TOPIC III
MEASURING THE EARTH

Computer graphics are used to create sophisticated models of the earth.

CHAPTER 4
A Model of the Earth

You will know something about the earth as a planet if you can:

1. Describe various ways in which models are used.
2. Explain how the earth's shape and size are known.
3. Identify and describe the three parts of the earth's surface.

We are all accustomed to the "fact" that the earth is round. We take it so much for granted that we don't realize how hard it is to conceive of this idea without modern means of travel and observation. Yet 2,000 years ago, scientists (or "philosophers," as they were often called) had shown that the earth must be shaped like a ball. Eratosthenes (whom we will meet later in this chapter) had even calculated its size with remarkable accuracy. How could this be done without telescopes, radio, clocks precise to a billionth of a second, spacecraft, or even high-speed cars?

In this chapter and in the following chapters we are going to show you how the scientists of the past developed their model of the earth, using careful observation and simple instruments.

Since we are going to develop a model of the earth, the first thing we should do is make clear what we mean by the term model. We should also find out what kinds of models we can use.

MODELS

We can begin by saying that a model is anything that represents the properties of an object or a system. Some models are miniature copies of the things they represent, while other models represent things that cannot be seen.

Types of Models. There are a number of different kinds of models, and some of them we see every day.

1. *Physical and mechanical models. Physical models* are models that provide us with information through our sense of sight. Common examples include things like globes, dollhouses, and model planes and cars. An architect's drawing of a building is another example of a physical model.

Some physical models have working parts so that they can perform the same functions or movements as the original object. This type of model is called a *mechanical model.* A model electric train is a mechanical model.

Figure 4-1. An electric train—a mechanical model.

In both physical and mechanical models, size is an important factor. In most models all parts of the model are made in the same proportions as the parts of the original. They are all made to the same *scale*. For example, if you were building a model car, you wouldn't make the model one-tenth as long as the actual car and only one-twentieth as wide. This would change the proportions of the car.

The blueprints for a skyscraper or an engineer's plans for a rocket engine must be exactly to scale and very accurate. But it is impossible to make a schoolroom model of our solar system to scale because of the differences in size between the sun and the planets and the great distances involved.

Figure 4-2. A scale model of a bridge.

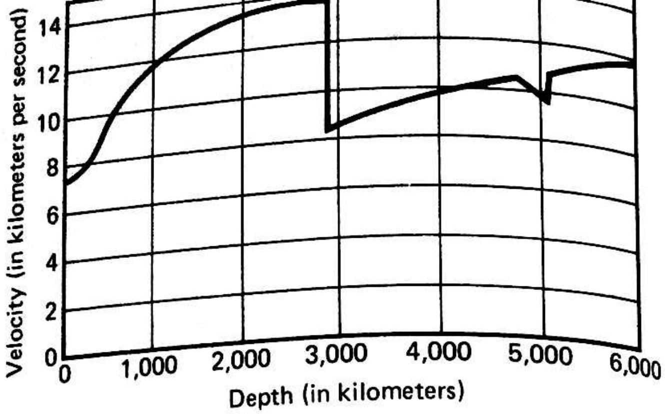


Figure 4-3. A graph showing how the velocity of one type of earthquake wave varies with depth below the earth's surface.

2. *Mental models.* Some models exist only in your mind. These are *mental models.* They are models of things that cannot be observed. There are many scientific concepts that cannot be illustrated with physical models. You cannot construct a physical model that shows you exactly what happens in an electric circuit when the current is turned on. But when you study physics and electricity you develop a mental model of this event. Another example of a mental model might be your idea of a friend's feelings.

3. *Mathematical models.* Scattered throughout this text are mathematical relationships, such as "density equals mass divided by volume," or "volume equals length times height times width." These relationships are usually expressed in mathematical symbols, such as $D = M/V$. These relationships, whether in words or symbols, are mathematical models that express certain properties of an object or system.

4. *Graphic models.* Graphs are commonly used to provide a picture of the relationship of one factor to another. For example, Figure 4-3 is a graph showing how the velocity of one type of earthquake wave varies with depth below the surface. Graphs are often used when no simple mathematical relationship between the factors can be found. But even when a mathematical relationship between two quantities is known, a graph may make it easier to see the nature of the relationship.

In this section we have talked about some of the kinds of models we use, both in science and in everyday life. What we call the models is not the important thing. What *is* important is to know *when* we are using a model and what we are using it for. We must always bear in mind that a model is not the real thing, but only a helpful device for trying to understand the real thing.

SUMMARY

1. A model is anything that represents the properties of an object or system.
2. Types of models include physical, mechanical, mental, mathematical, and graphic models.
3. The scale of a physical model is the ratio of the dimensions of the model to the dimensions of the real object.

THE SHAPE OF THE EARTH

Photographs of the earth taken from space have provided final proof that the earth is spherical in shape (see Figure 4-4). As we shall see later in this chapter, it is not a perfect sphere, but it is pretty close to one.

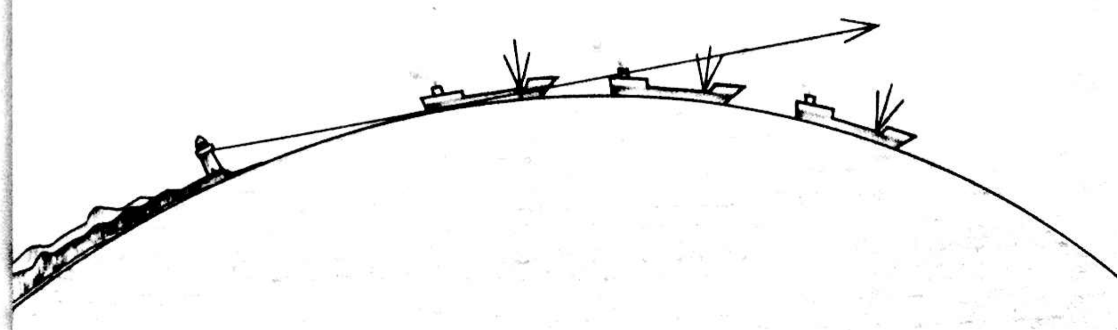
As we have already stated, scientists have known for over two thousand years that the earth is round. What observations led them to this conclusion? Let's begin with two everyday sights that, when you think about it, give us some evidence about the shape of the earth.

Figure 4-4. The earth as seen from space.

First, look around you as the sun is setting some evening. Notice how, as the sun slips below the horizon, the last sunlight lingers on the tops of the trees, then on hilltops, and finally, on clouds in the sky. (Jet plane condensation trails are startling when seen in a clear sky just after sunset.) The higher you are, the longer you can see the sun. People must have noticed this. What explanation could they have had?

Our second example involves a large object either disappearing or appearing over the horizon (see Figure 4-5). Suppose you are standing on shore watching a ship sail out to sea. As you watch, the ship begins to pass over the horizon. It disappears from the bottom up. First the hull, or bottom, of the ship is lost from view. Then the rest of it gradually disappears. The last parts of the ship you can see are the smokestacks, then the smoke from the smokestacks, and then nothing. If a ship were sailing toward you from over the horizon, it would appear in the opposite order. You would first see the smoke, then the stacks, and finally the ship itself. (Of course, 2,000 years ago you would have seen sails and masts, not smokestacks.) How can you account for the way things disappear and appear over the horizon?

Figure 4-5. Evidence for the shape of the earth. As a ship moves away toward the horizon, its upper portions remain visible after the lower portions have disappeared. The drawing shows why this is to be expected if the earth's surface is curved. As the ship sails away, it gradually drops below the observer's line of sight.



You may have jumped to the conclusion that these examples prove that the earth is round. They don't! The only inference you can really draw from these observations is that the earth is apparently curved, perhaps like an inverted saucer. They do not necessarily mean that the earth is a sphere.

Let's look at some other occurrences that give us evidence about the shape of the earth.

Eclipses. As you may know, there are two types of eclipses—eclipses of the sun and eclipses of the moon.

An eclipse of the sun (a solar eclipse) occurs when the moon passes between the earth and the sun. An eclipse of the moon (a lunar eclipse) occurs when the earth comes between the sun and the moon. In each case, one object cuts off the sun's light from the other.

The earth and the moon cast long, cone-shaped shadows in space (see Figure 4-6). These shadows can fall on another celestial object, just as your shadow might fall on another person's face. During a lunar eclipse the earth's shadow moves across the face of the moon, blacking it out. The shadow cast by the earth is larger than the moon. Therefore, you cannot see the whole of the earth's shadow on the moon. However, the part of the shadow that you can see is curved

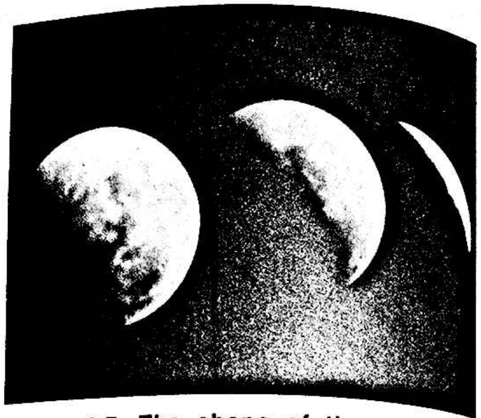
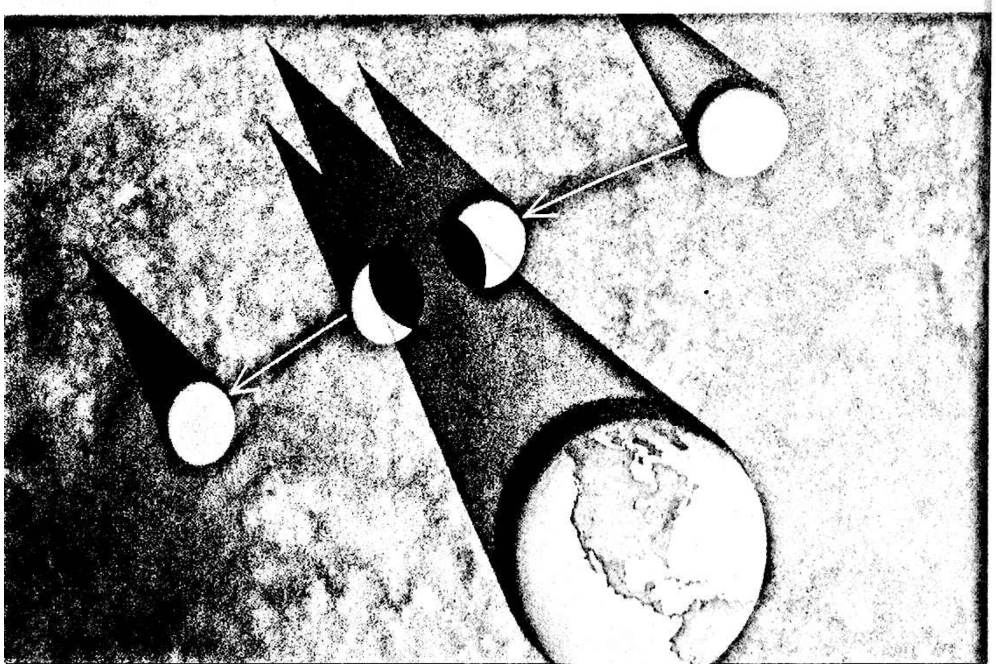


Figure 4-7. The shape of the earth's shadow. The curved shape of the earth's shadow on the face of the moon during an eclipse suggests that the earth is round.

Figure 4-6. The earth's shadow and eclipses of the moon. During a lunar eclipse the full moon enters and passes through the shadow that the earth casts in space.



(Figure 4-7). This suggests rather strongly that the earth is circular in shape. However, this does not prove that the earth is a ball. It could be a flat disk, like a coin, and still cast a circular shadow.

Polaris. In the Northern Hemisphere there is one star that seems to remain stationary in the sky. All the other stars appear to move around this star in the course of 24 hours. Because it is almost directly over the North Pole, this stationary star is called the North Star, the pole star, or Polaris. At the equator, Polaris is always on the horizon. As you travel northward, it appears higher and higher in the sky—its angle with the horizon increases. At the North Pole, Polaris is directly overhead. Its angle with the horizon is 90°.

If you traveled directly north from the equator from a number of locations around the earth, you might notice an interesting fact. From each location, the altitude of Polaris increases the same amount for each kilometer of northward movement. The only reasonable explanation for these observations is that the earth is spherical in shape.

Precise Shape of the Earth. Observations of the kind we have described lead to the conclusion that the earth is a sphere. However, as the observations are made more precise, we find evidence that the earth is slightly flattened at the poles and slightly bulging at the equator. For example, on a truly spherical earth, the altitude of Polaris and the distance north of the equator should change exactly in step. They don't. Careful measurements show a small variation from perfect agreement.

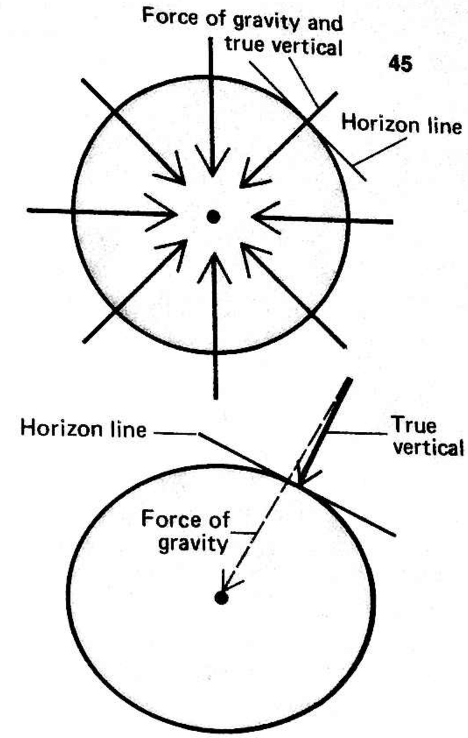


Figure 4-8. Force of gravity and the shape of the earth. The fact that the direction of the force of gravity is not a true vertical at every point on the earth's surface is evidence that the earth is not a perfect sphere.

Another measurement that we can make with high precision today gives similar results. This is the measurement of the force of gravity. According to Newton's theory of gravitation, the force of gravity on the surface of a perfect sphere is directed toward the center of the sphere. If the earth were a perfect sphere, the force of gravity would be straight down (at right angles to the horizontal) wherever you were on the earth's surface. Observations of gravity with very sensitive instruments show that this is not the case. The observations indicate that the earth is a slightly flattened sphere. Figure 4-8 shows why the force of gravity is not always vertical on a flattened sphere.

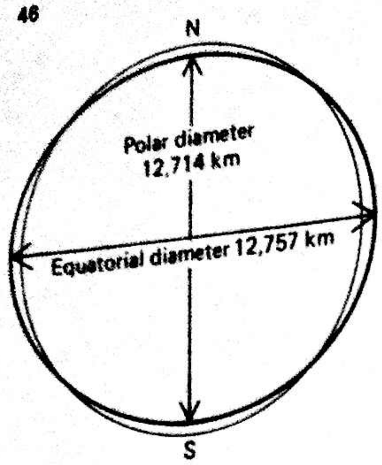


Figure 4-9. Exaggerated drawing of the shape of the earth. If drawn to scale, the drawing would look like a perfect circle.

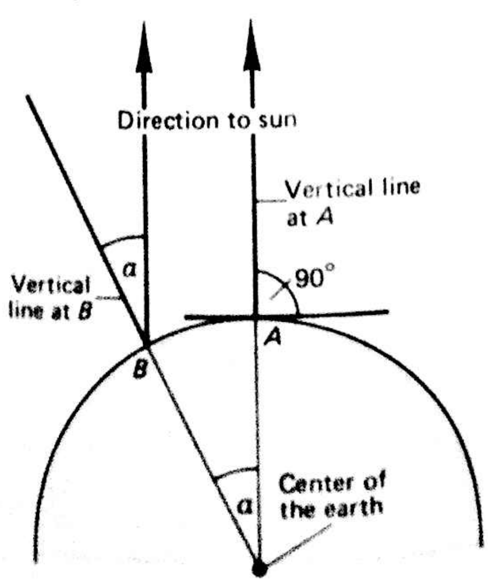
Furthermore, on a perfectly spherical earth, the force of gravity should have the same strength at all places on the surface. Measurements of the force of gravity with an instrument called a *gravimeter* show that gravity is not the same everywhere on the earth. It is slightly less at the equator than at the poles. These observations agree with the conclusion that the earth is slightly flattened at the poles. Because of this flattening, an object near the poles is closer to the earth's center than one at the equator and therefore is acted upon by a slightly stronger gravitational force. (A more complete discussion on the force of gravity and how it depends on distance will come up later, in Chapter 7.)

The shape of a ball that is flattened at the top and bottom and bulging around the middle is called an *oblate spheroid*. This is the shape that the earth appears to have from the observations just described. However, you should keep in mind that the amount of flattening at the poles and bulging at the equator is very slight, as shown by the small differences in diameters drawn through these two regions (see Figure 4-9).

SIZE OF THE EARTH

Among the ancient Greek philosopher-scientists, it was generally believed that the earth was a sphere. Aristotle used the fact that the visible stars shifted as you traveled north or south as evidence that the earth was spherical. He gave an estimate of its size (probably about 50% too large), but did not say how he had arrived at it. Eratosthenes is generally credited as the first man to make a scientific determination of the earth's circumference. He lived from about 275 to 195 B.C., and spent more than half his life in Alexandria, where he was head of the great library in that city. He was one of the greatest scholars of his time, an excellent mathematician, geographer, historian, and astronomer.

Figure 4-10. The angle of the sun at two different places on the earth's surface.



Eratosthenes knew that in the city of Syene in Egypt the noon sun was directly overhead at the summer solstice (the day the sun reaches its highest point in the sky). This fact was based on the observation that at noon that day the sun could be seen reflected from the water in a deep well.

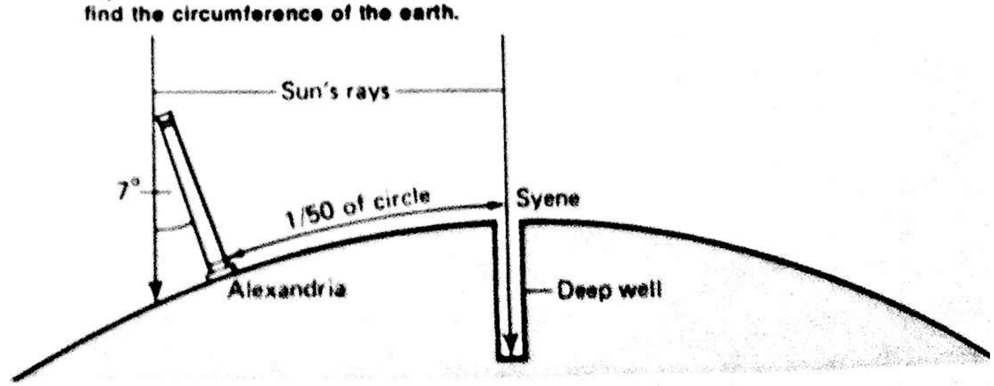
Eratosthenes also knew that Alexandria, where he was located, was almost exactly due north of Syene, and that at noon at the summer solstice the sun was not directly overhead in Alexandria. Eratosthenes saw that he could use these observations to calculate the circumference of the earth.

To understand Eratosthenes' method for calculating the circumference of the earth, examine Figure 4-10. We assume there is an observer at *A* for whom the sun is directly overhead. For him the altitude of the sun is 90° from the horizon. An observer at *B* measures the angle of the sun at the same time. He finds the altitude to be less than 90°. The sun is assumed to be so far from the earth that its rays reaching any part of the earth are practically parallel. The apparent change in angle in going from *A* to *B* is entirely the result of the curvature of the earth's surface. This change in angular elevation of the sun is the same as the angle *a* at the center of the earth. Angle *a* is some fraction of a full circle (360°), which we can calculate. The arc along the surface from *A* to *B* is the same fraction of the complete circle around the earth. If we know the distance from *A* to *B*, it is a simple matter to calculate the length of the full circle.

Now compare Figure 4-10 with Figure 4-11. You can see that Syene can serve as point *A* and Alexandria can serve as point *B*. So, all that Eratosthenes needed to do was to measure the angle of the sun at noon at the summer solstice in Alexandria. He found that the angle of the sun at that moment was a little more than 7° from the perpendicular, which corresponds to an arc of about 1/50 of a circle. He therefore could state that the circumference of the earth was 50 times the distance between Alexandria and Syene.

Eratosthenes expressed his estimate of the earth's size in units called *stadia* (singular, *stadium*). Taking the distance between Alexandria and Syene as 5,000 stadia, he obtained a value of 50 × 5,000, or 250,000, stadia as the circumference of the earth. Much has been made of the question of how close to our modern measurements he came. Nobody really knows, because nobody knows how long one stadium was. But this is quite

Figure 4-11. How Eratosthenes used the conditions at Alexandria and Syene to find the circumference of the earth.



unimportant. Eratosthenes was not trying for great accuracy. He knew he couldn't get it. The fraction 1/50, and the distance 5,000 stadia, are plainly numbers that have been rounded off. What is important is the beauty and simplicity of the method and the good result it gave for that time. The circumference of the earth *is* very nearly 50 times the distance from Alexandria to Syene (Aswan).

Many hundreds of years passed before anyone made a more accurate determination of the size of the earth. Today we can measure the earth with great accuracy through the use of orbiting satellites. Its various dimensions are given in Table 4-1.

Table 4-1. Measurements of the earth.

	ACCEPTED	APPROXIMATE
Mass	5.975×10^{27} gm	6×10^{27} gm
Volume	1.08×10^{27} cm^3	1.1×10^{27} cm^3
Average density	5.52 gm/cm^3	5.5 gm/cm^3
Radius (N–S Pole)	6,378 km	6,400 km
Radius (equator)	6,346 km	6,400 km
Circumference (polar)	40,008 km	40,000 km
Circumference (equator)	40, 076 km	40,000 km

SUMMARY

1. Several simple observations can lead to the conclusion that the earth is curved.
2. Observations of Polaris at various distances north of the equator and from different locations around the earth lead to the conclusion that the earth is spherical.
3. Precise measurements of the force of gravity at varying locations indicate that the earth is an oblate spheroid—slightly flattened at the poles and slightly bulging at the equator.
4. The circumference of the earth can be calculated from measurements of the sun's altitude at the same time in two different locations.
5. The circumference of the earth measured along a circle through the poles is less than the circumference measured along the equator.
6. The best evidence about the size and shape of the earth comes from photographs and measurements taken from orbiting satellites.

PARTS OF THE EARTH

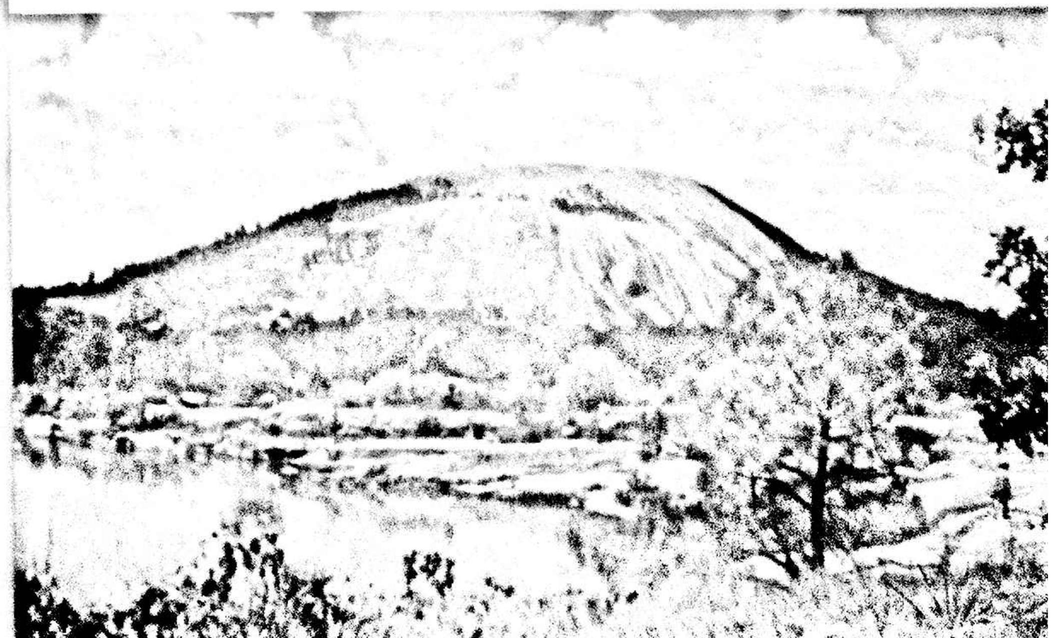
Now that we know something about the shape and size of the earth, we can continue to develop our model of this planet. Perhaps the next thing we should do is to describe the surface of the earth. We know that part of the earth's surface is land and part is water. We also know that the entire earth is surrounded by a layer of air. Thus the surface of the earth can be divided into a solid part, a liquid part, and a gaseous part.

The solid part of the earth's surface is called the *lithosphere*. The liquid part is the *hydrosphere*. And the gaseous layer surrounding the earth is the *atmosphere*. Although in the following paragraphs we will describe each of these "spheres" separately, you will learn in later chapters that the three are closely interrelated.

The Lithosphere. The term *lithosphere* refers to the solid rock that forms a continuous shell around the earth. The lithosphere extends under the oceans and all other bodies of water on the earth's surface. In most places the lithosphere is covered by a layer of soil or other loose material. But if you dig down deep enough, you hit solid rock. In some places the lithosphere is not covered by anything. One such place is shown in Figure 4-12.

The lithosphere has a thin, upper layer called the *crust*, in which the rocks are less dense than in the rest of the lithosphere. The thickness of the crust varies from about 10 km under the oceans to about 30 km under the continents. There is a sharp boundary, or interface, between the crust and the part of the lithosphere below it. The lower boundary of the lithosphere is less distinct, but it is believed to be a region about 100 km below the surface where the rocks are soft and plastic.

Figure 4-12. Stone Mountain, Georgia.



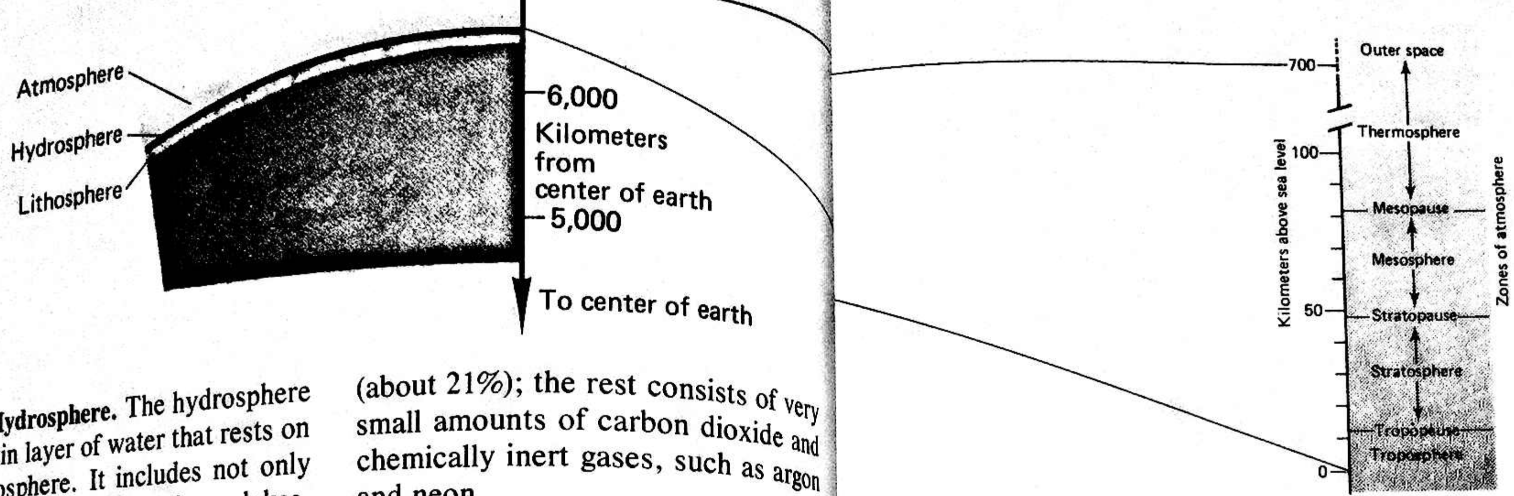


Figure 4-13. A cross section of the earth showing the three outer spheres. The drawing is not to scale.

The Hydrosphere. The hydrosphere is the thin layer of water that rests on the lithosphere. It includes not only the water of the oceans, rivers, lakes, and streams, but also the water in the icecaps of the Arctic and Antarctic and all the water below the surface in spaces between soil and rock particles.

About 70% of the earth's surface is covered by water. But as you can see in Figure 4-13, the layer of water is so shallow compared with the diameter of the earth that it is really like a thin film. The average depth of the water layer is less than 4 kilometers, while the diameter of the earth is more than 12,700 kilometers.

The Atmosphere. The atmosphere is a thin layer of gases that surrounds the earth. Not counting the variable amounts of water vapor, the atmosphere is made up almost completely of nitrogen (about 78%) and oxygen (about 21%); the rest consists of very small amounts of carbon dioxide and chemically inert gases, such as argon and neon.

The atmosphere extends upward from the earth to a height of several hundred kilometers, gradually thinning out to nothing. This shell of gas is made up of various layers, each with its own characteristics. Most of the mass of the atmosphere is concentrated in the layers nearest the earth. That is, the air is most dense at sea level and becomes progressively thinner as you go higher.

Figure 4-13 shows the layers, or zones, of the atmosphere. There is no sharp line between one zone and the next, but the transition occurs over a fairly narrow change in altitude. The layers differ from one another in temperature, chemical composition, and other general characteristics.

SUMMARY

1. The lithosphere is a layer of solid rock that forms a shell around the earth.
2. The hydrosphere is a thin film of water that rests on the lithosphere and covers about 70% of the earth's surface.
3. The atmosphere is a shell of gases that surrounds the earth, extending upward for several hundred kilometers. It is layered, or stratified, into distinct zones, each with its own characteristics.

REVIEW QUESTIONS

Group A

1. What is a *model?*
2. Identify and describe five different types of models.
3. What is meant by the *scale* of a physical model?
4. Describe two simple observations that lead to the conclusion that the earth is curved.
5. Explain how observations of Polaris indicate that the earth is spherical.
6. Explain how sensitive measurements of the force of gravity provide information about the shape of the earth.
7. Name and describe the actual shape of the earth.
8. Describe how measurements of the altitude of the sun at the same time at two different locations can be used to calculate the circumference of the earth.
9. From what do we obtain the best evidence for determining the exact size and shape of the earth?
10. What is the *lithosphere?*
11. What is the *hydrosphere?*
12. What is the *atmosphere?*

Group B

1. Describe two different types of models you could use to represent the earth. Explain how scale is involved in each of these models.
2. a. State one observation from which you might *infer* a round earth. Explain how this observation could also be interpreted as indicating a different shape for the earth.
   b. Is there any evidence that could be accepted as *proof* of the earth's shape?
3. Suppose you were to construct a model of the earth to scale, using 1 cm = 1000 km.
   a. How deep would the lithosphere appear on this model?
   b. How deep would the hydrosphere appear on this model?
   c. How deep would the atmosphere appear on this model?