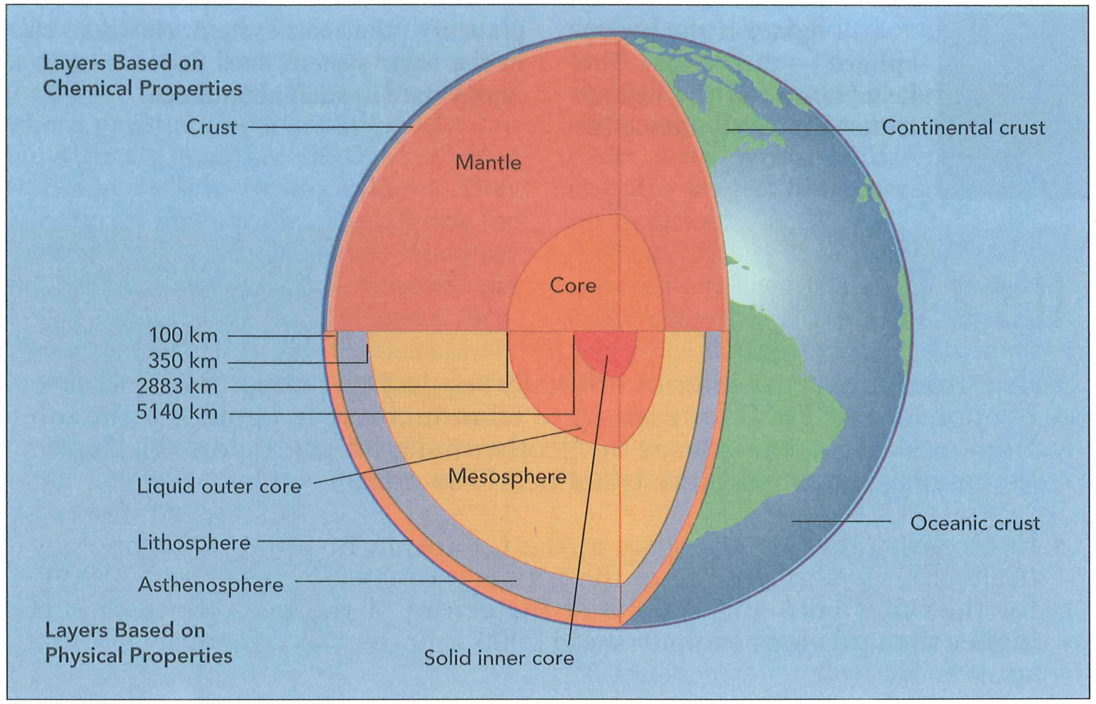
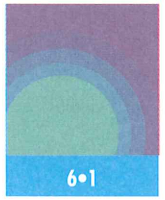


Figure 4.4 The Layered Interior of the Earth



A newly identified physical layer of the earth's interior is the **asthenosphere**, which only began to appear on diagrams of the earth's interior in the 1970s. Its existence was suggested by the need to account for the newly discovered movements of the earth's crust, then called continental drift. Scientists believe the asthenosphere is in a plastic state, part liquid and part solid. If this is not so, it would be difficult to explain the movements of the continents!

The outermost layer of the earth can be defined using either chemical or physical properties. Chemically, it consists of the thin layer (6-70 km) of the lightest materials in the earth and is called the crust. It is proportionally thinner than the skin of an apple or peach. Even this thin layer is differentiated: the deeper ocean floors are mainly composed of basalt, a silicate of iron and magnesium. The continents are mainly composed of somewhat less dense aluminum silicates in the form of granitic rocks. As a result, these lighter rocks "float" higher than the oceanic rocks, elevating the continental blocks. Physically, it is known as the lithosphere and is made up of the hard, rigid outer layer of the earth, approximately 100 km in depth, which consists of a dozen rigid plates that "float" on the underlying, more plastic layer called the asthenosphere. It is important to note that the terms "crust" and "lithosphere" are not interchangeable.

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Still lighter is the **hydrosphere** — the oceans. This layer is one of the unique features of earth among the planets of the solar system. Nowhere else in the solar system does water exist in a liquid state in such abundance.

It's a Fact . . .

- Heat from the earth's interior normally results in a temperature increase of approximately 1°C for each 30 to 60 m increase in depth, for the top 5 km or so. This is known as the geothermal gradient. Below this depth, the increase in temperature is not nearly so rapid.
- In recent studies by scientists at the California Institute of Technology (Caltech), the temperature of the core is estimated to be at least 4500°C for the outer core and 6600°C at the centre of the inner core. This is higher than previous estimates and 1000°C hotter than the surface of the sun!

QUESTIONS

5. What sort of vehicle would you need to travel to the centre of the earth? Explain your ideas.
6. a) Indicate the conditions necessary before the interior of the earth could separate into layers of different densities.
   b) What name is given to this process and why is it an appropriate term to use?
   c) Based on the information given in Figure 4.2, indicate which elements were most likely to contribute to the formation of the core, and which ones would make up the bulk of the mantle and crust.
7. Describe a simple experiment to illustrate the process of differentiation of the earth's interior. If you have the time and equipment, carry out the experiment to see if it actually works.
8. As you move out from the centre of the earth, the layers of materials become increasingly less dense.
   a) Draw a diagram or sketch to prove this statement is correct.
   b) What accounts for this fact?
9. Granite and basalt have a lot to do with the fact that the earth has continents and ocean basins. Explain this statement.

4·3 Uncovering the Earth's Interior

Despite all our advanced technology, we have not been able to drill much more than 16 km into the crust. This is barely enough to puncture the "skin" of the earth. We have more direct evidence about the stars in distant galaxies than we have about the interior of our own planet.

Direct evidence about the upper mantle is found only in scattered places over the surface of the earth where rocks very different from those commonly found at the surface have been thrust up by movements of the ocean floors. One place where unusual upper mantle rocks can be directly seen is in Gros Morne National Park in Newfoundland. They were thrust up above sea level during the formation of the Appalachian Mountain belt, when North America, Europe, and Africa collided in the Paleozoic Era. These rocks contain chemicals that are poisonous to most plants, and thus result in barren hills in a normally forest and tundra landscape. Figure 4.5 shows an aerial view of part of this outcrop and its barren appearance.

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Much of what we know about the earth's interior has been derived from "indirect" evidence. We know, for example, that the average density of the earth is about 4.3 g/cm^3, whereas the average density of rocks that make up the earth's crust ranges from 2.6 to 3.0 g/cm^3. This means that the interior of the earth must differ significantly in density from the rocks at the surface. Differences in density also suggest differences in chemical composition.

Three different sources of indirect information have been used to gain an understanding of the interior of the earth. The first is the study of meteorites; the second comes from the increasingly developed science of seismology; and the third is a very recent, high-tech method known as "seismic tomography".

Meteorites: Evidence About the Interior

Meteorites are a very important source of information about the solar system and its date of origin. In addition, they provide clues about the interior of the earth, as strange as this may seem at first glance. **Meteorites** are the fragments of asteroids and small early planets that broke up on impact with other bodies out in space. It is believed that these asteroids and planetesimals formed in the

Figure 4.5
Upper Mantle Ocean Floor Rocks Exposed, Gros Morne National Park, Newfoundland

same way and from similar materials as the earth. Therefore, by studying meteorites, we can make some inferences about the interior of the earth.

Meteorites are not all the same in composition. In fact, they fit into three main divisions: iron-nickel meteorites (Figure 4.6); stony meteorites (Figure 4.7); and stony-iron meteorites. Scientists believe that the iron-nickel meteorites came from the cores of the original bodies, and the stony meteorites from areas that would correspond to the earth's mantle. The stony-iron meteorites would have originated between the cores and mantles of the asteroids and planetesimals. The densities and characteristics of the meteorites, then, provide clues about the interior of the earth.

Seismology: Key to the Earth's Interior

Seismology is the scientific study of earthquakes, the seismic waves they generate, and the passage of these waves through the earth's interior. It is largely through this science that much of what is presently believed to be true about the earth's interior has been determined.

When an earthquake occurs, the energy it releases causes seismic waves to move outward from its **focus**, or centre, in all directions. The ripples caused by dropping a rock into a still pond are similar to such waves. Seismic waves are detected by seismographs (Figure 4.8), sensitive instruments positioned hundreds and even thousands of kilometres from an earthquake.

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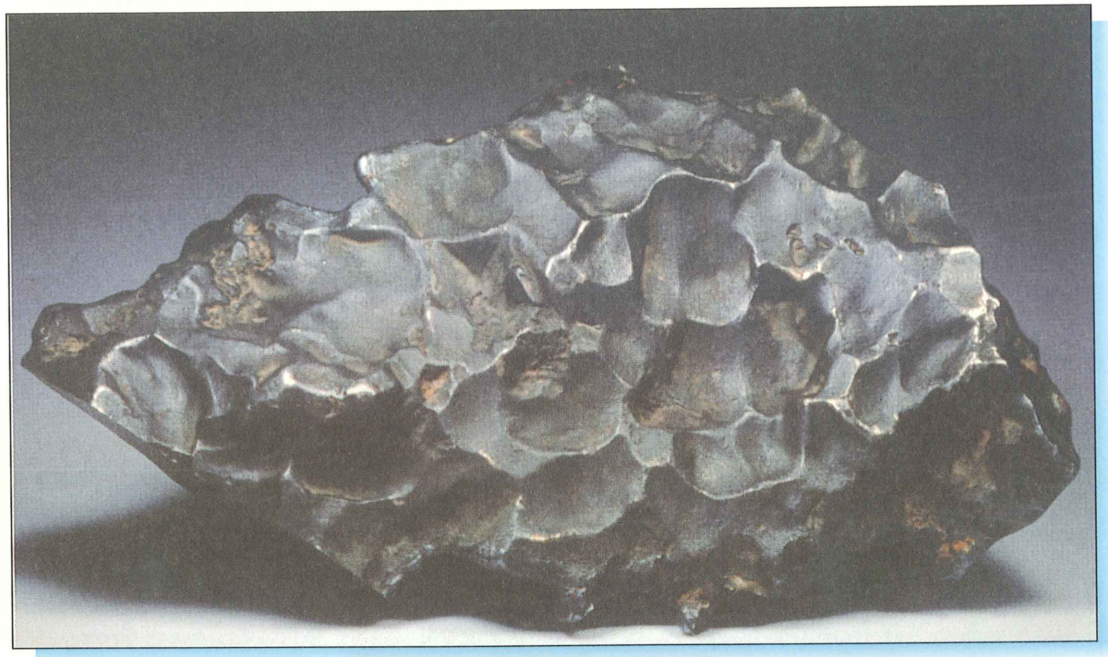

Figure 4.6 **An Iron-Nickel Meteorite** Composition: 90% iron, 9% nickel, with traces of other metals

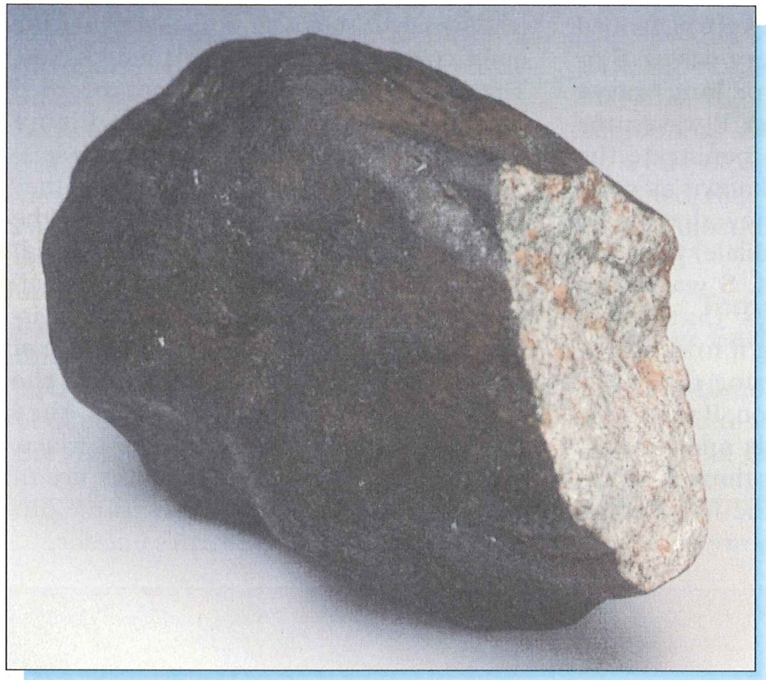

Figure 4.7
A Stony Meteorite
Similar composition to the earth's mantle, with little metal content

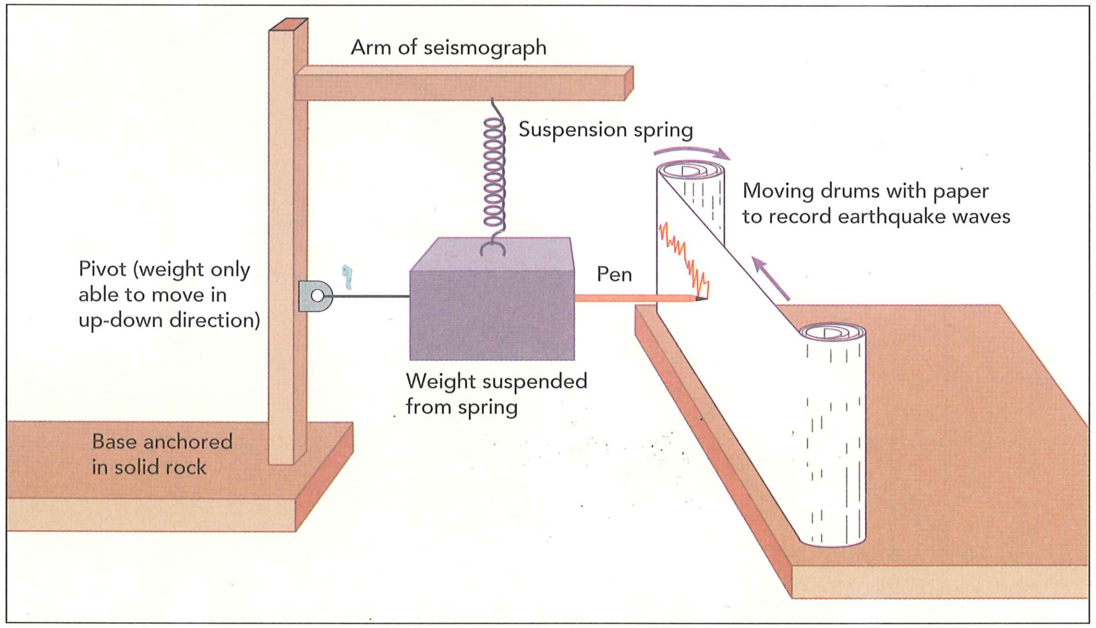

Figure 4.8 **A Simple Seismograph** The weight is isolated from the movements of the earth by the spring, so it tends to remain stationary, while the earth around it moves during a tremor. It is the paper that moves, not the pen.

Three main types of waves are generated by earthquakes: **P** or **primary waves**, **S** or **secondary waves**, and **L** or **long waves** (also known as Love waves). P waves, the fastest of the waves, can penetrate the earth's interior. They are known as compressional waves since they alternately push (compress) and pull (dilate) the rocks through which they pass. S waves are slower, transverse waves that travel through the rock by moving it from side to side (also known as shearing the rock). Because of the type of motion, P waves will travel through both solids and liquids, while S waves can only pass through solids. At some distances from the focus of an earthquake, only P waves are recorded, leading earth scientists to believe that the outer core of the earth is in a liquid state. The areas where S waves are not recorded by seismographs are shown on Figure 4.11. This diagram also shows how seismic waves are bent, or refracted, as they move across the boundaries between the layers with differing densities. This bending creates two shadow zones, where neither P nor S waves are recorded by seismographs. L waves travel on the surface of the earth and shake the rocks sideways as they progress across the surface. Only P and S waves are of great use in finding out about the earth's interior.

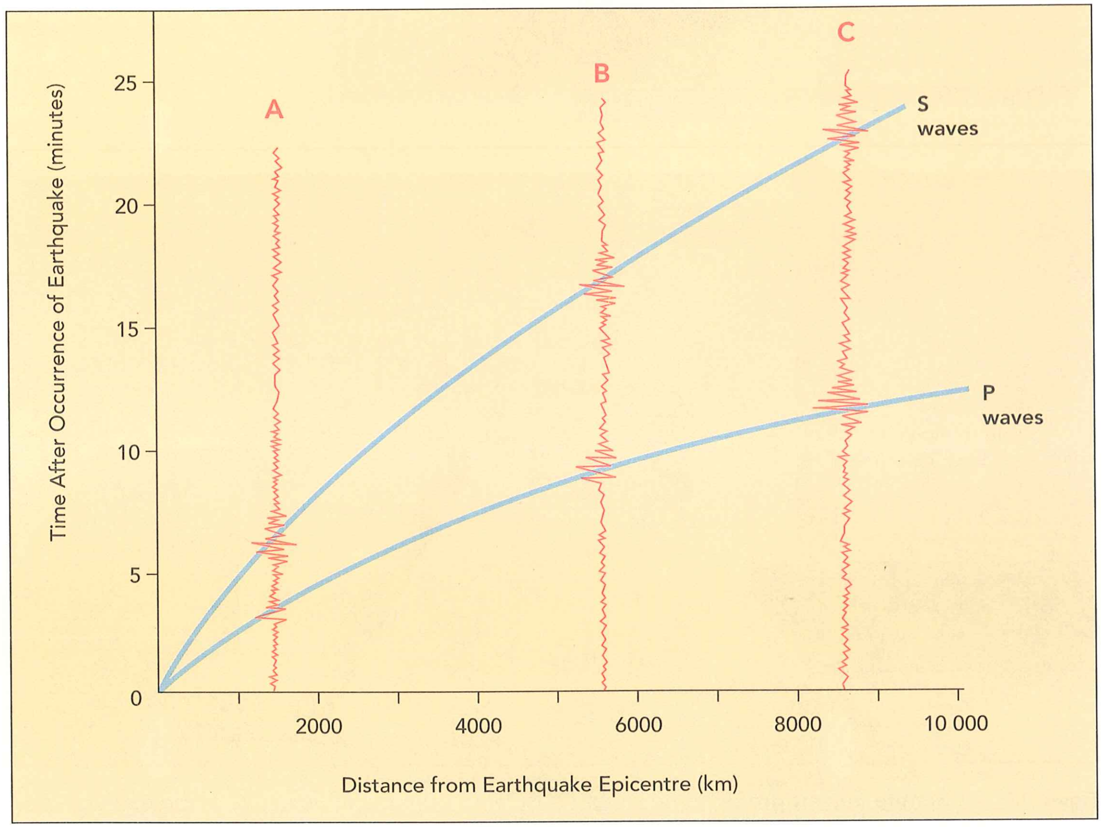

Figure 4.9 Arrival Times of P and S Waves at Various Seismic Stations

Figure 4.9 shows the arrival times of different seismic waves from an earthquake. By measuring the time difference between the arrival of P and S waves, the distance from the seismic station to the earthquake's **epicentre** (the point on the earth's surface directly above the focus) can be determined. The actual location of the earthquake can be plotted on a map using distance calculations from at least three different seismic stations. Earth scientists use the seismic information obtained from earthquakes to determine the nature of the interior of the earth. The speed of the seismic waves gives an indication of density since the denser the material, the faster the wave travels. In addition, as shock waves pass from zones or layers of different densities, they are refracted; that is, the waves change direction, as illustrated in Figure 4.11.

Seismic Tomography: A "Window" Into the Earth's Interior

Seismic tomography is the latest technique used to uncover greater detail about variations in the density and temperature

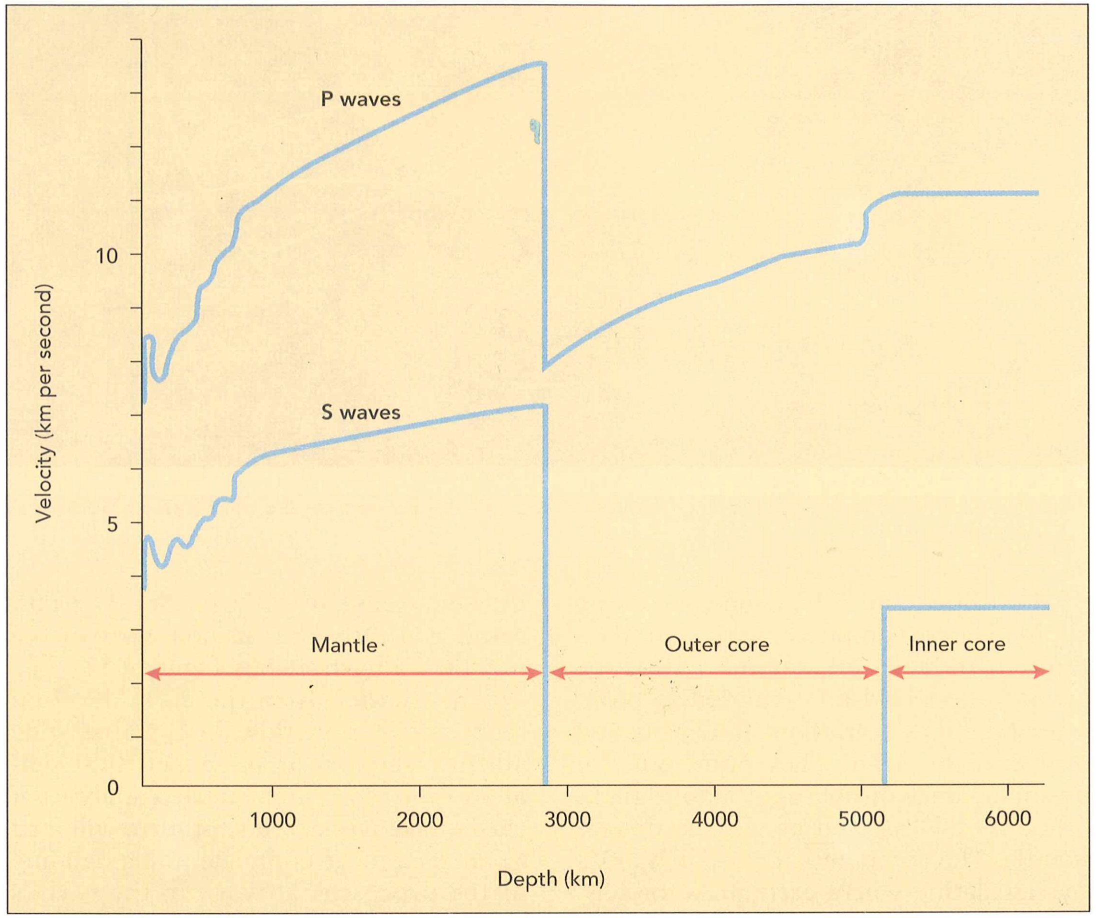

Figure 4.10 The Speed of Seismic Waves in the Earth's Interior

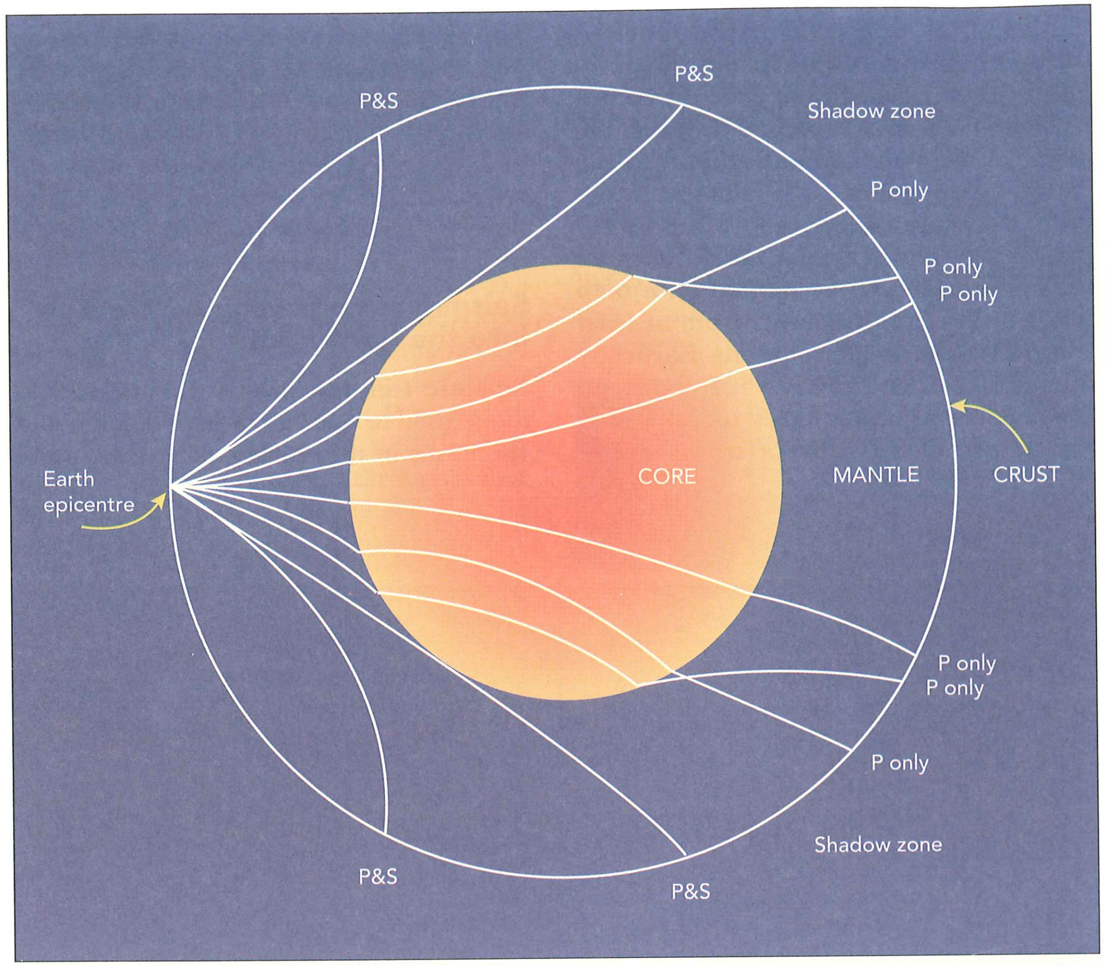

Figure 4.11 Refraction of Earthquake Waves as They Pass Through Layers of Different Densities

of the upper and lower mantle. Using sophisticated computer programs, data from hundreds of seismic stations around the world are analysed to point out where these variations in density and temperature occur. They point out, for example, areas of hot, light mantle rocks ("hot spots") as well as cooler, denser mantle. The computers locate such areas by calculating where earthquake or seismic waves either slow down (in hotter, less dense rocks) or speed up (in cooler, denser areas) in the mantle. The end result is a three-dimensional view of the mantle, as illustrated by Figure 4.12.

This method is in the early development stages. A worldwide digital seismic station network is proposed that will allow even more sophisticated analyses of earthquake waves. This, in turn, will lead to an even more complete understanding of the processes at work in the earth's interior.

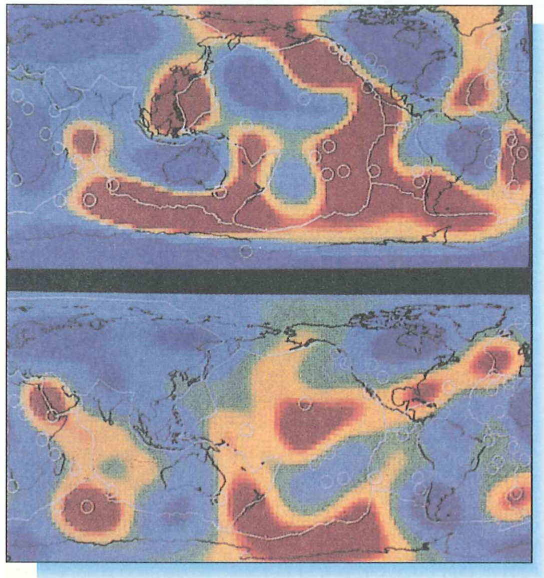

Figure 4.12 **Seismic Tomography** A CAT Scan of the Temperature Variations in the Earth's Interior

The Importance of the Interior Heat Engine

The interior of the earth seems very remote from our daily lives, except, of course, for people who live near volcanoes or hot springs. Otherwise, we are generally unaware of its impact upon us.

Nevertheless, life on earth has been profoundly influenced by the interior and its basic characteristics. Take magnetism, for example. The **magnetic field** of the earth, shown in Figure 4.13, is generated by movements of the molten iron and nickel layer of the outer core. Convection currents in the electrically conducting fluid of the core act as a dynamo, generating and maintaining a magnetic field. Without this dynamo effect, the magnetic field would die out within 10 000 years or so. Physicists are still debating exactly how this magnetic field is actually created, but it is known that the magnetic field has existed over at least the last 3.5 billion years of the earth's history. How would compasses be useful without a magnetic field?

We see the effects of the interior of the earth in other ways, as well. The heat generated by radioactive decay powers very slow moving convection currents in the asthenosphere and mantle. These currents in the asthenosphere cause the movements of the huge, rigid plates that make up the lithosphere, movements that are responsible for the formation of the mountain ranges, deep sea trenches, volcanic belts,

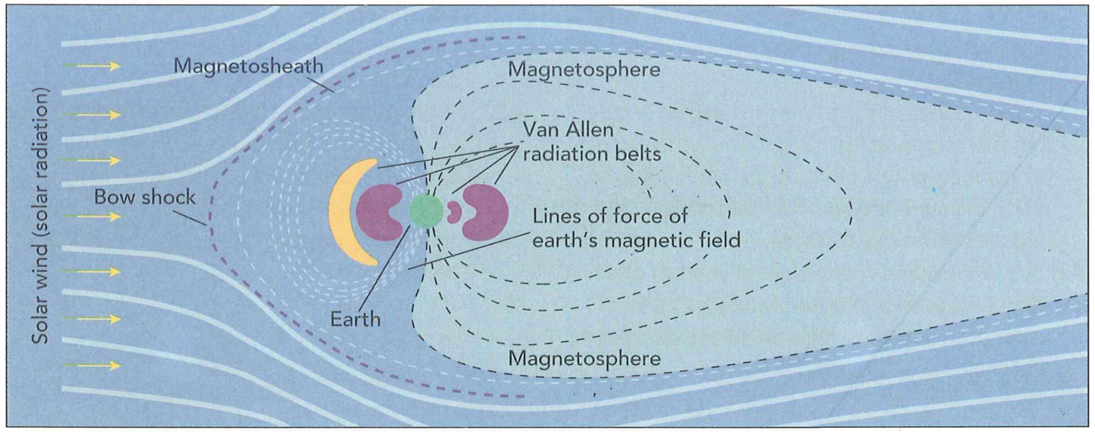

Figure 4.13 The Earth's Magnetosphere and Magnetic Field, Including the Van Allen Radiation Belts