

# Chapter 15

## What You'll Learn

- How scientists study oceans, how the oceans formed, and where they are located.
- How the physical and chemical properties of seawater differ from those of freshwater.
- What causes tides, waves, and ocean currents.

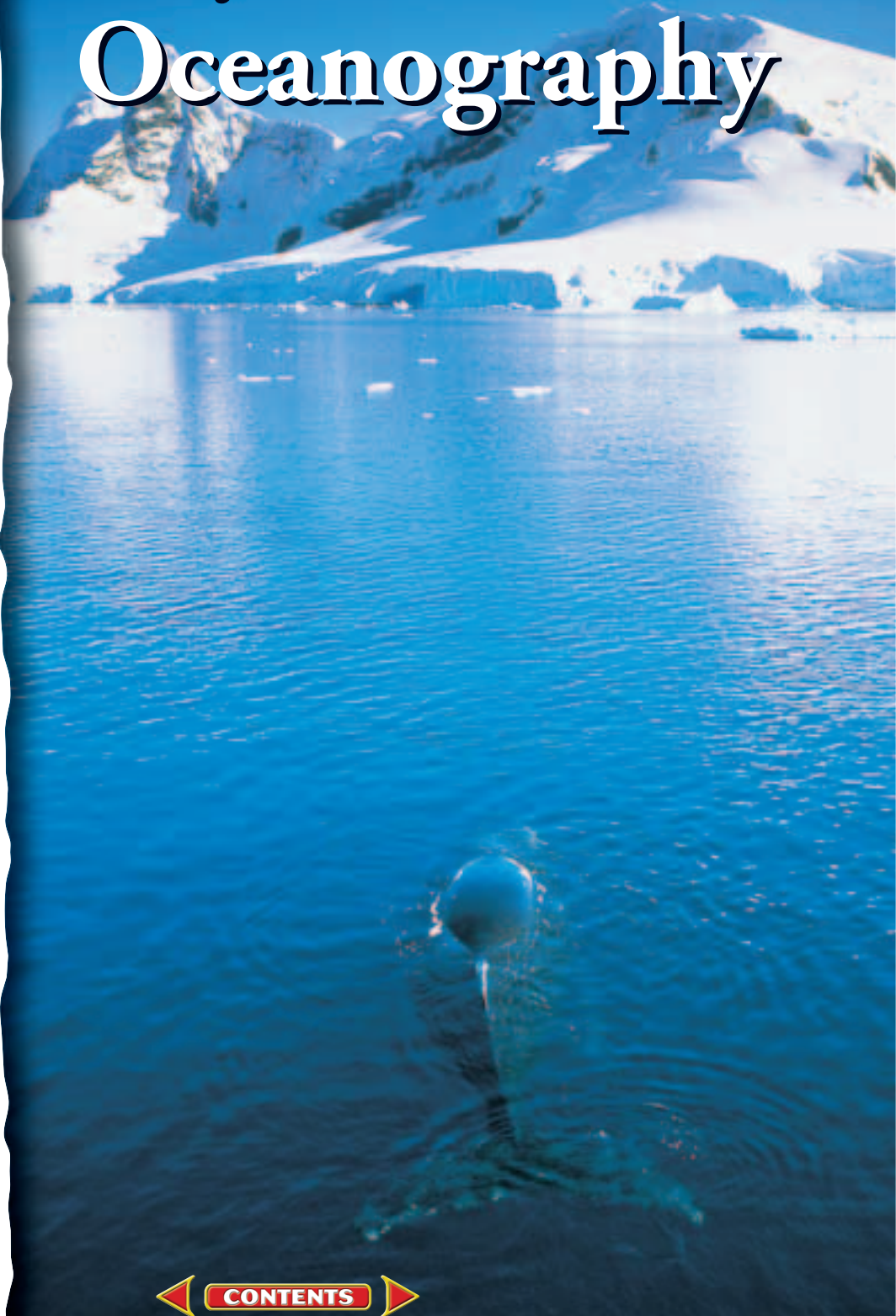
## Why It's Important

More than 71 percent of Earth's surface is covered by oceans. These vast bodies of water affect weather, climate, food supplies, recreation, global trade, and marine life, such as this humpback whale in Paradise Bay, Antarctica.



To learn more about oceanography, visit the Earth Science Web Site at [earthgeu.com](http://earthgeu.com)

# Physical Oceanography



## Discovery Lab

### Measure Earth's Land and Water

Earth is often referred to as the “blue planet” because so much of its surface is made up of water. If you study a globe or a photograph of Earth taken from space, you can clearly see that oceans cover much more of Earth than landmasses do. This activity will help you to quantify the amount of water on Earth's surface.

1. Stretch a piece of string about 1 m in length around the equator of a globe.
2. Use a blue marker to color the sections of the string that cross the oceans.

3. Measure the length of the globe's equator, then measure the length of each blue section on the string. Add the lengths of the blue sections.

4. Divide the total length of the blue sections by the length of the globe's equator.

**Observe** What percentage of the globe's equator is made up of oceans? What percentage of the globe's equator is made up of land? Study the globe again. Are the oceans separate bodies of water, or do they interconnect? Describe your observations in your science journal.



## SECTION

## 15.1

## The Oceans

### OBJECTIVES

- **Identify** methods used by scientists to study Earth's oceans.
- **Discuss** the origin and composition of the oceans.
- **Describe** the distribution of oceans and major seas.

### VOCABULARY

oceanography  
side-scan sonar  
sea level

Since prehistoric times, people have used Earth's oceans for travel and recreation and to obtain food. Early Polynesians and Phoenicians were accomplished sailors who discovered new lands and sea routes for commerce. These seafarers acquired considerable knowledge of the oceans, but they lacked the technology to explore the ocean depths. Such exploration had to wait until the late 1800s, when the British *Challenger* expedition became the first research ship to use relatively sophisticated measuring devices to study the oceans. *Challenger* also was the first expedition devoted exclusively to the scientific study of Earth's oceans, known as **oceanography**. The discipline of oceanography is usually considered to have started with the *Challenger*.

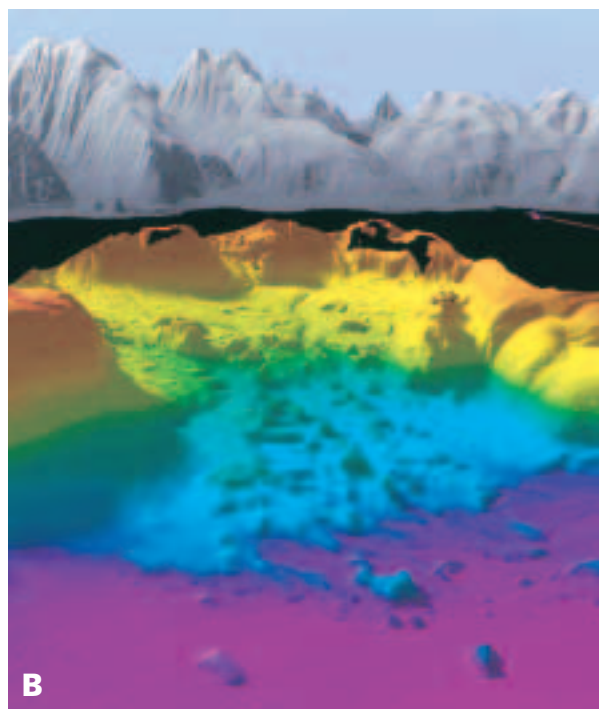
### MODERN OCEANOGRAPHY

The *Challenger* expedition investigated ocean currents, water temperature and chemical composition, seafloor sediments and topography,

and marine life. The expedition used nets, bottom dredges, and other tools to gather enough research to fill 50 thick volumes. Later expeditions, such as that of the German research ship *Meteor* in the 1920s, used sonar for the first time to map the seafloor features of the South Atlantic Ocean, including the Mid-Atlantic Ridge. *Sonar* stands for *sound navigation and ranging*. It uses the return time of an echo and the known velocity of sound in water to determine water depth. The velocity of sound in water is 1500 m/s. To determine ocean depth in a particular place, scientists send a sonar signal to the ocean floor and time its return, or echo. They multiply the time by 1500 m/s, then divide by 2 to calculate the distance to the ocean floor. **Figure 15-1** has more information about sonar.

**Figure 15-1** A ship equipped with sonar can gather data about deep-lake and ocean-floor features **(A)**. Computers use the resulting data to make maps of underwater features such as this color-enhanced map of Lake Tahoe in Nevada **(B)**.

**Advanced Technology** Recent technological advances such as the one shown in **Figure 15-2** have tremendously expanded scientific knowledge of the oceans. Satellites such as the *Topex/Poseidon* continually monitor the ocean's surface temperatures, currents, and wave conditions. Submersibles, or underwater vessels, investigate the deepest ocean trenches. Large portions of the seafloor have been mapped using **side-scan sonar**, a technique that directs sound waves to the seafloor at an angle, so that the sides of underwater hills and other topographic features can be mapped. You'll





**Figure 15-2** The *Topex/Poseidon* satellite orbits 1331 km above Earth, gathering data about the oceans.

learn more about seafloor topography in the next chapter. For now, let's examine what all the various oceanography studies have taught us about the ocean's origin and composition.

## ORIGIN OF THE OCEANS

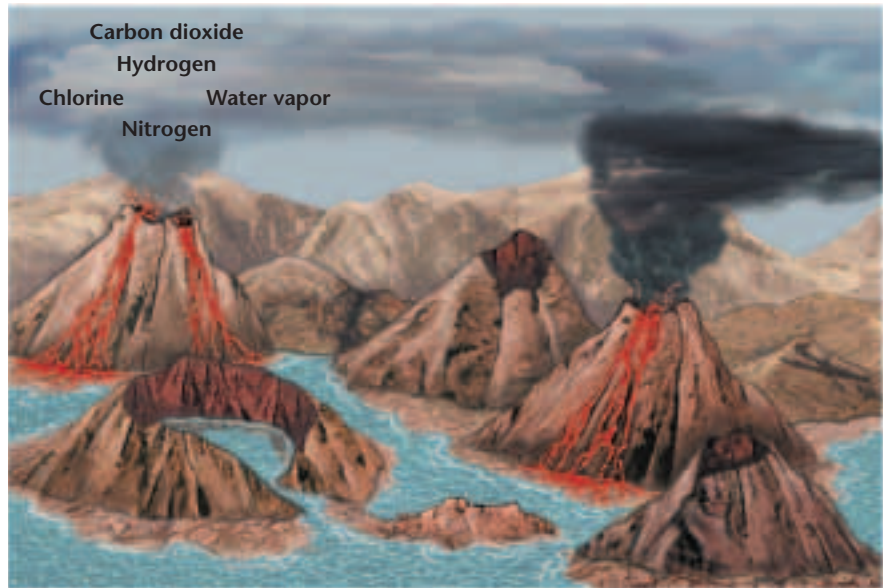
Have you ever wondered whether Earth has always had oceans? Several geological clues indicate that oceans have existed almost since the beginning of geologic history. Studies of radioactive isotopes indicate that Earth is about 4.6 billion years old. Scientists have found rocks nearly as old that formed from sediments deposited in water. Ancient lava flows are another clue—some of these lava flows have glassy crusts that form only when molten lava is chilled rapidly under water. Radioactive studies and lava flows offer evidence that there has been abundant water throughout Earth's geologic history.

**Where did the water come from?** Scientists hypothesize that Earth's water could have originated from two sources. Comets, such as the one shown in *Figure 15-3*, travel throughout the solar system and occasionally collide with Earth. These impacts release water, possibly enough to have filled the ocean basins over geologic time. In addition, studies of meteorites, which are composed of the same material that may have formed the early planets, indicate that meteorites contain up to 0.5 percent water. If the early Earth contained the same percentage of water, it would have been more than sufficient to form the early oceans. However, some mechanism must have existed to allow the water to rise from deep in Earth's interior to its surface. Scientists theorize that that mechanism was volcanism.

**Figure 15-3** Comets such as Hyakutake are composed of dust and rock particles mixed with frozen water and gases. Early in Earth's geologic history, collisions with comets may have released water that, over an extremely long period of time, formed the first oceans.



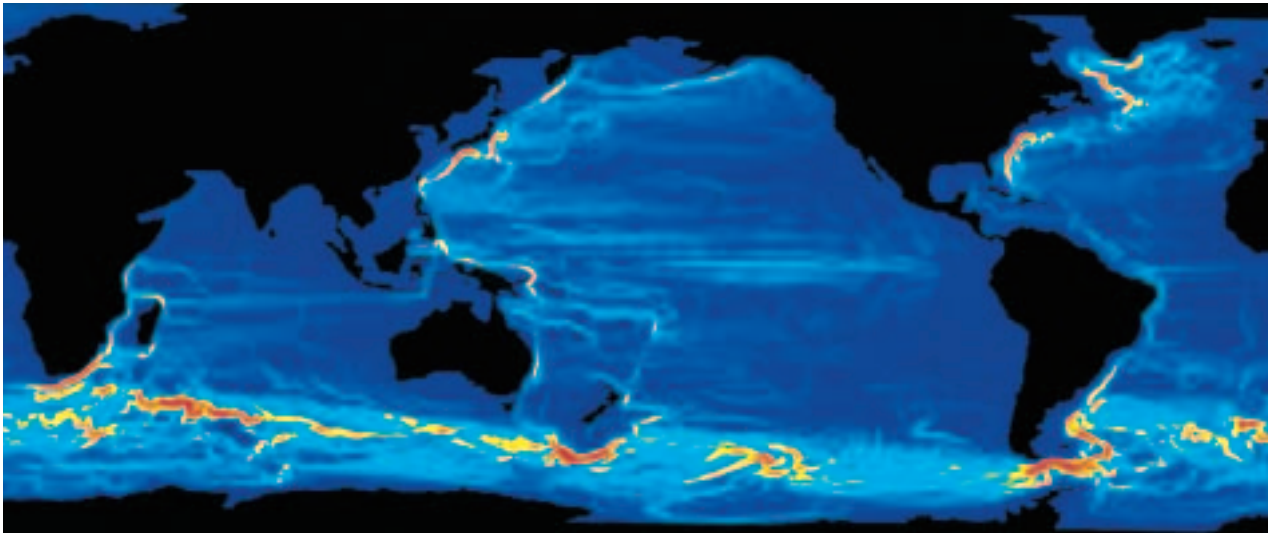
**Figure 15-4** In addition to comets, water for Earth's early oceans may have come from volcanic eruptions. An intense period of volcanism occurred shortly after the planet formed. This volcanism released large quantities of water vapor and other gases into the atmosphere. The water vapor eventually condensed into oceans.



**Volcanism** During volcanic eruptions, significant quantities of gases are emitted. These volcanic gases consist mostly of water vapor and carbon dioxide. Shortly after the formation of Earth, when the young planet was much hotter than it is today, an episode of massive, violent volcanism took place over the course of perhaps several hundred million years. As shown in *Figure 15-4*, this volcanism released huge amounts of water vapor, carbon dioxide, and other gases, which combined to form Earth's early atmosphere. As Earth's crust cooled, the water vapor gradually condensed into oceans. By the time the oldest known crustal rock formed some 4 billion years ago, Earth's oceans may have been close to their present size. Water is still being added to the hydrosphere by volcanism, but some water molecules in the atmosphere are continually being destroyed by ultraviolet radiation from the Sun. These two processes balance each other. What do you think would happen over geologic time if they didn't?

### DISTRIBUTION OF EARTH'S WATER

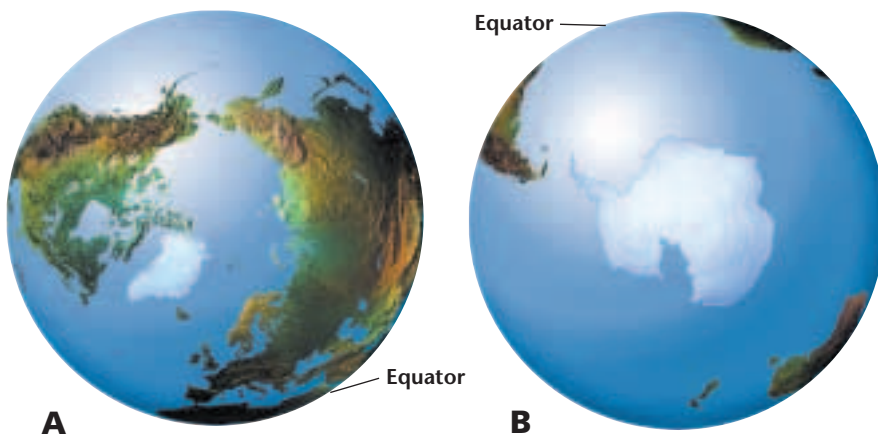
The oceans contain 97 percent of the water found on Earth. Another 3 percent is freshwater located in the frozen ice caps of Greenland and Antarctica and in rivers, lakes, and underground sources. The percentage of ice on Earth has varied over geologic time from near zero to perhaps as much as 10 percent of the hydrosphere. Thus, global **sea level**, which is the level of the oceans' surfaces, has risen and fallen by hundreds of meters in response to melting ice during warm periods and expanding glaciers during ice ages. Other processes that affect sea level are tectonic forces that lift or lower portions of the seafloor. A rising seafloor causes a rise in sea level, while



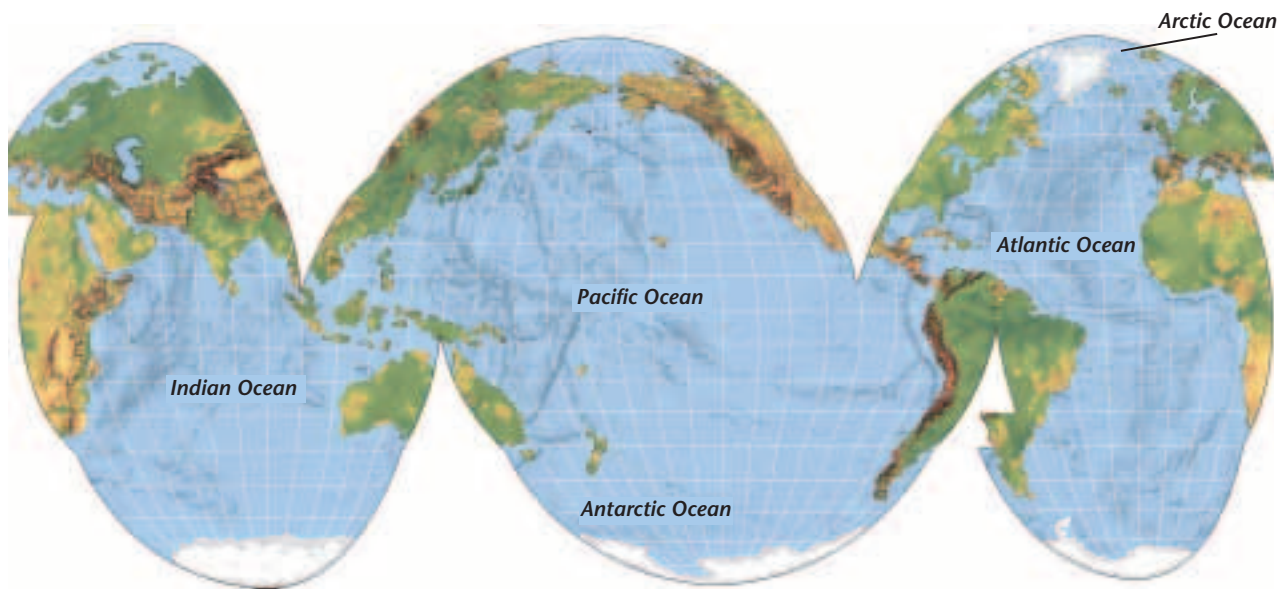
**Figure 15-5** The vast interconnected oceans of Earth, the “blue planet,” can clearly be seen in this computer image. The colors represent the speeds of ocean currents. Red is the fastest, blue is the slowest.

a sinking seafloor causes sea level to drop. At present, average global sea level is slowly rising at a rate of 1 to 2 mm per year in response to melting glaciers.

**The Blue Planet** As shown in the image of Earth in *Figure 15-5*, Earth is known as the “blue planet” for good reason—approximately 71 percent of its surface is covered by oceans. The average depth of these oceans is 3800 m. Earth’s landmasses are like huge islands, almost entirely surrounded by water. Because most landmasses are in the northern hemisphere, oceans cover only 61 percent of the surface there. However, 81 percent of the southern hemisphere is covered by water. *Figure 15-6* shows the distribution of water in the northern and southern hemispheres. Note that all the oceans are really one vast, interconnected body of water. They have been divided into specific oceans and seas largely because of historic and geographic considerations.



**Figure 15-6** The northern hemisphere is covered by slightly more water than land (**A**). The southern hemisphere, however, is covered mainly by water (**B**).



**Figure 15-7** The Pacific, Atlantic, and Indian Oceans stretch from Antarctica to the north. The smaller Arctic and Antarctic Oceans are located near the north and south poles, respectively.

**Major Oceans** As *Figure 15-7* shows, there are three major oceans: the Pacific, the Atlantic, and the Indian. The Pacific Ocean is the largest. Containing roughly half of Earth's seawater, it is larger than all of Earth's landmasses combined. The second-largest ocean, the Atlantic, extends for more than 20 000 km from Antarctica to the arctic circle. North of the arctic circle, the Atlantic Ocean is often referred to as the Arctic Ocean. The third-largest ocean, the Indian, is located mainly in the southern hemisphere. The storm-lashed region surrounding Antarctica, south of 50° south latitude, is known as the Antarctic Ocean.

**Figure 15-8** Ice is present in this polar sea year round.



**Sea Ice** The Arctic and Antarctic Oceans are covered by vast expanses of sea ice, particularly during the winter. In summer, the ice breaks up somewhat, as shown in *Figure 15-8*. Ice is less dense than water, so it floats. When sea-ice crystals first form, a sort of ice-crystal slush develops at the surface of the water. The thickening ice eventually solidifies into individual round pieces called pancake ice. Eventually, these pieces of pancake ice thicken and freeze into a continuous ice cover called pack ice. In the coldest parts of the Arctic and Antarctic Oceans, there is no summer thaw, and the pack ice is generally several meters thick. In the winter, the pack-ice cover may be more than 1000 km wide.



**Figure 15-9** The Aral Sea, located in Asia, is an example of a land-locked body of water.

**Seas** Seas are smaller than oceans and are partly or mostly land-locked. A prominent example, the Aral Sea, is shown in **Figure 15-9**. Another example, the Mediterranean Sea, is located between Africa and Europe. It was the first sea to be explored and mapped by ancient peoples such as the Egyptians, Phoenicians, Greeks, and Romans. Notable seas in the northern hemisphere include the Gulf of Mexico, the Caribbean Sea, and the Bering Sea, which is located between Alaska and Siberia. Keep in mind that all seas and oceans belong to one global ocean whose waters are thoroughly mixed. As a result, ocean water everywhere contains nearly identical proportions of dissolved salts, as you'll learn in the next section.

## SECTION ASSESSMENT

1. What is oceanography? What was learned from the *Challenger* expedition?
2. What is sonar? Which research vessel first used sonar to map the Mid-Atlantic Ridge?
3. What evidence indicates that oceans formed early in Earth's geologic history?
4. Where did the water in Earth's early oceans come from?
5. **Thinking Critically** The Great Lakes contain as much water as some seas. Why aren't they considered to be seas?

### SKILL REVIEW

6. **Measuring in SI** Calculate the distance to the ocean floor if a sonar signal takes six seconds to return to a ship's receiver. For more help, refer to the *Skill Handbook*.



**OBJECTIVES**

- **Compare and contrast** the physical and chemical properties of seawater.
- **Explain** ocean layering.
- **Describe** the formation of deep-water masses.

**VOCABULARY**

salinity  
temperature profile  
thermocline

Have you ever accidentally swallowed a gulp of seawater? If so, you've noticed its salty taste. Seawater is a solution of about 96.5 percent water and 3.5 percent dissolved salts. The most abundant salt in seawater is sodium chloride (NaCl). Other salts present in seawater are chlorides and sulfates of magnesium, potassium, and calcium. In fact, most elements on Earth are present in seawater. Because these substances are dissolved, they are in the form of ions. **Table 15-1** shows the concentrations of the most important ions in the oceans.

**CHEMICAL PROPERTIES OF SEAWATER**

**Salinity** is a measure of the amount of dissolved salts in seawater. Oceanographers express salinity as grams of salt per kilogram of water, or parts per thousand (ppt). The total salt content of seawater is, on average, 35 ppt, or 3.5 percent. In addition to salt ions, seawater contains dissolved gases and nutrients. The dissolved gases are mostly oxygen, nitrogen, and carbon dioxide, and the dissolved nutrients are commonly nitrates, phosphates, and silicates. As you might guess, the nutrients and dissolved gases in seawater greatly affect life in the oceans.

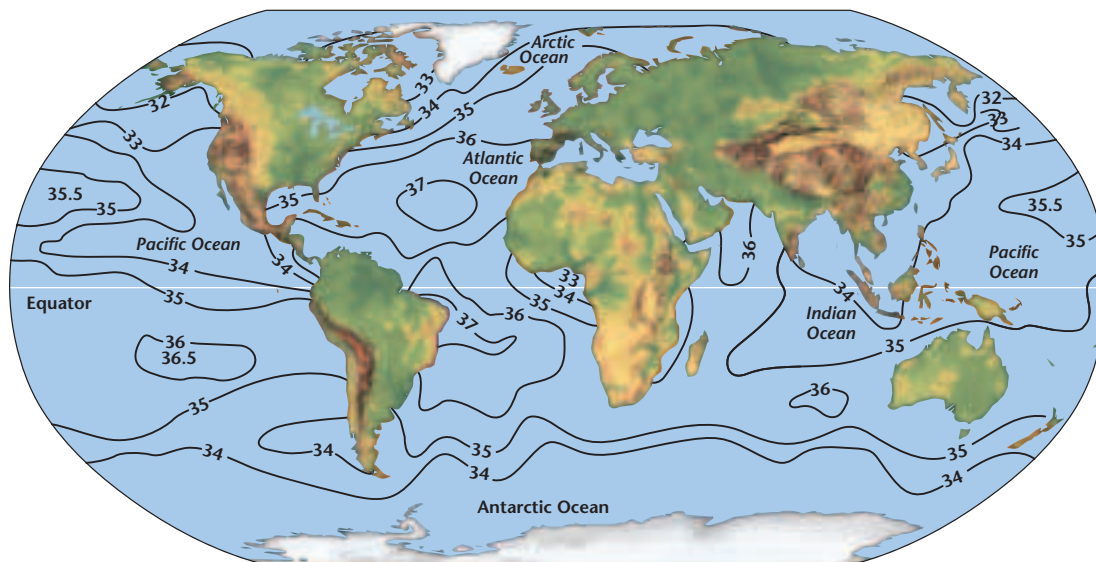


Sodium chloride crystals

**Table 15-1 Major Ions in Seawater**

Ion	Chemical Symbol	ppt in seawater
Chloride	Cl <sup>-</sup>	19.35
Sodium	Na <sup>+</sup>	10.76
Sulfate	SO <sub>4</sub> <sup>2-</sup>	2.71
Magnesium	Mg <sup>2+</sup>	1.29
Calcium	Ca <sup>2+</sup>	0.41
Potassium	K <sup>+</sup>	0.39
Bicarbonate	HCO <sub>3</sub> <sup>-</sup>	0.14
Bromide	Br <sup>-</sup>	0.067
Strontium	Sr <sup>2+</sup>	0.008
Boron	B <sup>3+</sup>	0.004
Fluoride	F <sup>-</sup>	0.001
Total		~35.00

## Ocean Salinity



\*All values are given in parts per thousand (ppt)

**Variations in Salinity** Although the average salinity of the oceans is 35 ppt, actual salinities vary from place to place, as shown in **Figure 15-10**. In subtropical regions where rates of evaporation exceed those of precipitation, salt ions left behind by the evaporation of water molecules accumulate in the surface layers of the ocean. There, salinities may be as high as 37 ppt. In equatorial regions where precipitation is abundant, salinities are lower. Even lower salinities of 32 or 33 ppt occur in polar regions where seawater is diluted by melting sea ice. The lowest salinities often occur where large rivers empty into the oceans. Even though salinities vary, the relative proportion of major sea salts is always constant because all ocean water continually intermingles and is thoroughly mixed. Do the *MiniLab* on the following page to further analyze the salinity of seawater.

**Sources of Sea Salt** Geological evidence indicates that the salinity of ancient seas was not much different from that of today's oceans. One line of evidence is based on the proportion of magnesium in the calcium-carbonate shells of some marine organisms. That proportion depends on the overall salinity of the water in which the shells form. Present-day shells, such as the one shown in **Figure 15-11**, contain about the same proportion of magnesium as similar shells throughout geologic time.

Just as the proportion of sea salts has remained the same over time, so too have the sources of sea salts. In addition to water vapor, volcanic gases contain chlorine and sulfur dioxide. These gases

**Figure 15-10** Ocean salinities vary from place to place. High salinities are common in areas with high rates of evaporation. Low salinities often occur where rivers empty into oceans.

**Figure 15-11** By comparing the proportion of magnesium in present-day shells, such as this nautilus, with those of ancient shells, scientists have determined that the salinity of Earth's oceans has remained nearly the same over geologic time.



## MiniLab

### What is the chemical composition of seawater?

**Determine** the chemical composition of seawater using the following ingredients. The salinity of seawater is commonly measured in parts per thousand (ppt).

sodium chloride (NaCl)	23.48 g
magnesium chloride (MgCl <sub>2</sub> )	4.98 g
sodium sulfate (Na <sub>2</sub> SO <sub>4</sub> )	3.92 g
calcium chloride (CaCl <sub>2</sub> )	1.10 g
potassium chloride (KCl)	0.66 g
sodium bicarbonate (NaHCO <sub>3</sub> )	0.19 g
potassium bromide (KBr)	0.10 g

#### Procedure

1. Carefully measure the ingredients and put them all in a large beaker.
2. Add 965.57 g of distilled water and mix.

#### Analyze and Conclude

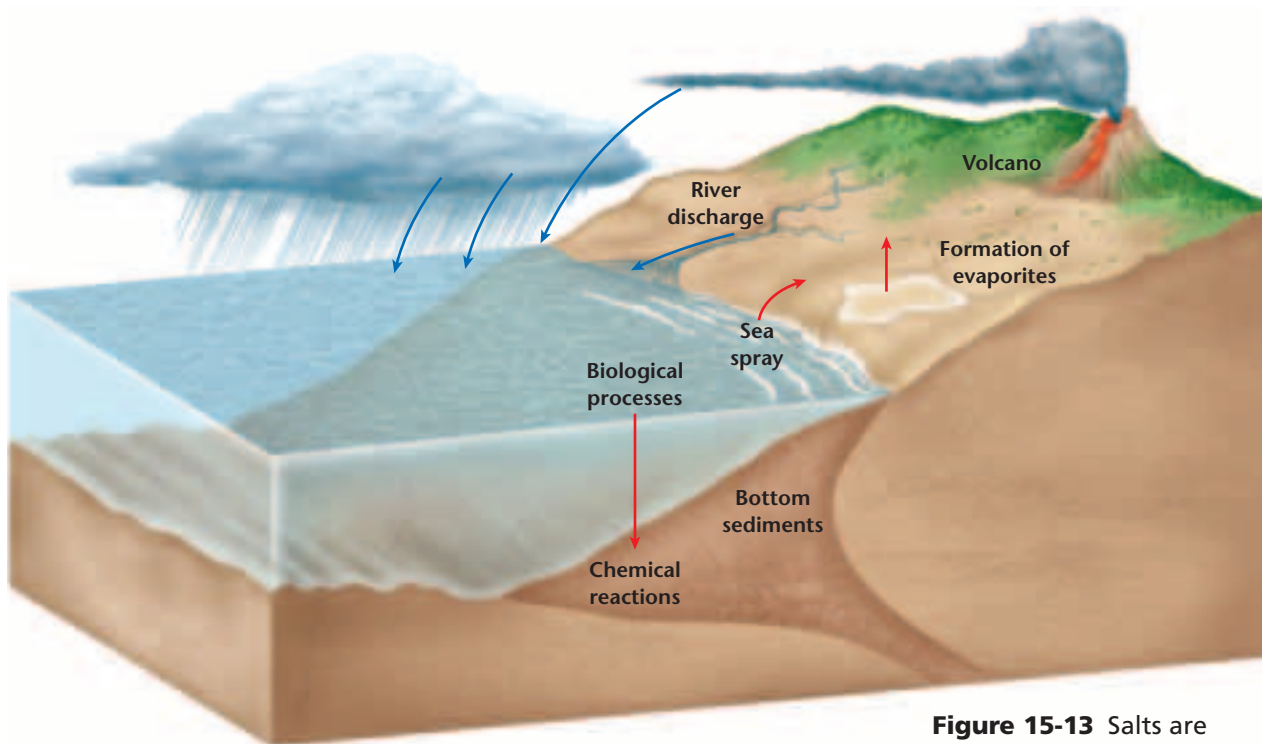
1. How many grams of solution do you have? What percentage of this solution is made up of salts?
2. Given that 1 percent is equal to 10 ppt, what is the salinity of your solution in parts per thousand?
3. Identify the ions in your solution.
4. Infer how your solution differs from actual seawater.

dissolve in water and form the chlorine and sulfate ions of seawater. The weathering of crustal rocks generates most of the other abundant ions in seawater. Sodium, calcium, and potassium come from the weathering of feldspars. Iron and magnesium come from the weathering of minerals and rocks rich in these elements. These ions are then flushed into rivers and transported to oceans.

**Removal of Sea Salts** Although salt ions are continuously added to seawater, the salinity of seawater does not increase. Why? Because salts are removed from the ocean at the same rate as they are added. The removal of sea salts involves several processes. Some precipitate from seawater near arid, coastal regions such as the one shown in *Figure 15-12*. This process removes immense quantities of sodium chloride, calcium sulfate, and other sea salts. In addition, small salty spray droplets from breaking waves are picked up by winds and deposited inland. Marine organisms also remove ions from seawater to build their shells, bones, and teeth. As these organisms die, their solid parts accumulate on the seafloor and become incorporated into the bottom sediments. All these



**Figure 15-12** Salts that have precipitated from seawater form deposits along the coast of Baja, Mexico.




**Figure 15-13** Salts are added to seawater by volcanic eruptions and by the weathering and erosion of rocks. Salts are removed from seawater by the formation of evaporites and biological processes. Salty droplets also are deposited inland by winds.

processes remove immense quantities of salt ions from the ocean. Thus, the existing salinity of seawater represents a balance between the processes that remove salts and those that add them, as shown in *Figure 15-13*.

## PHYSICAL PROPERTIES OF SEAWATER

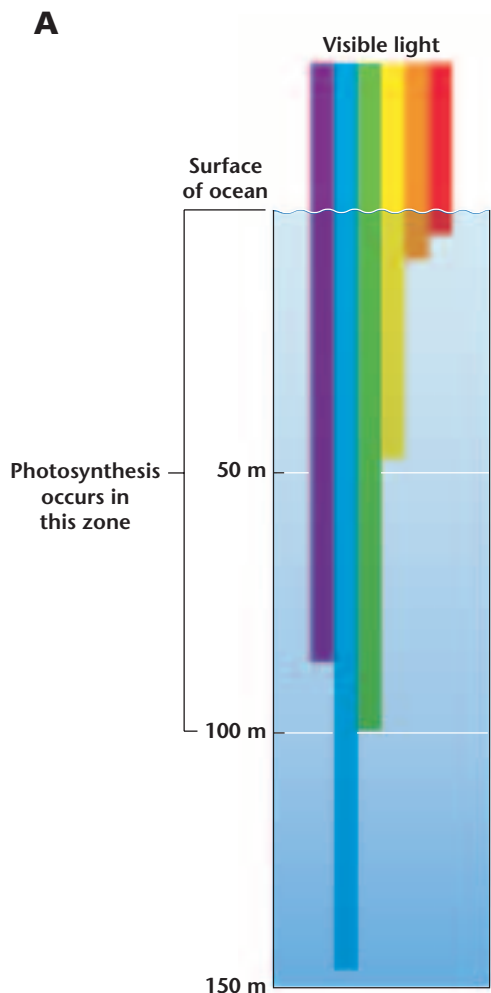
The presence of various salts causes the physical properties of seawater to be quite different from those of freshwater. Freshwater has a maximum density of  $1.00 \text{ g/cm}^3$ . Because salt ions are heavier than water molecules, they increase the density of water. Seawater is therefore denser than freshwater, and its density varies, depending on its salinity. Temperature also affects density—cold water is denser than warm water. Because of salinity and temperature variations, the density of seawater ranges from about  $1.02 \text{ g/cm}^3$  to  $1.03 \text{ g/cm}^3$ . These variations may seem small, but they are significant. They affect many oceanic processes, which you'll learn about in the next chapter. Variations in salinity also cause the freezing point of seawater to be somewhat lower than that of freshwater. Freshwater freezes at  $0^\circ\text{C}$ . Because salt ions interfere with the formation of hydrogen bonds, the freezing point of seawater is  $-2^\circ\text{C}$ .

**Absorption of Light** If you've ever swum in a lake, you may have noticed that the intensity of light decreases with depth. The water may be clear, but if the lake is deep, the bottom waters will be dark.



**Using Math**

**Using Numbers** If the density of a sample of seawater is  $1.02716 \text{ g/mL}$ , calculate the mass of  $4.00 \text{ mL}$  of the sample.



**Figure 15-14** Red light does not penetrate as far as blue light in the ocean (A). Thus, red marine organisms such as this deep-sea shrimp (B) appear black below a depth of 10 m. This helps them escape predators.



Water absorbs light, which gives rise to another physical property of oceans—they are dark. In general, light penetrates only the upper 100 m of seawater. Below that depth, all is darkness. **Figure 15-14** illustrates how light penetrates ocean water. Notice that red light penetrates less than blue light. Red objects appear black below the depth of penetration of red light, and other reflecting objects in the water appear green or blue. Although some fading blue light may reach depths of a few hundred meters, light sufficient for photosynthesis exists only in the top 100 m of the ocean.

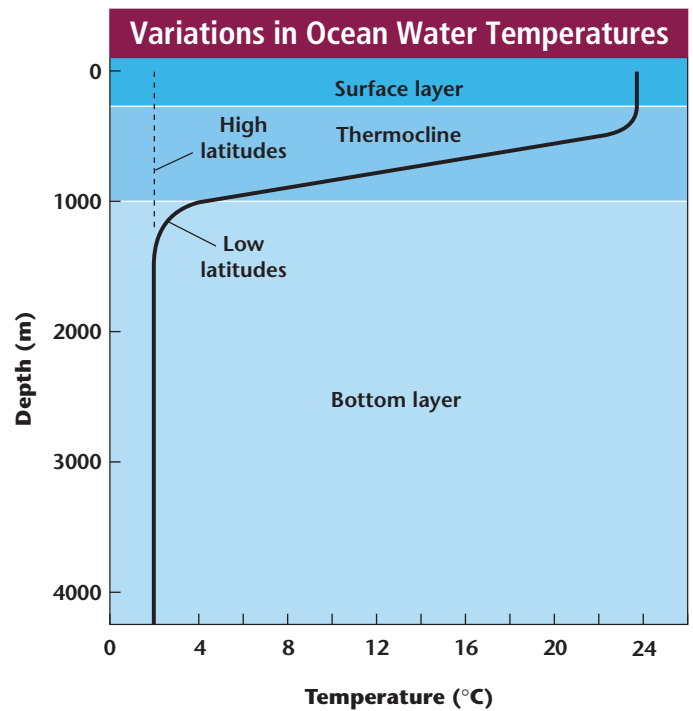
### OCEAN LAYERING

Ocean surface temperatures range from  $-2^{\circ}\text{C}$  in polar waters to  $30^{\circ}\text{C}$  in equatorial regions, with the average surface temperature being  $15^{\circ}\text{C}$ . Ocean water temperatures, however, decrease significantly with depth. Thus, deep ocean water is always cold, even in tropical oceans. **Figure 15-15** shows a typical ocean **temperature profile**, which plots changing water temperatures with depth. Such profiles vary, depending on location and season. In the temperature profile shown here, beneath roughly 100 m, temperatures decrease continuously with depth to around  $4^{\circ}\text{C}$  at 1 km. The dark waters below 1 km have fairly uniform temperatures of less than  $4^{\circ}\text{C}$ . Based on temperature variations, the ocean can be divided into three layers, as shown in **Figure 15-16**. The first is a relatively warm, sunlit, surface layer some 100 m thick. Under this is a transitional layer known as the **thermocline**, which is characterized by rapidly decreasing temperatures with depth. The bottom layer is cold and dark with temperatures near freezing. Both the thermocline and the warm surface layer are absent in polar seas, where water temperatures are cold from top to bottom. In general, ocean layering is caused by density differences. Because cold water is more dense than warm water, cold water sinks to the bottom, while less-dense, warm water is found near the ocean's surface.

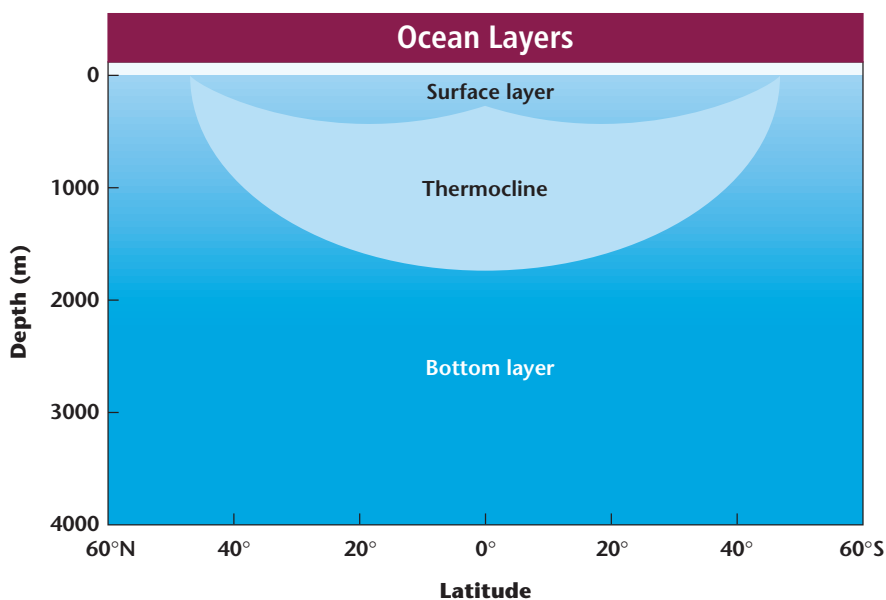
## WATER MASSES

The temperature of the bottom layer of ocean water is near freezing even in tropical oceans, where surface temperatures are warm. Where does all this cold water come from? The source is Earth's polar seas. Recall that high salinity and cold temperatures cause seawater to become more dense. When seawater freezes during the arctic or antarctic winter, sea ice forms. However, salt ions aren't incorporated into the growing ice crystals and accumulate beneath the ice. Consequently, the cold water beneath the ice becomes saltier and denser than the surrounding seawater, and this saltier water sinks. This salty water then migrates toward the equator as a cold, deep water mass along the ocean floor. Other cold, deep water masses form when surface currents in the ocean bring relatively salty midlatitude or subtropical waters into polar regions. In winter, these waters become colder and denser than the surrounding polar surface waters, and thus, they sink.

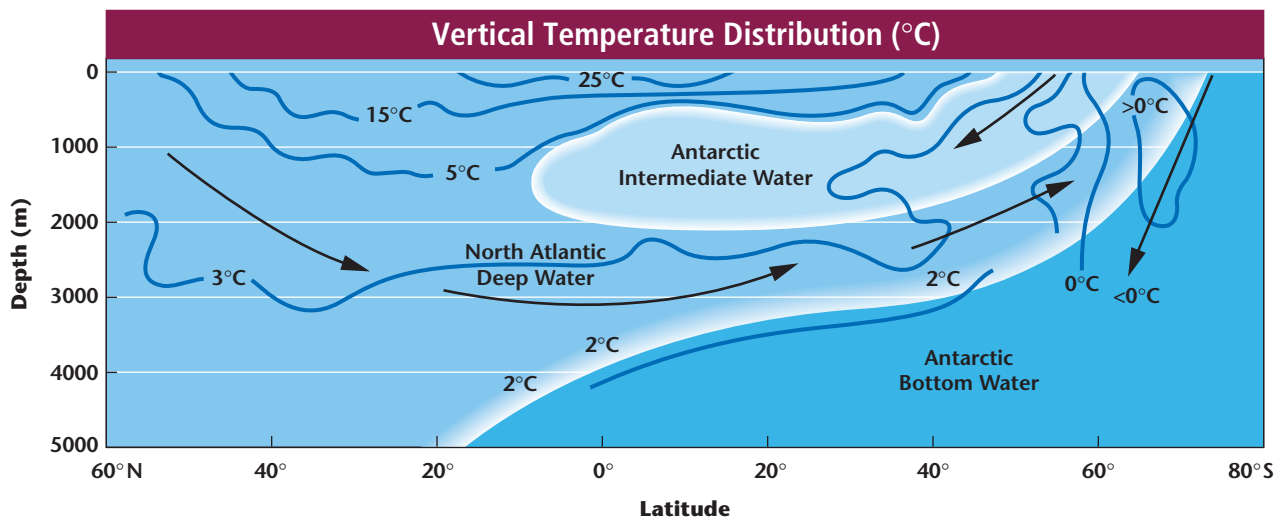
Three water masses account for most of the deep water in the Atlantic Ocean. Antarctic Bottom Water forms when antarctic seas freeze during the winter. With temperatures below 0°C, this water



**Figure 15-15** Ocean water temperatures decrease with depth. Areas near the equator have warmer ocean surface temperatures than do midlatitudes or areas near the poles.



**Figure 15-16** Based on water temperatures, the ocean can be divided into three layers: the relatively warm surface layer, the transitional thermocline, and the cold bottom layer.



**Figure 15-17** Antarctic Bottom Water is the densest and coldest deep water mass. It is overridden by the slightly warmer and less dense North Atlantic Deep Water. Antarctic Intermediate Water is still warmer and less dense, and thus it overrides the other two deep water masses.

mass is the coldest and densest in all the oceans, as shown in *Figure 15-17*. North Atlantic Deep Water forms in a similar manner offshore from Greenland. It is warmer and less dense than Antarctic Bottom Water and thus overrides it. Antarctic Intermediate Water forms when the relatively salty waters of the Antarctic Ocean decrease in temperature during winter and sink. Being slightly warmer and less dense than North Atlantic Deep Water, Antarctic Intermediate Water overrides the other two water masses. While the Atlantic Ocean contains all three major deep-water masses, the Indian and Pacific Oceans contain only the two deep antarctic water masses. You'll model water masses in the *GeoLab* at the end of this chapter. In the next section, you'll learn about other water movements in the ocean.

## SECTION ASSESSMENT

1. What is the most abundant salt in seawater? How do salts enter the ocean?
2. How does the salinity of seawater affect its density?
3. The salinity of seawater is higher in subtropical regions than at the equator. Why?
4. Explain why North Atlantic Deep Water and Antarctic Intermediate Water override Antarctic Bottom Water.
5. Which is more dense, cold freshwater or warm seawater? Explain.
6. **Thinking Critically** Why do red fish look black at ocean water depths greater than about 10 m?

### SKILL REVIEW

7. **Recognizing Cause and Effect** Based on what you have learned about the freezing point of seawater, explain why salt is often used to de-ice roads in the winter. For more help, refer to the *Skill Handbook*.

Oceans are never completely motionless. Their most obvious movement is the constant motion of the waves. A **wave** is a rhythmic movement that carries energy through space or matter—in this case, ocean water. Ocean waves are generated mainly by wind flowing over the water's surface. As an ocean wave passes, the water moves up and down in a circular pattern and returns to its original position, as shown in **Figure 15-18A**. Only the energy moves steadily forward. The water itself moves in circles until the energy passes, but it does not move forward.

### WAVE CHARACTERISTICS

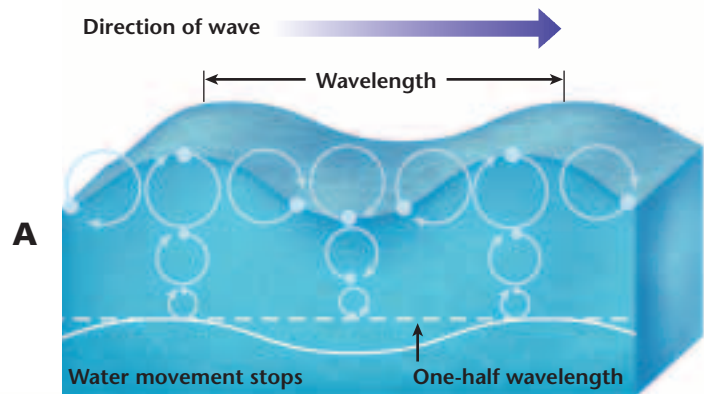
In the open ocean, a typical wave has the characteristics shown in **Figure 15-18B**. The highest point of a wave is the **crest**, and the lowest point is the **trough**. The vertical distance between crest and trough is the wave height; the horizontal crest-to-crest distance is the wavelength. The wavelength determines the depth to which the wave disturbs the water. That depth, called the wave base, is equal to half the wavelength. The wavelength also determines the speed with which waves move through deep water. Wave speed increases with wavelength.

### OBJECTIVES

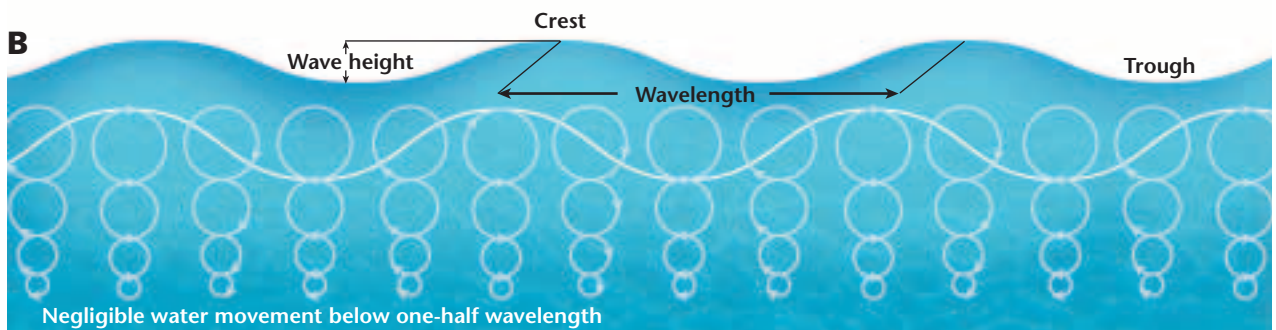
- **Describe** the physical properties of waves.
- **Explain** how tides form.
- **Compare and contrast** various ocean currents.

### VOCABULARY

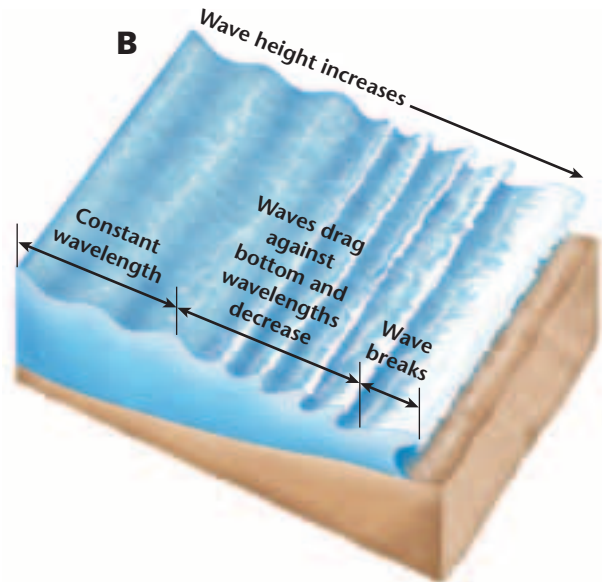
wave	tide
crest	density current
trough	surface current
breaker	upwelling



**Figure 15-18** In a wave, water moves in circles that decrease in size with depth. At a depth equal to half the wavelength, water movement stops (**A**). Wave characteristics include wave height, wavelength, crest, and trough (**B**).







**Figure 15-19** A breaker (A) forms when wavelength decreases and wave height increases as the wave nears the shore (B).

**Wave Height** Wave heights depend upon three factors: wind speed, wind duration, and fetch. Fetch refers to the expanse of water that the wind blows across. Large storm waves can be much higher than average. For instance, hurricanes can generate waves more than 10 m high. The greatest wave height ever recorded was more than 30 m. This monstrous wave occurred in the North Pacific.

**Breaking Waves** As ocean waves reach the shallow water near shorelines, they begin to lose energy because of friction with the ocean bottom. This causes the waves to slow down. As the water becomes shallower, incoming wave crests gradually catch up with the slower wave crests ahead. As a result, the crest-to-crest wavelength decreases. The incoming waves become higher, steeper, and unstable, and their crests collapse forward. Collapsing waves, such as those shown in *Figure 15-19*, are called **breakers**. The formation of breakers is also influenced by the motion of wave crests, which are less affected by friction than wave troughs and thus overrun the troughs. The collapsing crests of breakers moving at high speeds toward shore play a major role in shaping shorelines. You'll learn more about breakers and shoreline processes in the next chapter.



**Topic: High Tides**

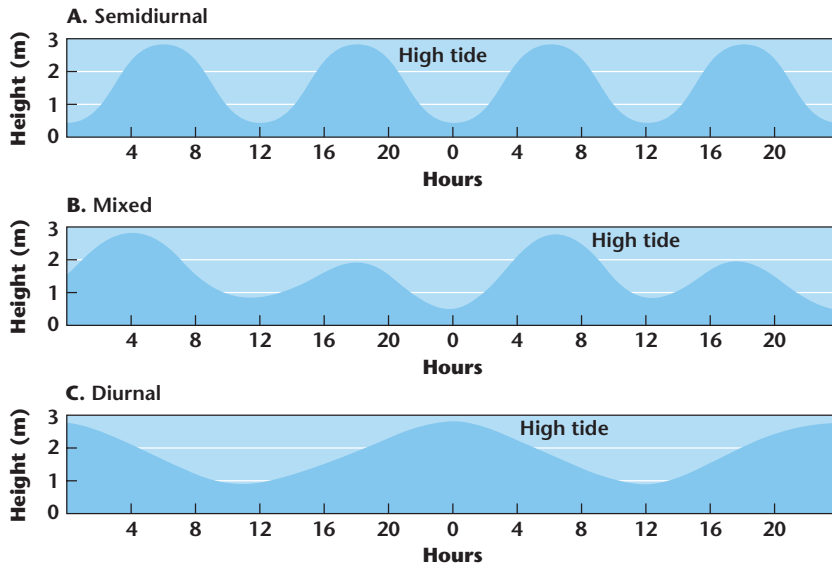
To learn more about tides, visit the Earth Science Web Site at [earthgeu.com](http://earthgeu.com)

**Activity:** Research the best places on Earth to observe high tides. Note these places on a map of the world.

## TIDES

**Tides** are the periodic rise and fall of sea level. The highest level to which water rises is known as high tide, and the lowest level is called low tide. Because of differences in topography and latitude, the tidal range—the difference between high tide and low tide—varies from place to place. In the Gulf of Mexico, the tidal range is less than 1 m. In New England, it can be as high as 6 m. The greatest tidal range





**Figure 15-20** Differences in topography and latitude cause three different daily tide cycles. Areas with semi-diurnal cycles experience two high tides per day. Areas with mixed cycles have one pronounced and one smaller high tide each day. Areas with diurnal cycles have one high tide per day.

occurs in the Bay of Fundy between New Brunswick and Nova Scotia, Canada, where it is as high as 15 m. Generally, a daily cycle of high and low tides takes 24 hours and 50 minutes. As shown in **Figure 15-20**, the daily cycle can follow three distinct patterns. You'll learn about tides in the *Problem-Solving Lab* on this page.

Problem-Solving Lab

Making and Using Graphs

**Analyze a tidal record** The water levels shown in the data table were measured over a 24-hour period.

**Analysis**

1. Plot these values on graph paper with time on the x-axis and water level on the y-axis.
2. Estimate the approximate times and water levels of high tides and low tides.

**Thinking Critically**

3. Refer to **Figure 15-20** to determine the tidal pattern shown in your graph.
4. What is the tidal range for this area?

Tidal Record			
Time (h)	Water Level (m)	Time (h)	Water Level (m)
00:00	3.08	13:00	2.78
01:00	3.35	14:00	2.81
02:00	3.33	15:00	2.59
03:00	3.03	16:00	2.16
04:00	2.53	17:00	1.64
05:00	1.95	18:00	1.15
06:00	1.44	19:00	0.84
07:00	1.10	20:00	0.78
08:00	1.02	21:00	1.00
09:00	1.21	22:00	1.46
10:00	1.59	23:00	2.07
11:00	2.07	24:00	2.67
12:00	2.51		

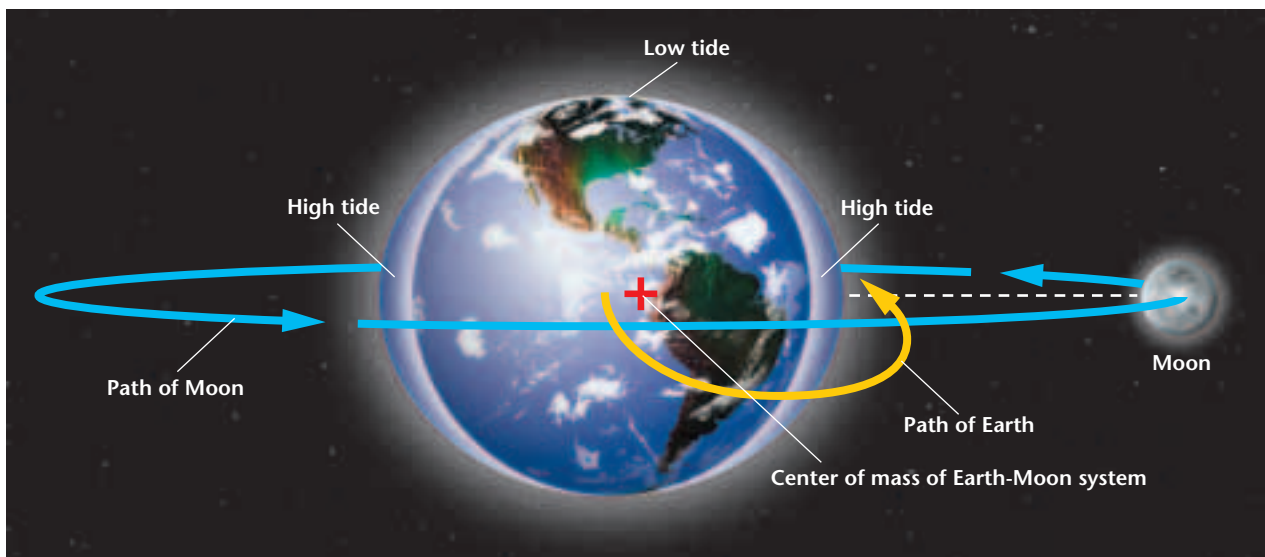
5. Predict the water level at the next high tide. Estimate when that high tide will occur.

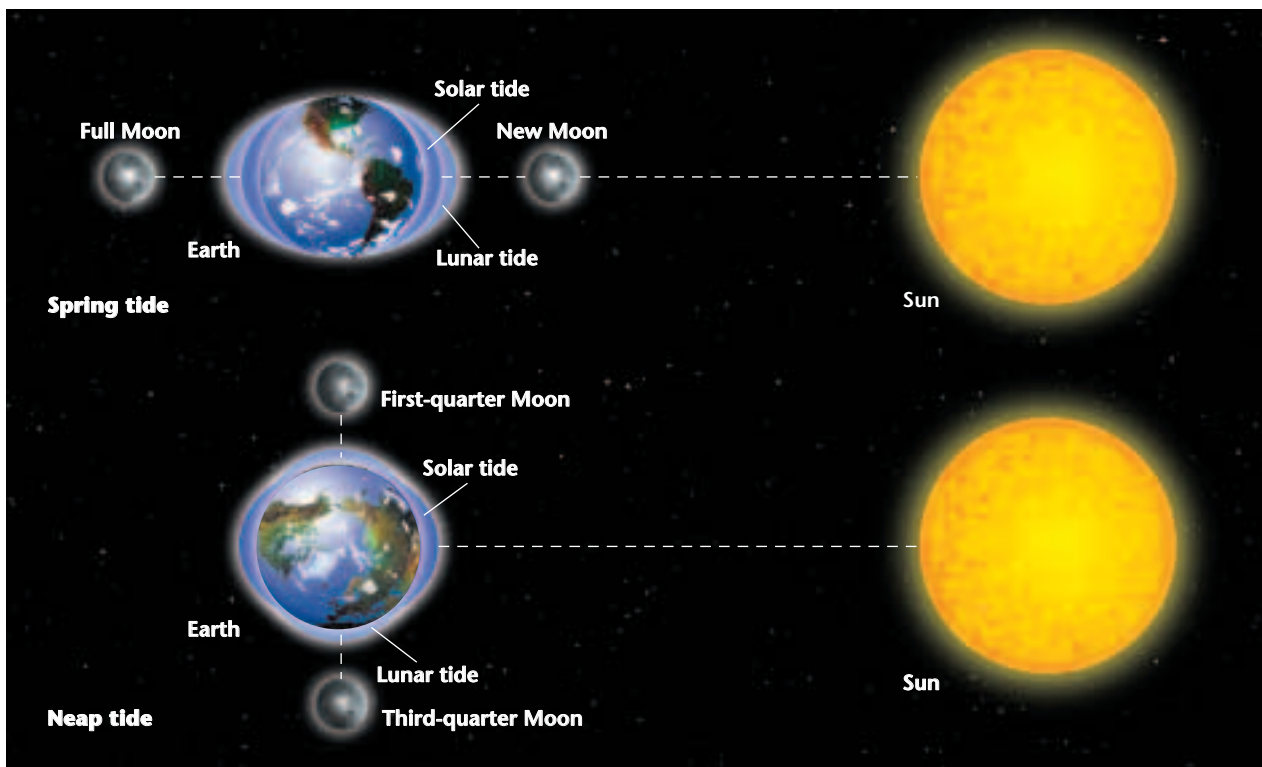
## CAUSES OF TIDES

The basic causes of tides are the gravitational attraction among Earth, the Moon and the Sun, as well as the fact that gravitational attraction decreases with distance. Consider the Earth-Moon system. As shown in *Figure 15-21*, the Moon does not actually orbit Earth. Rather, both Earth and the Moon orbit around a common center of gravity. As a result of their motions, both Earth and the Moon experience differing gravitational forces. The unbalanced forces generate tidal bulges on opposite sides of Earth. The gravitational effect on Earth's oceans is similar to what happens to the liquid in a coffee cup inside a car as the car goes around a curve. The liquid sloshes toward the outside of the curve.

**The Sun's Influence** The gravitational attraction of the Sun and Earth's orbital motion around the Sun also generate tides. However, even though the Moon is much smaller than the Sun, lunar tides are more than twice as high as those caused by the Sun because the Moon is much closer to Earth. Consequently, Earth's tidal bulges are always aligned with the Moon. Although the Sun's tidal effect is smaller than that of the Moon, it is still significant because of the Sun's great mass. Depending on the phases of the Moon, solar tides can either enhance or diminish lunar tides, as illustrated in *Figure 15-22*. Notice that large tidal ranges, called spring tides, occur when the Moon is either full or new. These phases of the Moon occur when the Sun, the Moon, and Earth are aligned. During spring tides, high tides are higher than normal and low tides are lower than normal. Small tidal ranges, called neap tides, occur when there is a first- or third-quarter Moon. During these times, the Sun, the Moon, and

**Figure 15-21** The Moon and Earth revolve around a common center of gravity and experience unbalanced gravitational and centrifugal forces. These forces cause tidal bulges on opposite sides of Earth.





**Figure 15-22** Spring tides occur when the Sun, the Moon, and Earth are aligned **(A)**. Neap tides occur when the Sun, the Moon, and Earth form a right angle **(B)**.

Earth form a right angle. During neap tides, high tides are lower and low tides are higher than normal. Spring and neap tides alternate every two weeks. On average, spring tides are three times higher than neap tides.

## OCEAN CURRENTS

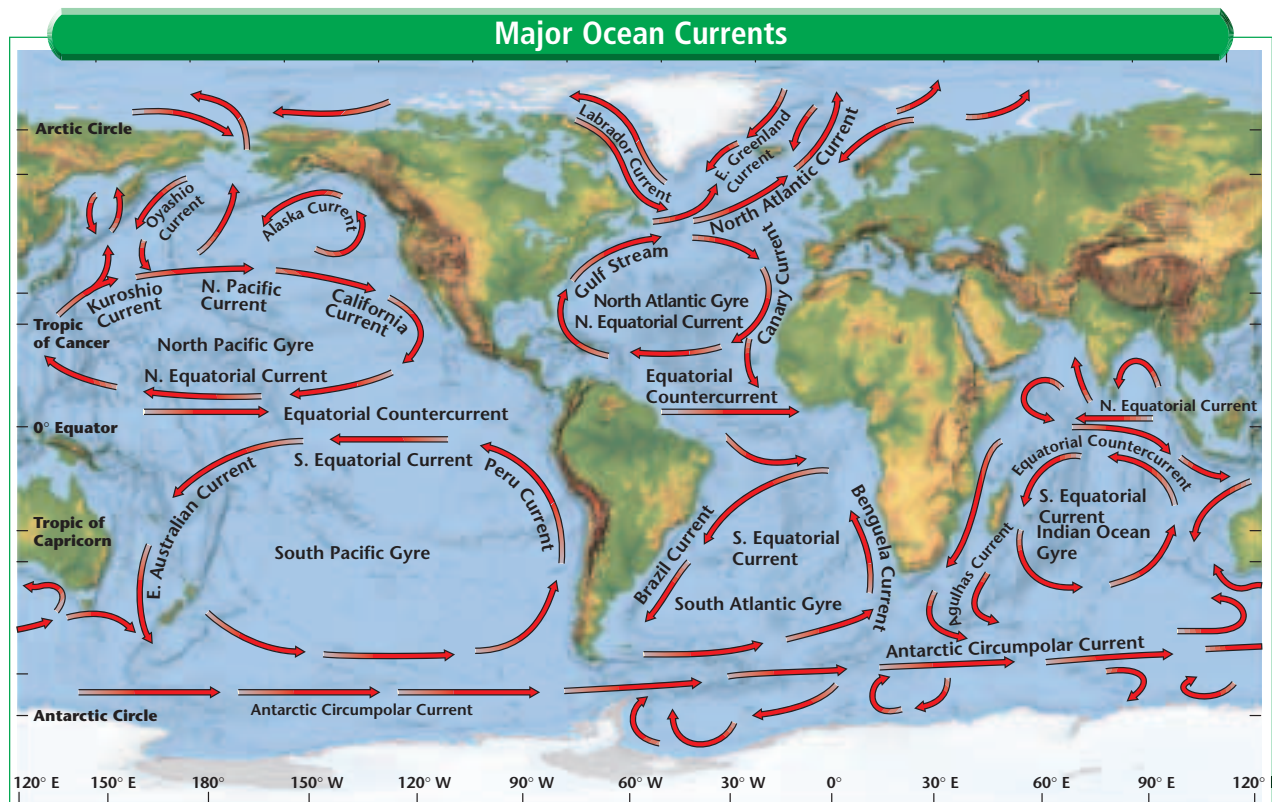
Recall the discussion of Antarctic Bottom Water in the previous section. The movement of Antarctic Bottom Water is an example of an ocean current. In this case, the current is called a **density current** because it is caused by differences in the temperature and salinity of ocean water, which in turn affect density. Density currents move slowly in deep ocean waters.

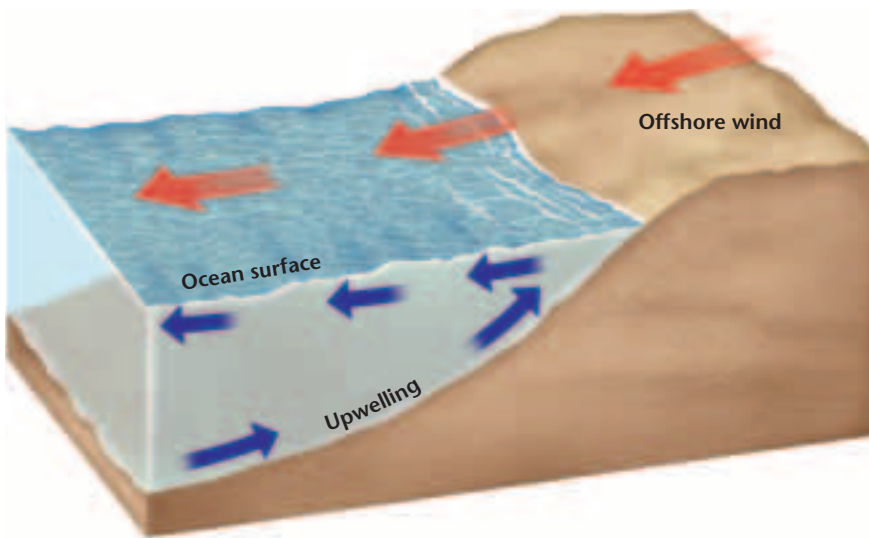
More noticeable than underwater density currents are wind-driven surface currents. **Surface currents** affect mainly the upper few hundred meters of the ocean, and they can move as fast as 100 km per day. Driven by Earth's global wind systems, surface currents follow predictable patterns. In the northern hemisphere, tropical trade winds blow from east to west. The resulting tropical ocean currents also flow from east to west. In northern midlatitudes, the prevailing westerlies and resulting ocean currents move from west to east. In northern polar regions, polar easterly winds push surface waters from east to west.

**Gyres** If Earth had no landmasses, the global ocean would have simple belts of easterly and westerly surface currents. But the continents deflect ocean currents to the north and south so that closed circular current systems, called gyres, develop. As shown in **Figure 15-23**, there are five major gyres: the North Pacific, the North Atlantic, the South Pacific, the South Atlantic, and the Indian Ocean. Because of the Coriolis effect, which you learned about in Chapter 12, the gyres of the northern hemisphere circulate in a clockwise direction, and those of the southern hemisphere circulate in a counterclockwise direction. The parts of all gyres closest to the equator move towards the west as equatorial currents. When these currents encounter a landmass, they are deflected toward the poles. These poleward-flowing waters carry warm, tropical water into higher, colder latitudes. A well-known example of a warm current is the Kuroshio, or Japan Current in the western North Pacific.

After these warm waters enter polar regions, they gradually cool and, deflected by landmasses, move back toward the equator. The resulting currents then bring cold water from higher latitudes into tropical regions. An example of such cold ocean currents is the California Current in the eastern North Pacific. You'll learn more about currents in the *Science in the News* feature at the end of this chapter.

**Figure 15-23** The Coriolis effect deflects water and other free-moving objects to the right north of the equator and to the left south of the equator. Thus, gyres in the northern hemisphere circulate in a clockwise direction. The motion is reversed in the southern hemisphere.





**Figure 15-24** Upwelling occurs when the trade winds blow surface water offshore, and deep, colder water rises to the surface.

## UPWELLING

In addition to moving horizontally, ocean water moves vertically. The upward motion of ocean water is called **upwelling**. Upwelling waters originate from the bottom of the ocean and thus are cold. Areas of upwelling exist mainly off the western coasts of continents in the trade-wind belts. As **Figure 15-24** shows, the trade winds blow surface water offshore, and the surface water is replaced by upwelling deep water. Upwelling waters are rich in nutrients, which support abundant populations of marine life. Consequently, some of the world's richest fishing grounds are found off the coasts of Peru and California.

### SECTION ASSESSMENT

- Describe how water moves as a wave passes.
- What three factors determine the height of a wave?
- What causes tides? Compare and contrast a spring tide and a neap tide.
- Why are upwelling waters always cold?
- Thinking Critically** Upwelling currents are rich in nutrients. Predict the effects on marine ecosystems if these currents stopped.

### SKILL REVIEW

- Concept Mapping** Use the following phrases to complete a concept map of wave characteristics. For more help, refer to the *Skill Handbook*.

lowest point of wave

wave characteristics

crest

wavelength

wave height

trough

horizontal crest-to-crest distance

highest point of wave

vertical distance between crest and trough

# Modeling Water Masses

**T**he water in the oceans is layered because water masses with higher densities sink below those with lower densities. The density of seawater depends on its temperature and salinity. In this activity, you'll model different types of water masses to observe the effects of density firsthand.

## Preparation

### Problem

Determine how changes in salinity and temperature affect water density.

### Materials

scale  
 graduated 500-mL cylinder  
 100-mL glass beakers (4)  
 water  
 red, yellow, and blue food coloring  
 salt  
 thermometer  
 eyedropper  
 graph paper  
 pencil  
 ruler  
 calculator

### Objectives

*In this GeoLab you will:*

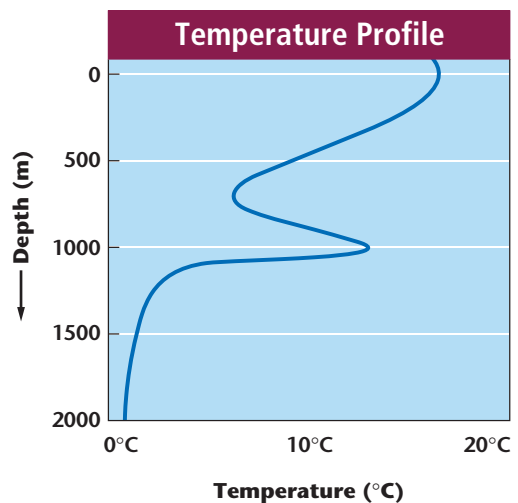
- **Compare** and **contrast** the movement of different water samples.
- **Determine** the relative densities of the water samples.

- **Predict** the arrangement of layers in a body of water.
- **Construct** and **interpret** a temperature profile.

### Safety Precautions



Always wear safety goggles and an apron in the lab. Wash your hands after completing the lab.



## Procedure

1. Mix 200 mL of water and 7.5 g of salt in the graduated cylinder. Pour equal amounts of the salt solution into two beakers. Fill each of the two other beakers with 100 mL of freshwater.
2. Put a few drops of red food coloring in one of the salt solutions. Put a few drops of yellow food coloring in the other salt solution. Put a few drops of blue food coloring in one of the beakers of freshwater. Do not add food coloring to the other beaker of freshwater.
3. Place the beakers with the red salt solution and the blue freshwater in the refrigerator. Refrigerate them for 30 minutes.
4. Measure and record the temperature of the water in all four beakers.
5. Put several drops of the cold, red saltwater into the beaker with the warm, yellow saltwater and observe what happens. Record your observations.
6. Put several drops of the cold, blue freshwater into the beaker with the warm, clear freshwater and observe what happens. Record your observations.
7. Put several drops of the cold, blue freshwater into the beaker with the warm, yellow saltwater and observe what happens. Record your observations.

## Analyze

1. In your science journal, describe the movement of the cold, red saltwater in step 5. Compare this to the movement of the cold, blue freshwater in step 7. What accounts for the differences you observed?
2. Based on your observations, list the water samples by color in order of increasing density.
3. If you poured the four water samples into the graduated cylinder, how would they arrange themselves into layers by color, from top to bottom?

## Conclude & Apply

1. Assume that four water masses in a large body of water have the same characteristics as the water in the four beakers. The warm water layers are 100 m thick, and the cold layers are 1000 m thick. Graph the temperature profile of the large body of water.
2. What is the salinity in parts per thousand of the combined saline solutions? (Hint: ppt equals grams of salt per kilogram of solution. Assume that 200 mL of water has a mass of 200 g. Be sure to include the mass of the salt in the total mass of the solution.)
3. The temperature profile on the opposite page was constructed from measurements taken in the Atlantic Ocean off the coast of Spain. Study the profile, then infer why a high-temperature layer exists beneath the thermocline. Is this layer denser than the colder water above? Explain.



# Science **in** the News



## Caught in the Current

**“T**he gale was still blowing from the northeast on January 21, drifting snow from the continental ice shelf...Held fast in the ice, the *Endurance* was being carried with the rest of the pack by the Weddell Sea’s current; soon she would be moving away from land.”—from *The Endurance: Shackleton’s Legendary Antarctic Expedition*, by Caroline Alexander (Knopf, 1999).

Alexander’s book tells the story of the *Endurance* and the 28 men who sailed in the ship to Antarctica in 1914. The explorers on board planned the first overland crossing of the Antarctic continent. The ship left South Georgia Island in the South Atlantic in December 1914. During the next two years, the expedition suffered both horrible misfortune and incredible luck.

### Frozen Solid

In mid-December, the *Endurance* neared the coast of Antarctica. The pack ice that year was especially dense, and by January 1915, the ship had frozen solidly into the ice just 126 km from its destination—126 km of solid ice. The ship and its crew could only drift aimlessly with the ice.

In this part of the sea a clockwise current churns the ice pack in endless circles. The ice crunches against the Antarctic Peninsula, generating massive waves of pressure. The *Endurance*, still frozen in the ice, was carried by the current farther and farther from land. In November 1915, the pressure of the ice pack crushed the ship to pieces. The crew escaped but was forced to camp on the drifting ice in sub-zero temperatures with thin tents as their only shelter. They managed to salvage some supplies and three small boats.

### As the Current Turns

The crew hoped that the ice would carry them

toward land. However, the ice carried them into the open waters of the South Atlantic. Desperate, they launched their boats into the ocean. They stayed awake for days, battling rough waves and towering icebergs that threatened to crush the small boats to pieces. In April 1916, they finally reached a small barren island. The largest of the boats continued on a perilous journey to South Georgia Island for help. The boat was crewed by Shackleton and five others. These men faced an almost impossible task: to travel in a tiny boat more than a thousand kilometers across the roughest expanse of sea in the world.

Despite the odds, Shackleton and his crew did reach South Georgia Island. By this time, winter was approaching and it was several months before they could rescue the shipwrecked members of the *Endurance*’s crew. All 28 men survived the adventure. They failed in their mission to cross Antarctica, but their survival remains a tale of great glory.

### Activity

Plot a course for a journey by boat from the coast nearest you to Antarctica. Use the map of ocean currents in **Figure 15-23** to identify the currents you would use and those you would avoid.



# CHAPTER 15 Study Guide

## Summary

### SECTION 15.1

#### The Oceans



#### Main Ideas

- Oceanography is the scientific study of Earth's oceans. Oceanographers use sonar, satellites, and submersibles, among other tools, to explore the ocean.
- Earth's first oceans likely formed more than 4 billion years ago. Some water may have come from impacting comets or from deep within Earth's interior. Scientists theorize that water from within Earth's interior was released by volcanism.
- Approximately 71 percent of Earth's surface is covered by oceans. The major oceans are the Pacific, Atlantic, Indian, Arctic, and Antarctic.

#### Vocabulary

oceanography (p. 385)  
sea level (p. 388)  
side-scan sonar (p. 386)

### SECTION 15.2

#### Seawater



#### Main Ideas

- Seawater contains 96.5 percent water and 3.5 percent dissolved salts. The average salinity of seawater is 35 ppt. The salinity of the ocean remains constant because salts are removed from the ocean at the same rate as they are added.
- Ocean surface temperatures range from  $-2^{\circ}\text{C}$  in polar waters to  $30^{\circ}\text{C}$  in equatorial waters. Seawater density changes with changes in salinity and temperature.
- Ocean water temperatures decrease with depth. The ocean can be divided into three layers: the surface layer, the transitional thermocline, and the bottom layer.

#### Vocabulary

salinity (p. 392)  
temperature profile (p. 396)  
thermocline (p. 396)

### SECTION 15.3

#### Ocean Movements



#### Main Ideas

- Ocean waves are generated by wind. Water in a wave moves in a circular motion but does not move forward. When waves reach shallow water, friction with the ocean bottom slows them, and they become breakers.
- Tides are caused by the gravitational attraction among Earth, the Moon, and the Sun. Lunar tides are twice as high as solar tides.
- Density currents are deep currents generated by salinity and temperature differences. Wind-driven surface currents affect the upper few hundred meters of the ocean. Upwelling occurs when winds push surface water aside and the surface water is replaced by cold, deep water.

#### Vocabulary

breaker (p. 400)  
crest (p. 399)  
density current (p. 403)  
surface current (p. 403)  
tide (p. 400)  
trough (p. 399)  
upwelling (p. 405)  
wave (p. 399)

# CHAPTER 15 Assessment

## Understanding Main Ideas

- Which of the following is used to measure ocean depth?
  - bottom dredges
  - nets
  - sonar
  - tidal patterns
- Which of the following are the most common gases emitted by volcanoes?
  - hydrogen and helium
  - oxygen and nitrogen
  - water vapor and carbon dioxide
  - chlorine and hydrogen
- What is the average depth of the oceans?
  - 380 m
  - 38 m
  - 3800 m
  - 3 km
- What is the average salinity of seawater?
  - 100 ppt
  - 50 ppt
  - 35 ppt
  - 3.5 ppt
- What is the average temperature of deep water below the thermocline?
  - 15°C
  - more than 4°C
  - less than 4°C
  - 0°C
- What basic motion does water follow during the passage of a wave?
  - forward
  - backward
  - up and down
  - circular
- Which of the following does not affect wave height in deep water?
  - wavelength
  - wind duration
  - wind speed
  - fetch
- Which type of seawater has the greatest density?
  - warm, with low salinity
  - warm, with high salinity
  - cold, with low salinity
  - cold, with high salinity
- To what average depth does light penetrate in the ocean?
  - 1 m
  - 10 m
  - 100 m
  - 1000 m
- What type of high tides occur during a full Moon?
  - spring tides
  - neap tides
  - tidal ranges
  - tidal cycles
- What is the the densest water mass in the Atlantic Ocean?
  - North Atlantic Deep Water
  - surface water
  - Antarctic Bottom Water
  - Antarctic Intermediate Water
- The Arctic Ocean is the northern part of which body of water?
  - Atlantic Ocean
  - Pacific Ocean
  - Bering Sea
  - Indian Ocean
- Explain why the Moon exerts a greater tidal influence than the Sun.
- What distinguishes a sea from an ocean?
- Where in the oceans are the highest values of salinity found? Explain.
- What would be the wave base for a wave that is 200 m long?
- Which gyre would have clockwise circulation: the North Pacific, the South Pacific, the South Atlantic, or the Indian Ocean? Explain.

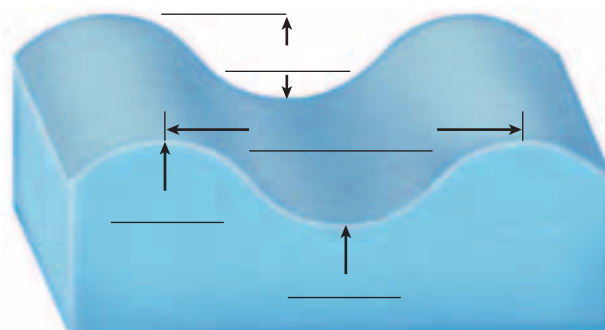
## Test-Taking Tip

**MAXIMIZE YOUR SCORE** If possible, find out how your standardized test will be scored. In order to do your best, you need to know if there is a penalty for guessing, and if so, how much of one. If there is no random-guessing penalty, you should always fill in an answer.

# CHAPTER 15 Assessment

## Applying Main Ideas

18. Why does a wave break?
19. Copy the illustration on this page. Then use the following terms to label the characteristics of an ocean wave: *crest*, *trough*, *wave height*, and *wavelength*.



20. Cold water masses are generally denser than warm water masses, yet warm water from the Mediterranean Sea sinks to a depth of more than 1000 m when it flows into the Atlantic Ocean. Why?

## Thinking Critically

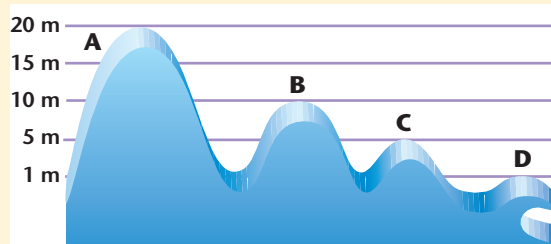
21. One of the effects of El Niño, which you learned about in the previous chapter, is that the trade winds reverse direction. Predict how this might affect upwelling off the coast of Peru.
22. Based on what you have learned about water density, describe the movement of freshwater from a river as it flows into the sea.
23. Surface currents can affect coastal climates. Would the Gulf Stream and the Peru Current, both of which are surface currents, have the same effect on coastal climate? Explain.
24. Use your knowledge of global warming to hypothesize why sea level is rising.

## Standardized Test Practice

1. Which sea was the first to be mapped?
- the Bering Sea
  - the Caribbean Sea
  - the Gulf of Mexico
  - the Mediterranean Sea
2. Which region's seawater is most likely to have the highest concentration of dissolved salts?
- an equatorial region
  - a subtropical region
  - a polar region
  - a delta where rivers empty into oceans

### INTERPRETING SCIENTIFIC ILLUSTRATIONS

Use the illustration below to answer questions 3 and 4.



3. Which wave is most likely caused by a strong hurricane?
- A
  - B
  - C
  - D
4. Why is Wave D most likely collapsing?
- friction from the ocean floor
  - storm activity
  - increased crest-to-crest wavelength
  - opposing tidal movement
5. Which ocean movement is slow-moving and occurs in deep waters?
- surface currents
  - upwelling
  - density currents
  - gyres

