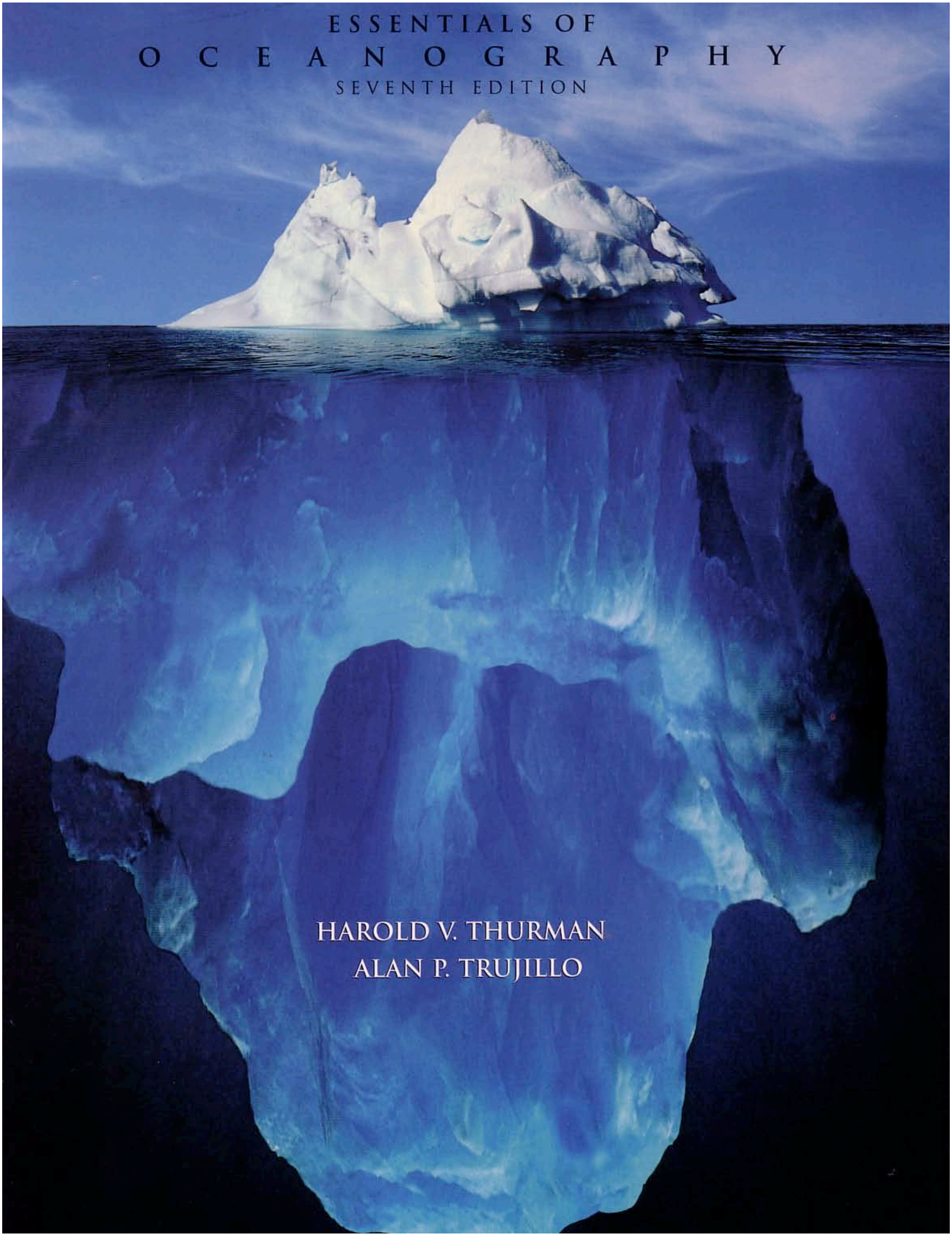
ESSENTIALS OF OCEANOGRAPHY

SEVENTH EDITION



HAROLD V. THURMAN
ALAN P. TRUJILLO

HTTP://WWW.PRENHALL.COM/THURMAN

CHAPTER

8

Waves and Water Dynamics

key questions

- What causes waves?
- How do waves move?
- What are differences between deep- and shallow-water waves?
- How do destructive and constructive interference affect waves?
- What physical changes occur in waves as they approach shore and break?
- How is wave refraction different from wave reflection?
- How are tsunamis formed and what kinds of destruction do they cause?

There's no time to put on survival suits or grab a life vest; the boat's moving through the most extreme motion of her life and there isn't even time to shout. The refrigerator comes out of the wall and crashes across the galley. Dirty dishes cascade out of the sink. The TV, the washing machine, the VCR tapes, the men, all go flying. And, seconds later, the water moves in.

—*Sebastian Junger,* The Perfect Storm *(1997)*

THE BIGGEST WAVE IN RECORDED HISTORY: LITUYA BAY, ALASKA (1958)

Lituya Bay is located in southeast Alaska about 200 kilometers (125 miles) west of Juneau, Alaska's capital. It is a deep, T-shaped, 11-kilometer (7-mile)-long bay with a sand bar named La Chaussee Spit that separates it from the Pacific Ocean (Figure 8A). The largest wave ever authentically recorded occurred in Lituya Bay. Remarkably, the wave was witnessed by six people on board three small fishing boats that were near the bay's entrance (Figure 8A, *top*).

At about 10:00 P.M. on July 9, 1958, an earthquake of magnitude $M_w = 7.9$[1] occurred along the Fairweather Fault, which runs along the top of the "T" portion of the bay. The earthquake didn't produce the wave directly, but it triggered an enormous rockslide that dumped at least 90 million tons of rock—some of it from as high as 914 meters (3000 feet) above sea level—into the upper part of the bay. The rockslide created a huge **splash wave** (a long-wavelength wave produced when an object splashes into water) that swept over the ridge facing the rockslide area and uprooted, de-barked, or snapped off trees up to 530 meters (1740 feet) above the water level of the bay—a full 87 meters (285 feet) *higher* than the world's tallest building, the Sears Tower in Chicago. As the giant wave raced down the bay toward the boats at a speed of over 160 kilometers (100 miles) per hour, it continued to snap off trees and completely overtopped the island in the middle of the bay.

During the summer in Alaska, it was still light enough at 10:00 P.M. for the people on board the boats to see the rockslide occur—and the giant wave bearing down on them. The *Badger*, a 13.4-meter (44-foot) fishing vessel, had its anchor chain snapped and was lifted up bow-first into the oncoming wave. Amazingly, the vessel surfed the wave over the sand bar! The two people on board reported looking down from a height of 24 meters (80 feet) above the tops of the trees on the sand bar, in an area where trees reach heights of 30 meters (100 feet). The *Badger* plunged into the Pacific Ocean on the other side of the sand bar stern-first, where it foundered and eventually sank. The people on board were able to launch a small skiff before the *Badger* sank and were rescued a few hours later, shaken but alive.

The *Edrie* was at anchor in the bay when the wave arrived. Its anchor chain snapped, and the vessel (including two people on board) was washed onto land. After the wave passed, the withdrawal of water washed it back into the bay, leaving the vessel largely undamaged. The two people on board the *Sunmore* were not nearly so lucky. The wave hit their vessel

[1]The symbol M_w indicates the *moment magnitude* of an earthquake, as discussed in Chapter 2.

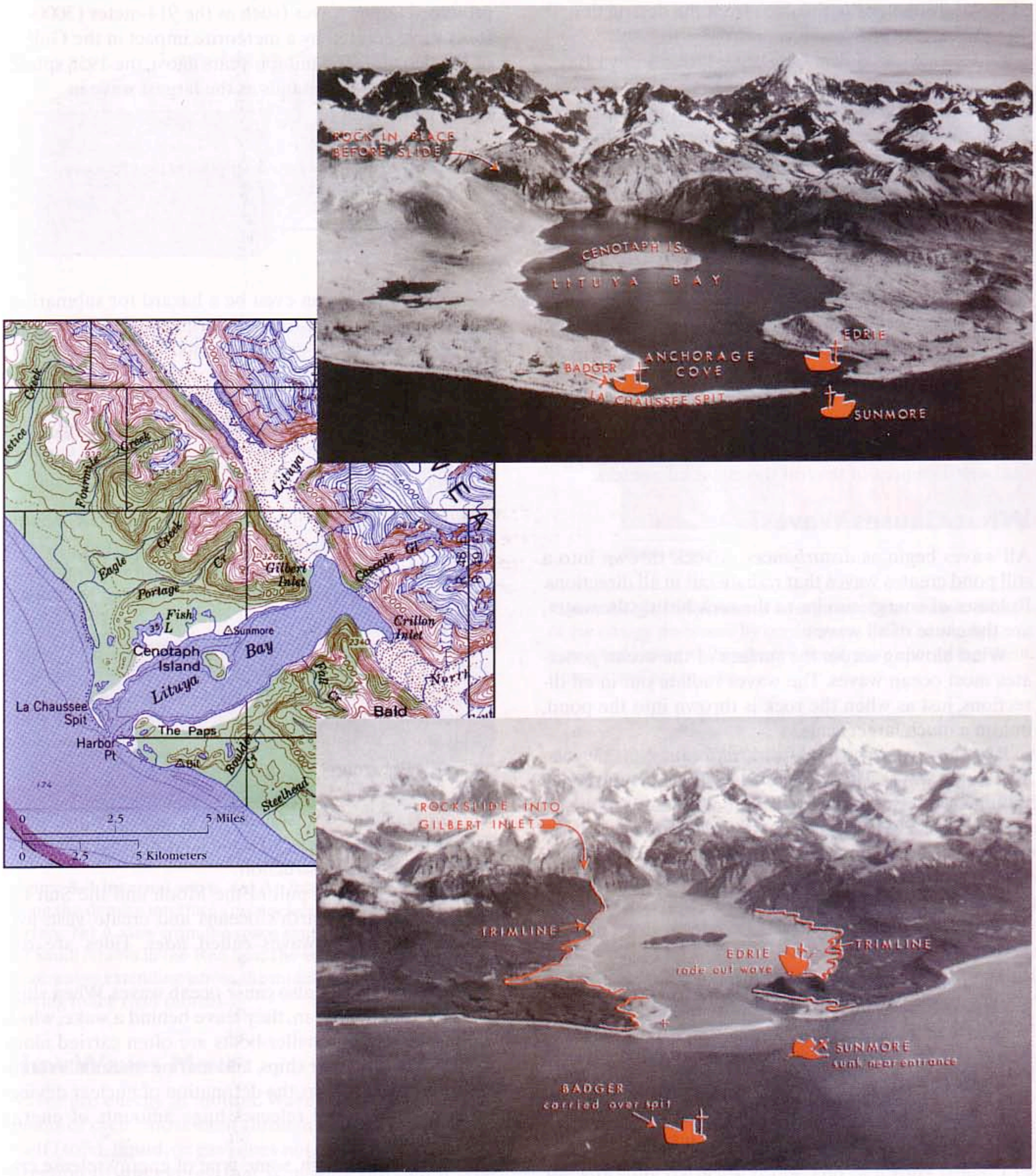


Figure 8A **Lituya Bay, Alaska, with aerial view before the 1958 splash wave (*top*) and after (*bottom*).**

broadside, which capsized and sank the *Sunmore*, killing both people on board. The wave spread out into the Pacific, and was even detected over six hours later at a tide-recording station in Hawaii, where the wave was only 10 centimeters (4 inches) tall.

The most noticeable damage to the shoreline of the bay included a trimline of trees extending around the bay and across the island (Figure 8A, *bottom*). The wave also knocked down all the trees on the sand bar and killed most of the shellfish living near the water's edge. Additionally, floating logs from the destruction filled Lituya Bay for many years.

Older knocked-down trees suggest that Lituya Bay periodically experiences rockslides that generate giant splash waves. For instance, there is evidence of a 120-meter (395-foot) wave in 1853, a 61-meter (200-foot) wave in 1899, and a 150-meter (490-foot) wave on October 27, 1936. Even though other events may have produced larger waves (such as the 914-meter (3000-foot) wave created by a meteorite impact in the Gulf of Mexico about 65 million years ago[2]), the 1958 splash wave in Lituya Bay stands as the largest wave in recorded history.

[2]See Box 4–3 in Chapter 4 for a description of the Cretaceous-Tertiary (K–T) impact event.

Even on calm days, the ocean is in continual motion as waves travel across its surface. Most waves are driven by the wind and release their energy gently, although ocean storms can push waves ashore hard and fast, with devastating effects. Waves are *moving energy* traveling along the interface between ocean and atmosphere, often transferring energy from a storm far out at sea over distances of several thousand kilometers.

What Causes Waves?

All waves begin as *disturbances*. A rock thrown into a still pond creates waves that radiate out in all directions. Releases of energy, similar to the rock hitting the water, are the cause of all waves.

Wind blowing across the surface of the ocean generates most ocean waves. The waves radiate out in all directions, just as when the rock is thrown into the pond, but on a much larger scale.

The movement of fluids with different densities can also create waves. These waves travel along the interface (boundary) between the two different fluids. Both the air and the ocean are fluids, so waves can be created along interfaces *between* and *within* these fluids as follows:

- Along an *air–water interface*, the movement of air across the ocean surface creates **ocean waves** (simply called *waves*).
- Along an *air–air interface*, the movement of different air masses creates **atmospheric waves**, which are often represented by ripple-like clouds in the sky. Atmospheric waves are especially common when cold fronts (high-density air) invade an area.
- Along a *water–water interface*, the movement of water of different densities creates **internal waves**, as shown in Figure 8–1a. Because these waves travel along the boundary between waters of different density, they are associated with a *pycnocline*.[3] Internal waves can be much larger than surface waves, with heights exceeding 100 meters (330 feet). Tidal movement, turbidity currents, wind stress, or even passing ships at the surface create internal waves, which can sometimes be observed from space (Figure 8–1b). Internal waves can even be a hazard for submarines because they can carry submarines to depths exceeding their designed pressure limits. At the surface, parallel slicks caused by a film of surface debris may indicate the presence of internal waves below. On a smaller scale, internal waves are prominently featured sloshing back and forth in "desktop oceans," which contain two fluids that do not mix.

Mass movement into the ocean, such as coastal landslides and calving icebergs, also create waves. These waves are commonly called *splash waves* (see the chapter-opening feature for a description of a large splash wave).

Sea floor movement, which changes the shape of the ocean floor and can release large amounts of energy to the entire water column (compared to wind-driven waves, which affect only surface water), can create very large waves. Examples include underwater avalanches (turbidity currents), volcanic eruptions, and fault slippage. The resulting waves are called *seismic sea waves* or *tsunami*. Fortunately, tsunami occur infrequently. When they do, however, they can flood coastal areas and cause large amounts of destruction.

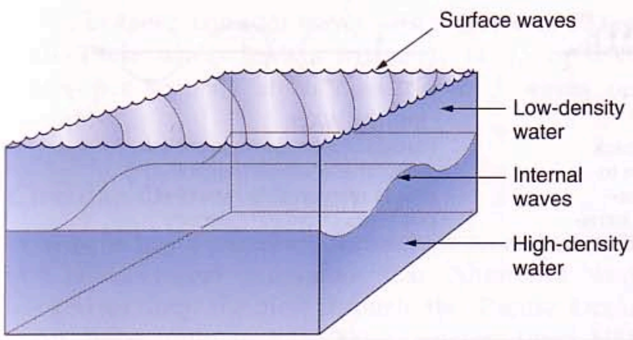
The gravitational pull of the Moon and the Sun tug on every part of Earth's oceans and create vast, low, highly predictable waves called *tides*. Tides are discussed in Chapter 9.

Human activities also cause ocean waves. When ships travel across the ocean, they leave behind a wake, which is a wave. In fact, smaller boats are often carried along in the wake of larger ships, and marine mammals sometimes play there. Also, the detonation of nuclear devices at or near sea level releases huge amounts of energy that creates waves.

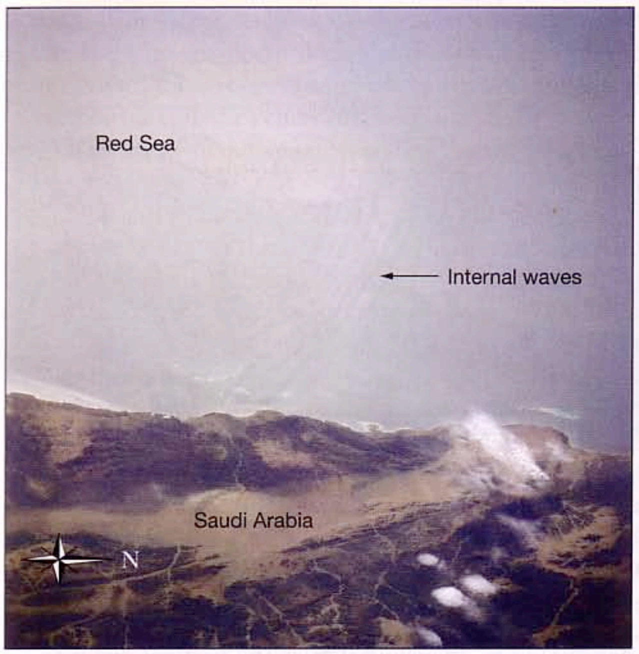
In all cases, though, some type of energy release creates waves. Figure 8–2 shows the distribution of energy in waves, indicating that most ocean waves are wind-generated.

Most ocean waves are caused by wind, but many other waves are created by releases of energy in the ocean, including internal waves, splash waves, tsunami, tides, and human-induced waves.

[3]As discussed in Chapter 5, a *pycnocline* is a layer of rapidly changing density.



(a)



(b) Internal waves, Red Sea

Figure 8–1 Internal wave. **(a)** An internal wave moving along the density interface (*pycnocline*) below the ocean surface. **(b)** A view from the space shuttle of internal waves off Saudi Arabia in the Red Sea. The internal waves are the large waves extending across the middle of the image and are moving to the right (north).

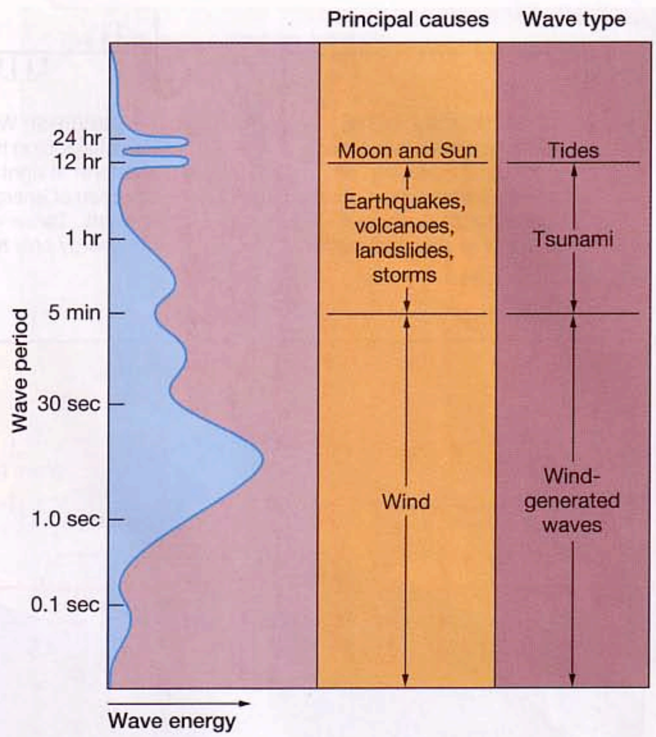


Figure 8–2 Distribution of energy in ocean waves. Most of the energy possessed by ocean waves exists as wind-generated waves while other peaks of wave energy represent tsunami and ocean tides.

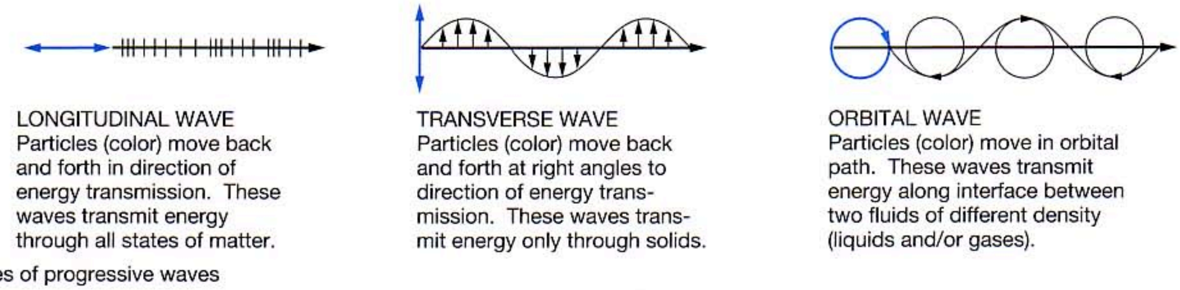
How Waves Move

Waves are energy in motion. Waves transmit energy by means of cyclic movement through matter. The medium itself (solid, liquid, or gas) does not actually travel in the direction of the energy that is passing through it. The particles in the medium simply oscillate, or cycle, back-and-forth, up-and-down, or around-and-around, transmitting energy from one particle to another. If you thump your fist on a table, for example, the energy travels through the table as waves that someone sitting at the other end can feel, but the table itself does not move.

Waves move in different ways. Simple *progressive waves* (Figure 8–3a) are waves that oscillate uniformly and *progress* or travel without breaking. Progressive waves may be *longitudinal*, *transverse*, or a combination of the two motions, called *orbital*.

In **longitudinal waves** (also known as push-pull waves), the particles that vibrate "push and pull" in the same direction that the energy is traveling, like a spring whose coils are alternately compressed and expanded. The shape of the wave (called a *waveform*) moves through the medium by compressing and decompressing as it goes. Sound, for instance, travels as longitudinal waves. Clapping your hands initiates a percussion that compresses and decompresses the air as the sound moves through a room. Energy can be transmitted through all states of matter—gaseous, liquid, or solid—by this longitudinal movement of particles.

In **transverse waves** (also known as side-to-side waves), energy travels at right angles to the direction of the vibrating particles. If one end of a rope is tied to a doorknob while the other end is moved up and down by hand, for example, a waveform progresses along the rope and energy is transmitted from the motion of the hand to the doorknob. The waveform moves up and down with the hand, but at right angles to the direction in which energy is transmitted (from the hand to the doorknob). Generally, transverse waves transmit energy only through solids, because the particles in solids are bound to one another strongly enough to transmit this kind of motion.



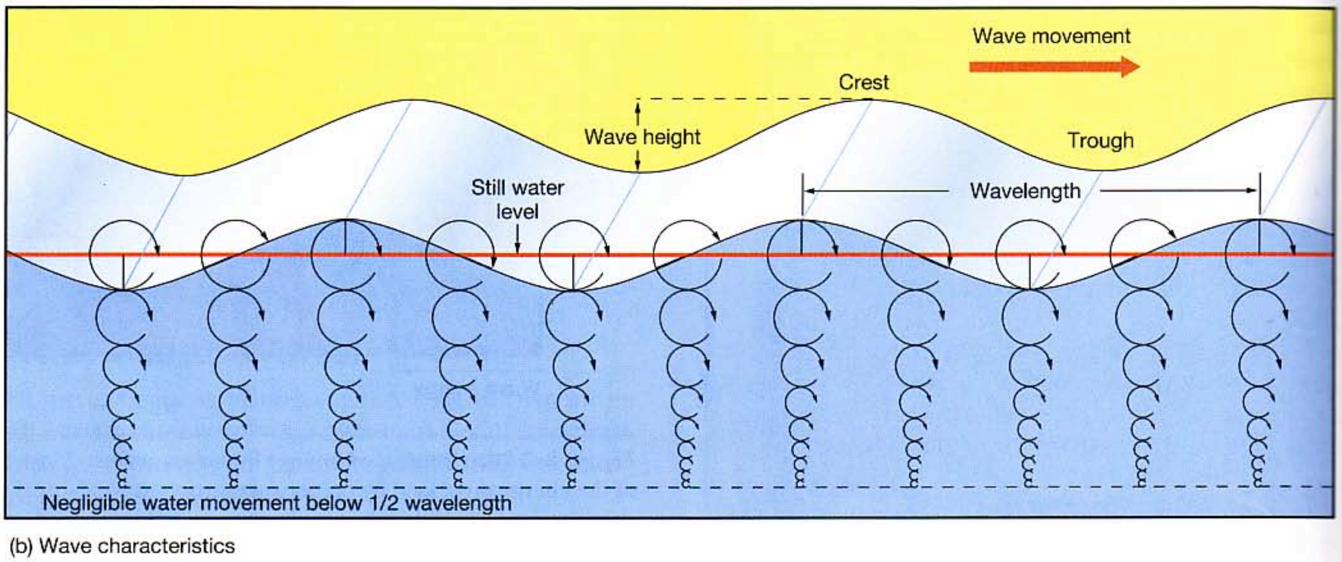


Figure 8–3 Types and characteristics of progressive waves. (a) Types of progressive waves. **(b)** A diagrammatic view of an idealized ocean wave showing its characteristics.

Longitudinal and transverse waves are called *body waves* because they transfer energy through a body of matter. Ocean waves, on the other hand, transmit energy along an interface between the atmosphere and the ocean. The movement of particles along the interface involves components of *both* longitudinal and transverse waves, so particles move in circular orbits. Thus, waves at the ocean surface are **orbital waves** (also called *interface waves*).

Wave Characteristics

Figure 8–3b shows the characteristics of an idealized ocean wave. The simple, uniform, moving waveform transmits energy from a single source and travels along the ocean–atmosphere interface. These waves are also called *sine waves* because their uniform shape resembles the oscillating pattern expressed by a sine curve. Even though idealized waveforms do not exist in nature, they help us understand wave characteristics.

As the idealized wave passes a permanent marker, such as a pier piling, a succession of high parts of the waves, called **crests**, alternate with low parts, called **troughs**. Halfway between the crests and the troughs is the **still water level**, or *zero energy level*. This is the level of the water if there were no waves. The **wave height**, designated by the symbol H, is the vertical distance between a crest and a trough.

The horizontal distance between any two corresponding points on successive waveforms, such as from crest to crest or from trough to trough, is the **wavelength**, L. **Wave steepness** is the ratio of wave height to wavelength:

$$\text{Wave steepness} = \frac{\text{wave height } (H)}{\text{wavelength } (L)}$$

If the wave steepness exceeds $^1/_7$, the wave *breaks* (spills forward) because the wave is too steep to support itself. A wave can break anytime the 1:7 ratio is exceeded, either along the shoreline or out at sea. This ratio also dictates the maximum height of a wave. For example, a wave 7 meters long can only be 1 meter high or it will break.

The time it takes one full wave—one wavelength—to pass a fixed position (like a pier piling) is the **wave period**, T. Typical wave periods range between 6 and 16 seconds. The **frequency** (f) is defined as the number of wave crests passing a fixed location per unit of time and is the inverse of the period:

$$\text{Frequency } (f) = \frac{1}{T}$$

For instance, consider waves with a period of 12 seconds. These waves have a frequency of $^1/_{12}$ or 0.083 waves per second, which converts to 5 waves per minute.

Circular Orbital Motion

Waves can travel great distances across ocean basins. In one study, waves generated near Antarctica were tracked as they traveled through the Pacific Ocean basin. After more than 10,000 kilometers (over 6000 miles), the waves finally expended their energy a week later along the shoreline of the Aleutian Islands of Alaska. The water itself doesn't travel the entire distance, but the waveform does. As the wave travels, the water passes the energy along by moving in a circle. This movement is called **circular orbital motion**.

Observation of an object floating in the waves reveals that it moves not only up-and-down, but also slightly forward and backward with each successive wave. Figure 8–4 shows that a floating object moves up and backward as the crest approaches, up and forward as the crest passes, down and forward after the crest, down and backward as the trough approaches, and rises and moves backward again as the next crest advances. When the movement of the rubber duck shown in Figure 8–4 is traced as a wave passes, it can be seen that the duck moves in a circle and returns close to its original position.[4] This motion allows a waveform (the wave's shape) to move forward through the water while the individual water particles that transmit the wave move around in a circle and return to essentially the same place. Wind moving across a field of wheat causes a similar phenomenon: The wheat itself doesn't travel across the field, but the waves do.

The circular orbits of an object floating at the surface have a diameter equal to the wave height (Figure 8–3b). Figure 8–5 shows that circular orbital motion dies out quickly below the surface. At some depth below the surface, the circular orbits become so small that movement is negligible. This depth is called the **wave base**, and it is equal to one-half the wavelength ($L/2$) *measured from still water level*. Only wavelength controls the depth of the wave base, so the longer the wave, the deeper the wave base.

The decrease of orbital motion with depth has many practical applications. For instance, submarines can avoid large ocean waves simply by submerging below the wave base. Even the largest storm waves will go unnoticed if a submarine submerges to only 150 meters (500 feet). Floating bridges and floating oil rigs are constructed so that most of their mass is below wave base, so they will be unaffected by wave motion. In fact, offshore floating airport runways have been designed using similar principles. Additionally, seasick scuba divers find relief when they submerge into the calm, motionless water below wave base. Finally, as you walk from the beach into the ocean, you reach a point where it is easier to dive under an incoming wave than to jump over it. It is easier to swim through the smaller orbital motion below the surface than to fight the large waves at the surface.

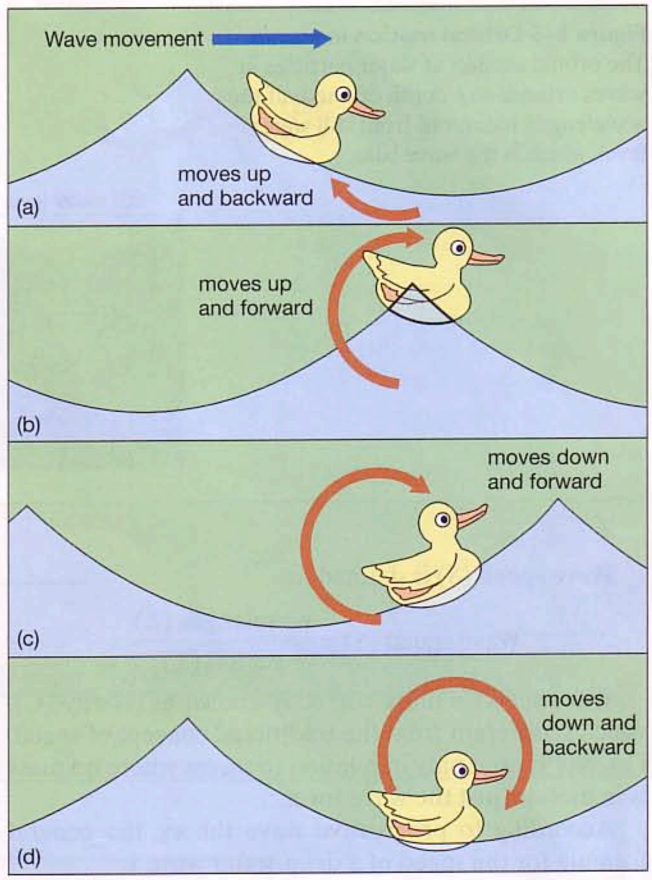


Figure 8–4 A rubber duck in water. As waves pass, the motion of a floating rubber duck resembles that of a circular orbit.

> The ocean transmits wave energy by circular orbital motion, where the water particles move in circular orbits and return to approximately the same location.

Deep-Water Waves

If the water depth (d) is greater than the wave base ($L/2$), the waves are called **deep-water waves** (Figure 8–6a). Deep-water waves have no interference with the ocean bottom, so they include all wind-generated waves in the open ocean, where water depths far exceed wave base.

[4]Actually, the circular orbit does not quite return the floating object to its original position because the half of the orbit accomplished in the trough is slower than the crest half of the orbit. This slight forward movement is called *wave drift*.

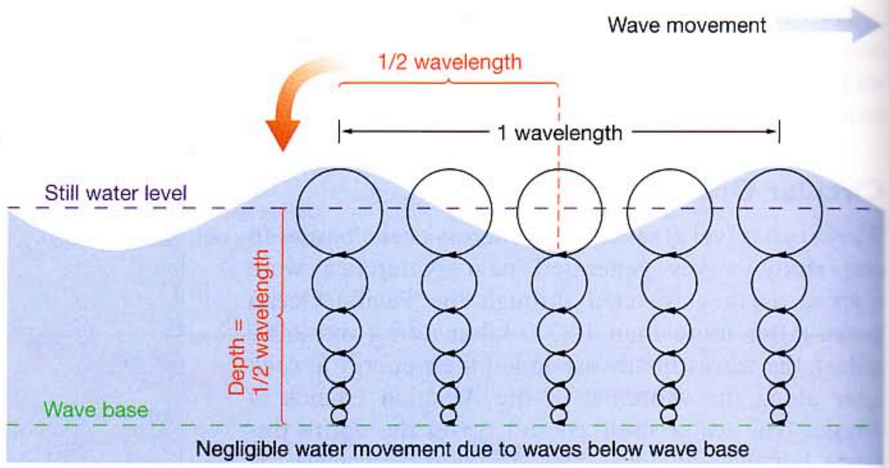


Figure 8–5 Orbital motion in waves. The orbital motion of water particles in waves extends to a depth of one-half the wavelength, measured from still water level, which is the wave base.

Wave speed (S) is defined as:

$$\text{Wave speed } (S) = \frac{\text{wavelength } (L)}{\text{period } (T)}$$

Wave speed is more correctly known as *celerity* (C), which is different from the traditional concept of speed. Celerity is used only in relation to waves where no mass is in motion, just the wave form.

According to progressive wave theory, the general formula for the speed of a deep-water wave is:

$$\text{Wave speed } (S) = \sqrt{\frac{gL}{2\pi}}$$

where g is the acceleration due to gravity [9.8 meters (32.2 feet) per second per second] and L is the wavelength. Filling in the numbers gives:

$$\text{Wave speed } (S) \text{ in meters per second} = 1.25\sqrt{L, \text{ in meters}}$$

or:

$$\text{Wave speed } (S) \text{ in feet per second} = 2.26\sqrt{L, \text{ in feet}}$$

Since wave speed (S) is defined as L/T, we can replace S with L/T and square both sides of the equation as follows:

$$\frac{L^2}{T^2} = \frac{gL}{2\pi}$$

Then, using algebra to reduce terms in the equation, wave speed becomes:

$$S = \frac{L}{T} = \frac{gT}{2\pi}$$

Filling in numbers gives:

$$S = 1.56T, \text{ in meters per second}$$

or:

$$S = 5.12T, \text{ in feet per second}$$

The graph in Figure 8–7 uses these equations to relate the wavelength, period, and speed of deep-water waves. Of the three variables, the wave period is usually easiest to measure. Since all three variables are related, the other two can be determined using Figure 8–7. For example, the vertical red line in Figure 8–7 shows that a wave with a period of 8 seconds has a wavelength of 100 meters. Thus, the speed of the wave is shown by horizontal red line in Figure 8–7, which is:

$$\text{Speed } (S) = \frac{L}{T} = \frac{100 \text{ meters}}{8 \text{ seconds}} = 12.5 \text{ meters per second}$$

The general relationship shown by Figure 8–7 is the *longer the wavelength, the faster the wave travels*. A fast wave does not necessarily have a large wave height, however, because wave speed depends *only* on wavelength.

Shallow-Water Waves

Waves in which depth (d) is less than $^1/_{20}$ of the wavelength ($L/20$) are called **shallow-water waves**, or *long waves* (Figure 8–6b). Shallow-water waves are said to *touch bottom* or *feel bottom* because the ocean floor interferes with their orbital motion.

The speed of shallow-water waves is influenced only by gravitational attraction (g) and the water depth (d):

$$\text{Wave speed } (S) = \sqrt{gd}$$

Since gravitational attraction remains constant, the equation gives:

$$\text{Wave speed } (S) \text{ in meters per second} = 3.13\sqrt{d, \text{ in meters}}$$

or:

$$\text{Wave speed } (S) \text{ in feet per second} = 5.67\sqrt{d, \text{ in feet}}$$

Thus, wave speed in shallow-water waves is determined *only* by water depth.

Shallow-water waves include wind-generated waves that have moved into shallow near-shore areas; *tsunami* (seismic sea waves), generated by earthquakes in the ocean floor; and the *tides*, which are a type of wave generated by the gravitational attraction of the Moon and the Sun. Tsunami and tides are very long-wavelength waves, which far exceeds even the deepest ocean water depths.

Particle motion in shallow-water waves is in a very flat elliptical orbit that approaches horizontal (back-and-forth) oscillation. The vertical component of

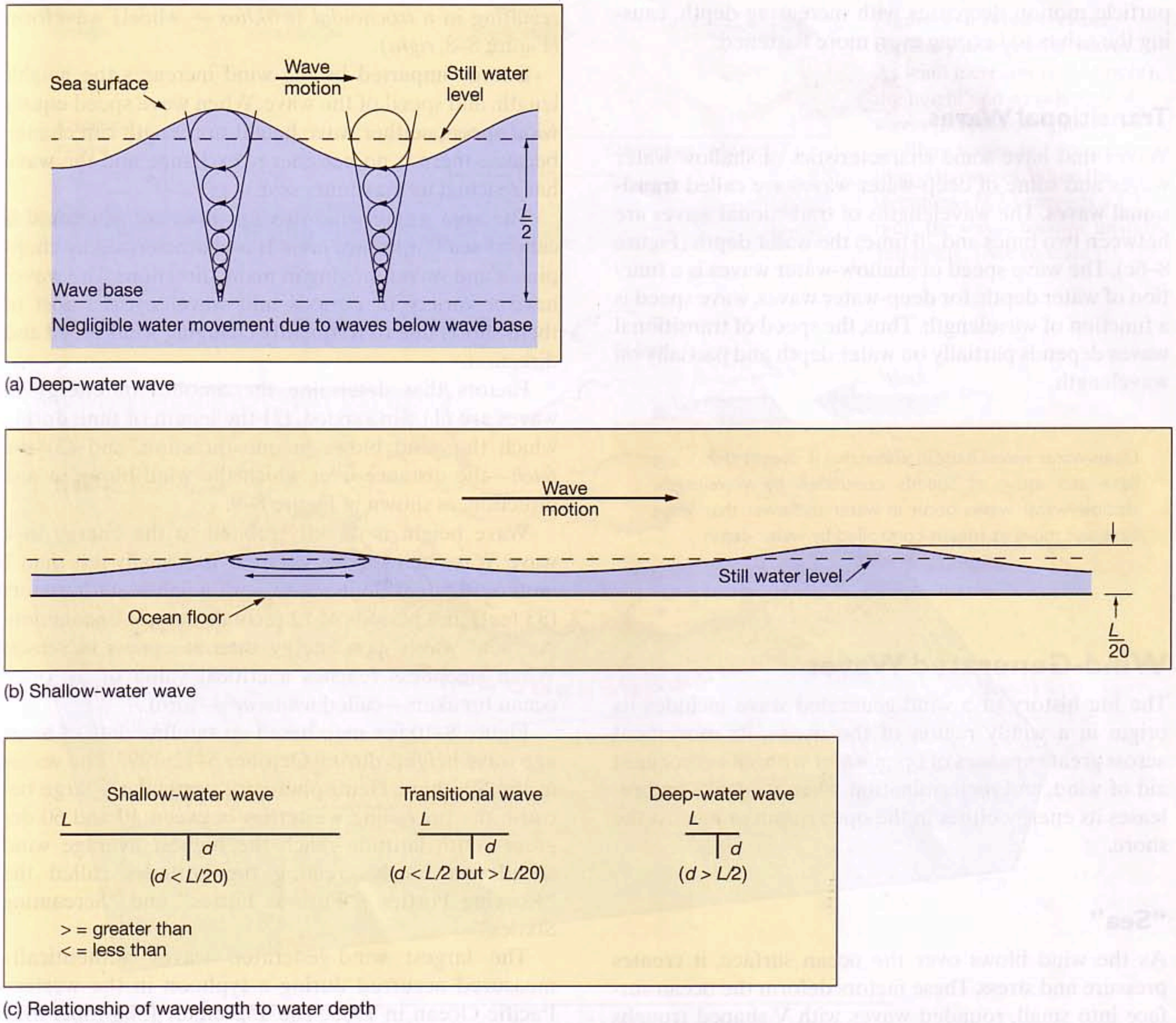


Figure 8–6 Deep-water and shallow-water waves. (a) Wave profile and water-particle motions of a deep-water wave, showing the diminishing size of the orbits with increasing depth. **(b)** Motions of water particles in shallow-water waves, where water motion extends to ocean floor. **(c)** Relationship of wavelength to water depth.

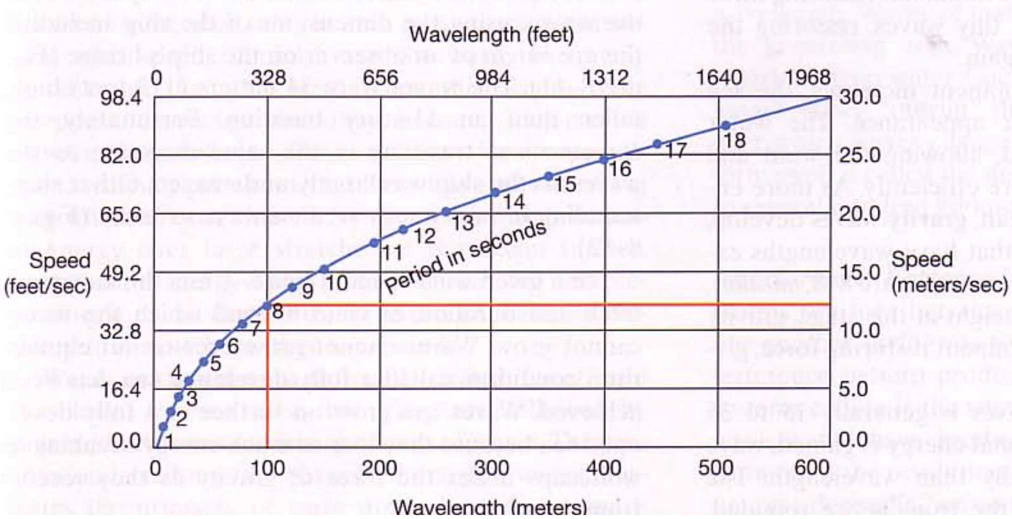


Figure 8–7 Speed of deep-water waves. Ideal relations among wavelength, period (*blue line*), and wave speed for deep-water waves. Red lines show an example wave with a wavelength of 100 meters, a period of 8 seconds, and a speed of 12.5 meters per second.

particle motion decreases with increasing depth, causing the orbits to become even more flattened.

Transitional Waves

Waves that have some characteristics of shallow-water waves and some of deep-water waves are called **transitional waves**. The wavelengths of transitional waves are between two times and 20 times the water depth (Figure 8–6c). The wave speed of shallow-water waves is a function of water depth; for deep-water waves, wave speed is a function of wavelength. Thus, the speed of transitional waves depends partially on water depth and partially on wavelength.

Deep-water waves exist in water that is deeper than wave base and move at speeds controlled by wavelength; shallow-water waves occur in water shallower than wave base and move at speeds controlled by water depth.

Wind-Generated Waves

The life history of a wind-generated wave includes its origin in a windy region of the ocean, its movement across great expanses of open water without subsequent aid of wind, and its termination when it breaks and releases its energy, either in the open ocean or against the shore.

"Sea"

As the wind blows over the ocean surface, it creates pressure and stress. These factors deform the ocean surface into small, rounded waves with V-shaped troughs and wavelengths less than 1.74 centimeters (0.7 inch). Commonly called *ripples*, oceanographers call them **capillary waves** (Figure 8–8, *left*). The name comes from *capillarity*, a property that results from the surface tension of water. Capillarity is the dominant **restoring force** that works to destroy these tiny waves, restoring the smooth ocean surface once again.

As capillary wave development increases, the sea surface takes on a rougher appearance. The water "catches" more of the wind, allowing the wind and ocean surface to interact more efficiently. As more energy is transferred to the ocean, **gravity waves** develop, which are symmetric waves that have wavelengths exceeding 1.74 centimeters (0.7 inch) (Figure 8–8, *middle*). Because they reach greater height at this stage, gravity replaces capillarity as the dominant restoring force, giving these waves their name.

The length of gravity waves is generally 15 to 35 times their height. As additional energy is gained, wave height increases more rapidly than wavelength. The crests become pointed and the troughs are rounded, resulting in a *trochoidal* (*trokhos* = wheel) waveform (Figure 8–8, *right*).

Energy imparted by the wind increases the height, length, and speed of the wave. When wave speed equals wind speed, neither wave height nor length can change because there is no net energy exchange and the wave has reached its maximum size.

The area where wind-driven waves are generated is called **"sea"** or the *sea area*. It is characterized by choppiness and waves moving in many directions. The waves have a variety of periods and wavelengths (most of them short) due to frequently changing wind speed and direction.

Factors that determine the amount of energy in waves are (1) wind speed, (2) the length of time during which the wind blows in one direction, and (3) the *fetch*—the distance over which the wind blows in one direction, as shown in Figure 8–9.

Wave height is directly related to the energy in a wave. Wave heights in a sea area are usually less than 2 meters (6.6 feet), but waves with heights of 10 meters (33 feet) and periods of 12 seconds are not uncommon. As "sea" waves gain energy, their steepness increases. When steepness reaches a critical value of $^1/_7$, open ocean breakers—called *whitecaps*—form.

Figure 8–10 is a map based on satellite data of average wave heights during October 3–12, 1992. The waves in the Southern Hemisphere are particularly large because the prevailing westerlies between 40 and 60 degrees south latitude reach the highest average wind speeds on Earth, creating the latitudes called the "Roaring Forties," "Furious Fifties," and "Screaming Sixties."

The largest wind-generated waves authentically measured occurred during a typhoon in the western Pacific Ocean in 1935. The 152-meter (500-foot)-long U.S. Navy tanker USS *Ramapo* encountered 108-kilometer (67-mile)-per-hour winds en route from the Philippines to San Diego, California. The resulting waves were symmetrical, uniform, and had a period of 14.8 seconds. The vessel's officers carefully measured the waves, using the dimensions of the ship including the *eye height* of an observer on the ship's bridge (Figure 8–11). The waves were 34 meters (112 feet) high, taller than an 11-story building. Fortunately, the *Ramapo* was traveling in the same direction as the waves, so the ship was largely undamaged. Other ships traveling in heavy seas aren't always so lucky (Figure 8–12).

For a given wind speed, Table 8–1 lists the maximum fetch and duration of wind beyond which the waves cannot grow. Waves cannot grow because an equilibrium condition, called a **fully developed sea**, has been achieved. Waves can grow no further in a fully developed sea because they lose as much energy breaking as whitecaps under the force of gravity as they receive from the wind.

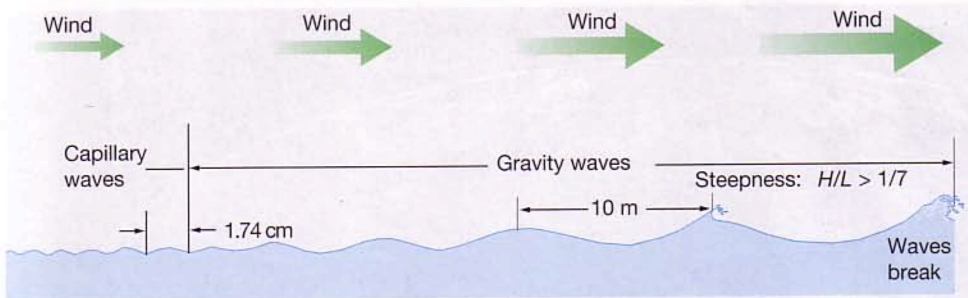


Figure 8–8 Wind creates capillary and gravity waves. As wind increases (*left to right*), the height and wavelength of waves increases, beginning as capillary waves and progressing to gravity waves. When the wave steepness (H/L) exceeds a 1:7 ratio, the waves become unstable and break. (Not to scale.)

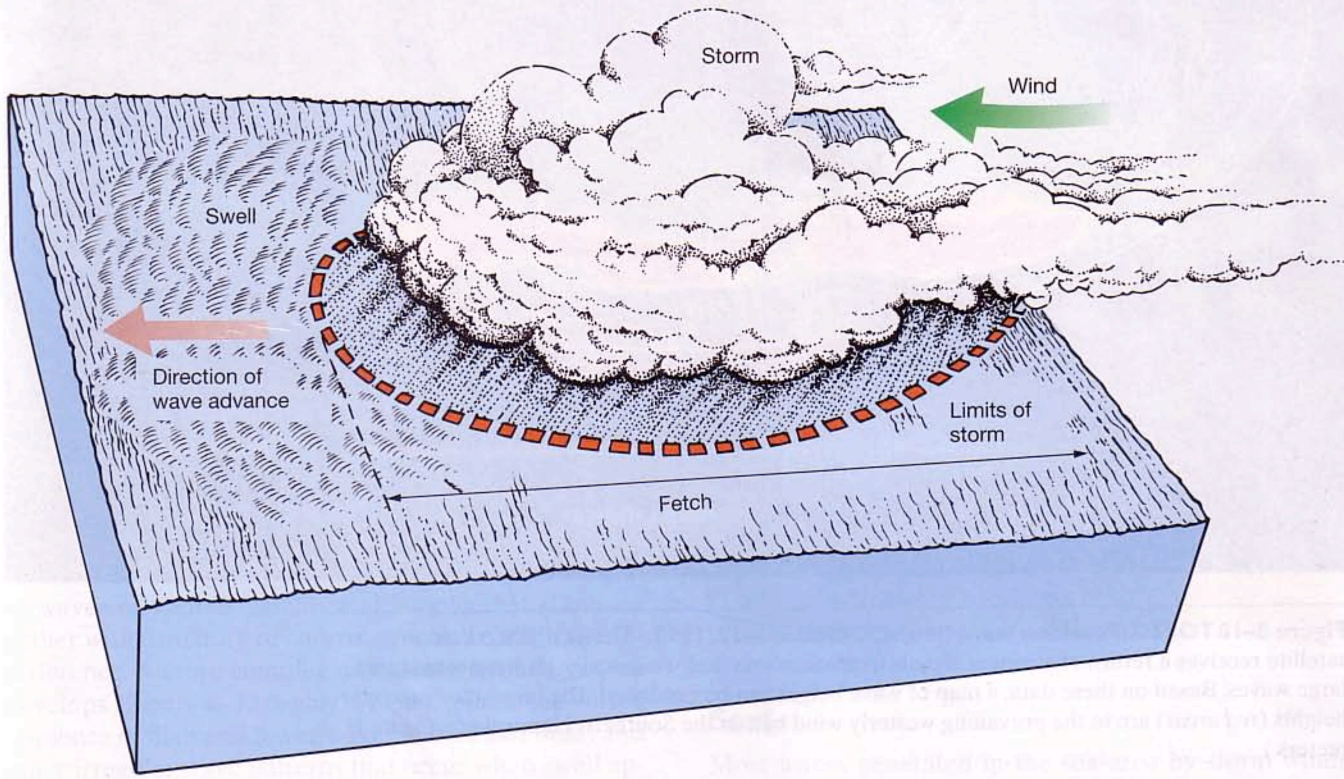


Figure 8–9 The "sea" and swell. As wind blows across the "sea" (*red dash*), wave size increases with increasing wind speed, duration, and fetch. As waves advance beyond their area of origination, they advance across the ocean surface and become sorted into uniform, symmetric swell.

Swell

As waves generated in a sea area move toward its margins, wind speeds diminish and the waves eventually move faster than the wind. When this occurs, wave steepness decreases, and they become long-crested waves called **swells** (*swellan* = swollen). Swells are uniform, symmetrical waves that have traveled out of the area where they originated. Swells moves with little loss of energy over large stretches of the ocean surface, transporting energy away from one sea area and depositing it in another. Thus, there can be waves at distant shorelines where there is no wind.

Waves with longer wavelengths travel faster, and thus leave the sea area first. They are followed by slower, shorter **wave trains**, or groups of waves. The progression from long, fast waves to short, slow waves illustrates the principle of **wave dispersion** (*dis* = apart, *spargere* = to scatter)—the sorting of waves by their wavelength. Waves of many wavelengths are present in the generating area. Wave speed depends on wavelength in deep water (see Figure 8–7), however, so the longer waves "outrun" the shorter ones. The distance over which waves change from a choppy "sea" to uniform swell is called the **decay distance**, which can be up to several hundred kilometers.

Interference Patterns When swells from different storms run together, the waves clash, or *interfere* with one another, giving rise to **interference patterns**. An interference pattern produced when two or more wave systems collide is the sum of the disturbance that each wave would have produced individually. Figure 8–13 shows that the result may be a larger or smaller trough or crest, depending on conditions.

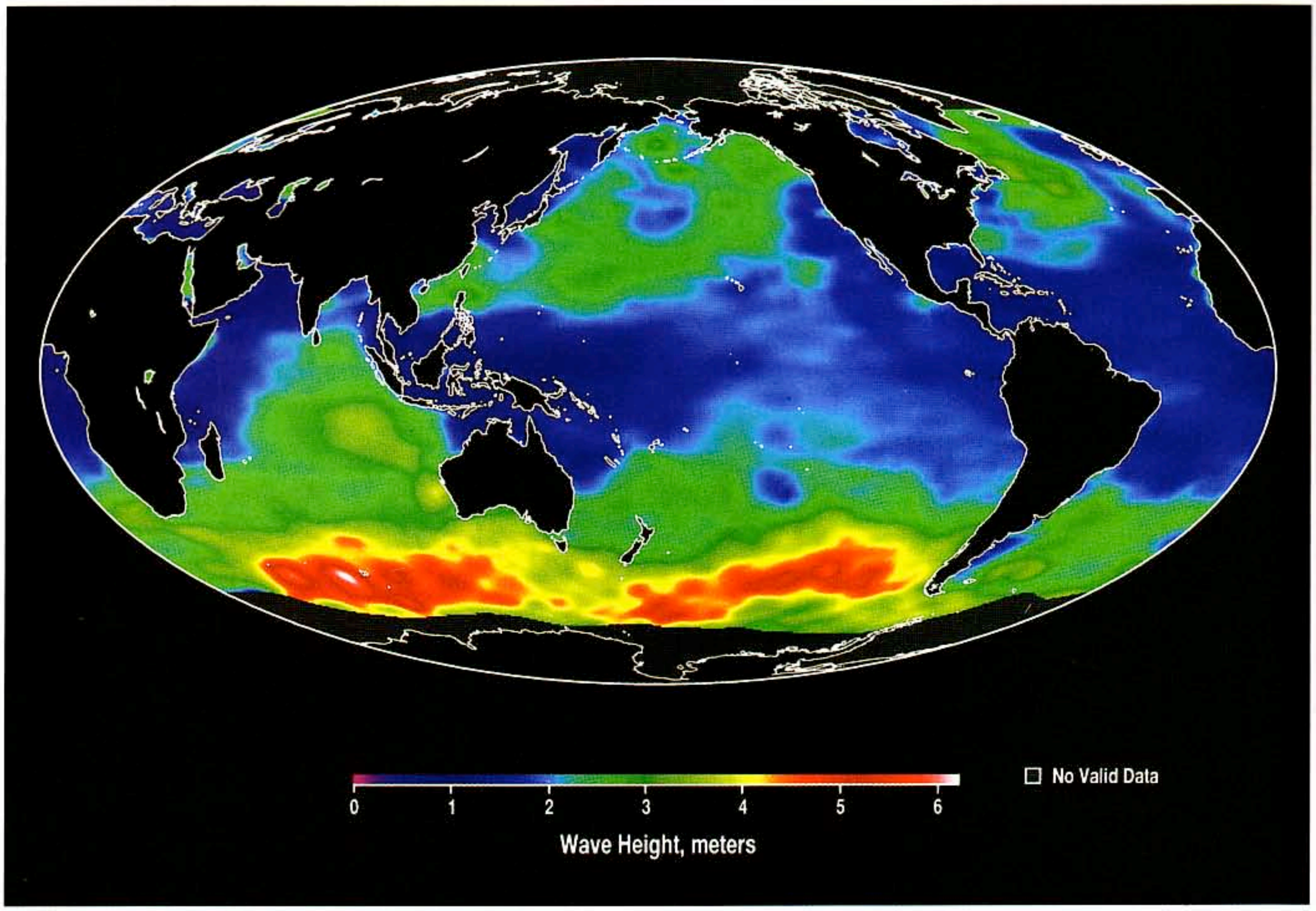


Figure 8–10 TOPEX/Poseidon wave height, October 3–12, 1992. The TOPEX/Poseidon satellite receives a return of stronger signals from calm seas and weaker signals from seas with large waves. Based on these data, a map of wave height can be produced. The largest average wave heights (*red areas*) are in the prevailing westerly wind belt in the Southern Hemisphere. (Scale in meters.)

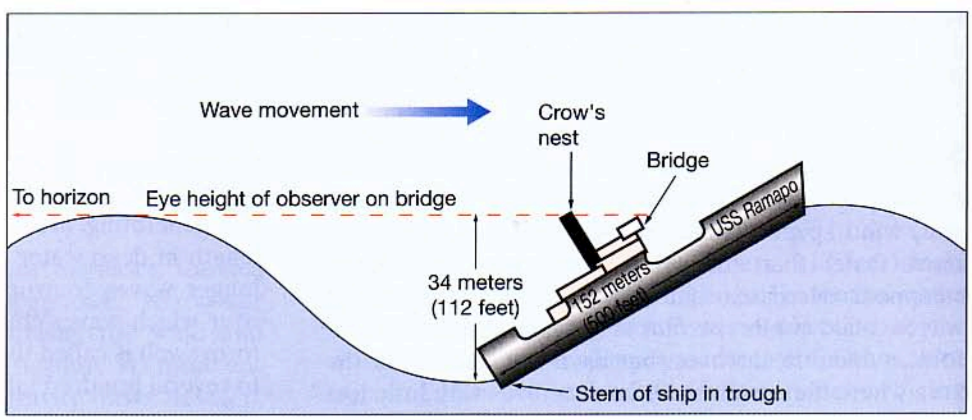


Figure 8–11 USS *Ramapo* in heavy seas. Bridge officers aboard the USS *Ramapo* measured the largest authentically recorded wave by sighting from the bridge across the crow's nest to the horizon while the ship's stern was directly in the trough of a large wave. A wave height of 34 meters (112 feet) was calculated based on geometric relationships of the vessel and the waves.

When swells from two storm areas collide, the interference pattern may be constructive or destructive, but it is more likely to be mixed. **Constructive interference** occurs when wave trains having the same wavelength come together *in phase*, meaning crest to crest and trough to trough. If the displacements from each wave are added together, the interference pattern results in a wave with the same wavelength as the two overlapping wave systems, but with a wave height equal to the sum of the individual wave heights (Figure 8–13, *left*).

Destructive interference occurs when wave trains having the same wavelength come together *out of phase*, meaning the crest from one wave coincides with the trough from a second wave. If the waves have

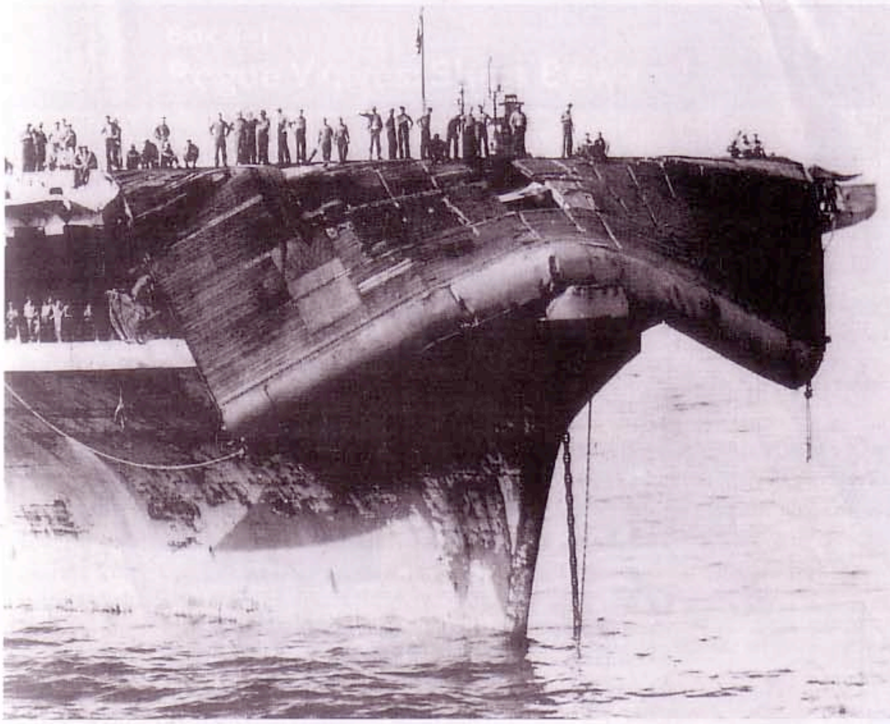


Figure 8–12 Wave damage on the aircraft carrier *Bennington*. The *Bennington* returns from heavy seas encountered in a typhoon off Okinawa in 1945 with part of its reinforced steel flight deck bent down over the bow. Damage to the flight deck, which is 16.5 meters (54 feet) above still water level, was caused by large waves.

identical heights, the sum of the crest of one and the trough of another is zero, so the energy of these waves cancel each other (Figure 8–13, *center*).

It is more likely, however, that the two swells consist of waves of various heights and lengths that come together with a mixture of constructive and destructive interference. A more complex **mixed interference** pattern develops (Figure 8–13, *right*), which explains the varied sequence of high and lower waves (called **surf beat**) and other irregular wave patterns that occur when swell approaches the seashore. In the open ocean, several swell systems often interact, creating complex wave patterns (Figure 8–14) and, sometimes, large waves that can be hazardous to ships (Box 8–1).

Constructive interference results from in phase overlapping of waves and creates larger waves, while destructive interference results from waves overlapping out of phase, reducing wave height.

Surf

Most waves generated in the sea area by storm winds move across the ocean as swell. These waves then release their energy along the margins of continents in the **surf zone**, which is the zone of breaking waves. Breaking waves exemplify power and persistence, sometimes

Table 8–1 Description of a fully developed sea for a given wind speed.

Wind speed in km/h (mi/h)	*Average height in m (ft)*	*Average length in m (ft)*	*Average period in sec*	*Highest 10% of waves in m (ft)*
20 (12)	0.33 (1.0)	10.6 (34.8)	3.2	0.75 (2.5)
30 (19)	0.88 (2.9)	22.2 (72.8)	4.6	2.1 (6.9)
40 (25)	1.8 (5.9)	39.7 (130.2)	6.2	3.9 (12.8)
50 (31)	3.2 (10.5)	61.8 (202.7)	7.7	6.8 (22.3)
60 (37)	5.1 (16.7)	89.2 (292.6)	9.1	10.5 (34.4)
70 (43)	7.4 (24.3)	121.4 (398.2)	10.8	15.3 (50.2)
80 (50)	10.3 (33.8)	158.6 (520.2)	12.4	21.4 (70.2)
90 (56)	13.9 (45.6)	201.6 (661.2)	13.9	28.4 (93.2)

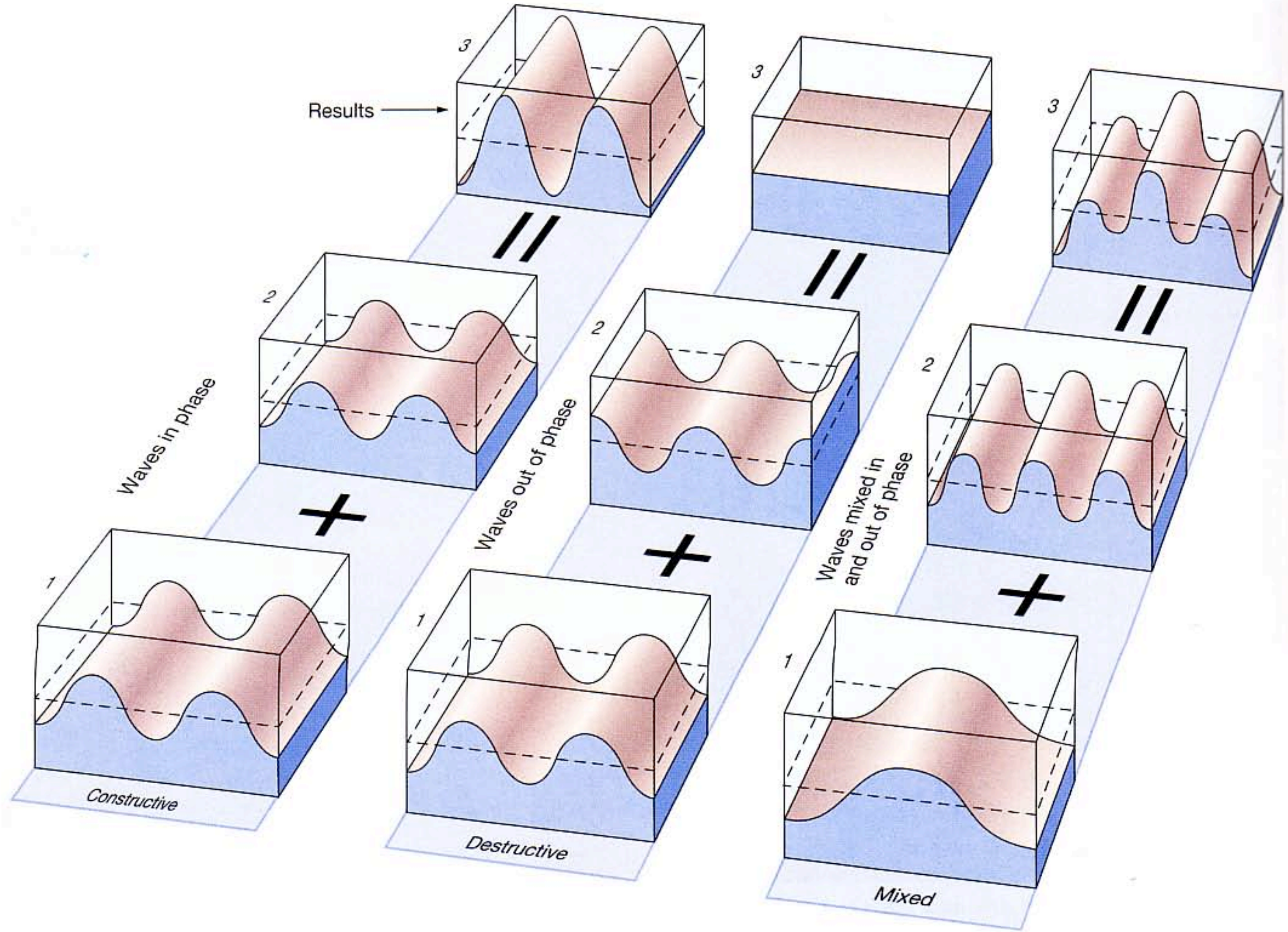


Figure 8–13 Constructive, destructive, and mixed interference patterns. Constructive interference (*left*) occurs when waves of the same wavelength come together in phase (crest to crest and trough to trough), producing waves of greater height. Destructive interference (*center*) occurs when overlapping waves have identical characteristics but come together out of phase, resulting in a canceling effect. More commonly, waves of different lengths and heights encounter one another and produce a complex, mixed interference pattern (*right*).

moving objects weighing several tons. In doing so, energy from a distant storm can travel thousands of kilometers until it is finally expended along a distant shoreline in a few wild moments.

As deep-water waves of swell move toward continental margins over gradually **shoaling** (*shold* = shallow) water, they eventually encounter water depths that are less than one-half of their wavelength (Figure 8–15) and become transitional waves. Actually, any shallowly submerged obstacle (such as a coral reef, sunken wreck, or sand bar) will cause waves to release some energy. Navigators have long known that breaking waves indicate dangerously shallow water.

Many physical changes occur to a wave as it encounters shallow water, becomes a shallow-water wave, and breaks. The shoaling depths interfere with water particle movement at the base of the wave, so the *wave speed decreases*. As one wave slows, the following waveform, which is still moving at its original speed, moves closer to the wave that is being slowed, causing a *decrease in wavelength*. The energy in the wave, which remains the same, must go somewhere, so *wave height increases*. This increase in wave height combined with the decrease in wavelength causes an *increase in wave steepness* (H/L). When the wave steepness reaches the 1:7 ratio, the waves break as surf (Figure 8–15).

If the surf is swell that has traveled from distant storms, breakers will develop relatively near shore in shallow water. The horizontal motion characteristic of shallow-water waves moves water alternately toward and away from the shore as an oscillation. The surf will be characterized by parallel lines of relatively uniform breakers.

If the surf consists of waves generated by local winds, the waves may not have been sorted into swell. The surf may be mostly unstable, deep-water, high-energy waves with steepness already near the 1:7 ratio. In this case, the waves will break shortly after feeling bottom some

Box 8–1
Rogue Waves: Ships Beware!

Rogue waves are massive, solitary waves that can reach enormous height and often occur at times when normal ocean waves are not unusually large. In a sea of 2-meter (6.5-foot) waves, for example, a 20-meter (65-foot) rogue wave may suddenly appear. *Rogue* means "unusual" and, in this case, the waves are unusually large. Rogue waves—sometimes called **superwaves**—can be quite destructive and have been popularized in literature and movies such as "*The Perfect Storm.*"

In the open ocean, one wave in 23 will be over twice the height of the wave average, one in 1175 will be three times as high, and one in 300,000 will be four times as high. The chances of a truly monstrous wave, therefore, are only one in several billion. Nevertheless, rogue waves do occur, though no one knows specifically when or where they will arise. For instance, the 17-meter (56-foot) NOAA research vessel R/V *Ballena* was flipped and sunk in November 2000 by a 4.6-meter (15-foot) rogue wave off the California coast while conducting a survey in shallow, calm water. Fortunately, the three people on board survived the incident.

Even with satellites that can measure average wave size and forecast storms, about 10 large ships each year are reported missing without a trace. Worldwide, the total number of vessels lost of all sizes may reach 1000 per year, some of which are the victims of rogue waves. Recent satellites designed to observe the ocean (see Table 3–1) have provided a wealth of data about ocean waves, but still don't allow the prediction of rogue waves.

The main cause of rogue waves is theorized to be an extraordinary case of constructive wave interference, where multiple waves overlap in phase to produce an extremely large wave. Rogue waves also tend to occur more frequently downwind from islands or shoals. In addition, rogue waves can occur when storm-driven waves move against strong ocean currents, causing the waves to steepen, shorten, and become larger. These conditions exist along the "Wild Coast" off the southeast coast of Africa, where the Agulhas Current flows directly against large Antarctic storm waves, creating rogue waves that can crash onto the bow of a ship, overcome its structural capacity, and cause the ship to sink (Figure 8b).

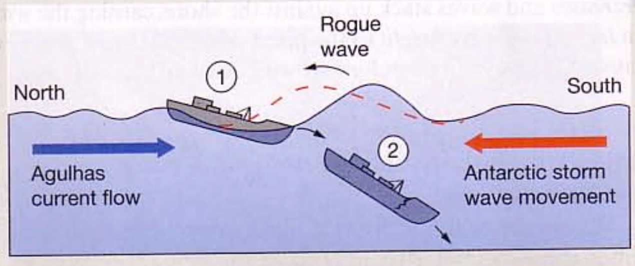


Figure 8B Rogue waves along Africa's "Wild Coast."

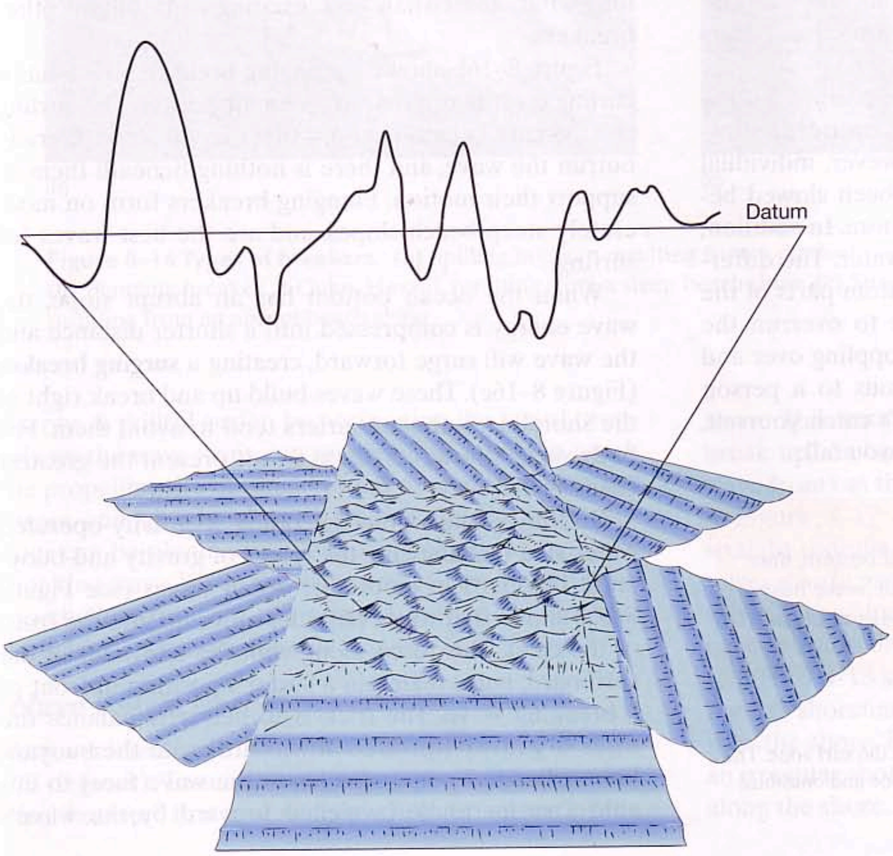


Figure 8–14 Mixed interference pattern. The observed wave pattern in the ocean (*above*) is often the result of mixed interference of many different overlapping wave sets (*below*).

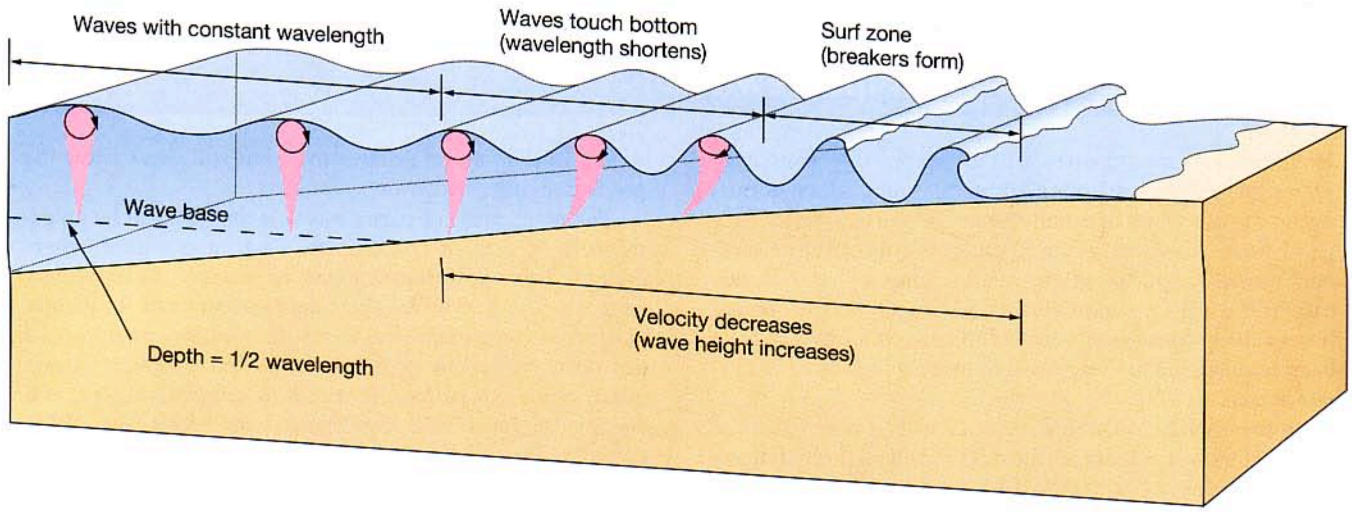


Figure 8–15 Physical changes of a wave in the surf zone. As waves approach the shore and encounter water depths of less than one-half wavelength, the waves "feel bottom." The *wave speed decreases* and waves stack up against the shore, causing the *wavelength to decrease.* This results in an *increase in wave height* to the point where the *wave steepness is increased* beyond the 1:7 ratio, causing the wave to pitch forward and break in the surf zone.

distance from shore, and the surf will be rough, choppy, and irregular.

When the water depth is about one and one-third times the wave height, the crest of the wave breaks, producing surf.[5] When the water depth becomes less than $^1/_{20}$ the wavelength, waves in the surf zone begin to behave as shallow-water waves (see Figure 8–6). Particle motion is greatly impeded by the bottom, and a significant transport of water toward the shoreline occurs (Figure 8–15).

Waves break in the surf zone because particle motion near the bottom of the wave is severely restricted, slowing the waveform. At the surface, however, individual orbiting water particles have not yet been slowed because they have no contact with the bottom. In addition, the wave height increases in shallow water. The difference in speed between the top and bottom parts of the wave cause the top part of the wave to overrun the lower part, which results in the wave toppling over and breaking. Breaking waves are analogous to a person who leans too far forward. If you don't catch yourself, you may also "break" something when you fall.

As waves come into shallow water and feel bottom, their speed and wavelength decrease while their wave height and wave steepness increase, causing the wave to break.

[5]This is a handy way of estimating water depth in the surf zone: The depth of the water where waves are breaking is one and one-third times the breaker height.

Breakers and Surfing Figure 8–16a shows a **spilling breaker**. Spilling breakers result from a gently sloped ocean bottom, which extracts energy from the wave more gradually, producing a turbulent mass of air and water that runs down the front slope of the wave instead of producing a spectacular cresting curl. Spilling breakers have a longer life span and give surfers a long—but somewhat less exciting—ride than other breakers.

Figure 8–16b shows a **plunging breaker**, which has a curling crest that moves over an air pocket. The curling crest occurs because the particles in the crest literally outrun the wave, and there is nothing beneath them to support their motion. Plunging breakers form on moderately steep beach slopes, and are the best waves for surfing.

When the ocean bottom has an abrupt slope, the wave energy is compressed into a shorter distance and the wave will surge forward, creating a **surging breaker** (Figure 8–16c). These waves build up and break right at the shoreline, so board surfers tend to avoid them. For body surfers, however, these waves present the greatest challenge.

Surfing is analogous to riding a gravity-operated water sled by balancing the forces of gravity and buoyancy. The particle motion of ocean waves (see Figure 8–3b) shows that water particles move up into the front of the crest. This force, along with the buoyancy of the surfboard, helps maintain a surfer's position in front of a breaking wave. The trick is to perfectly balance the force of gravity (directed downward) with the buoyant force (directed perpendicular to the wave face) to enable a surfer to be propelled forward by the wave's

(a)

(b)

(c)

Figure 8–16 Types of breakers. **(a)** Spilling breaker, resulting from a gradual beach slope. **(b)** Plunging breaker at Oahu, Hawaii, resulting from a steep beach slope. **(c)** Surging breaker, resulting from an abrupt beach slope.

energy. A skillful surfer, by positioning the board properly on the wave front, can regulate the degree to which the propelling gravitational forces exceed the buoyancy forces, and speeds up to 40 kilometers (25 miles) per hour can be obtained while moving along the face of a breaking wave. When the wave passes over water that is too shallow to allow the upward movement of water particles to continue, the ride is over.

Wave Refraction

Waves seldom approach a shore at a perfect right angle (90 degrees). Instead, some segment of the wave will "feel bottom" first and will slow before the rest of the wave. This results in the **refraction** (*refringere* = to break up) or *bending* of each wave crest (also called a wave front) as the waves approach the shore.

Figure 8–17 shows how waves coming toward a straight shoreline are refracted and tend to align themselves *nearly* parallel to the shore. This explains why all waves come almost straight in toward a beach, no matter what their original orientation was.

Figure 8–18 shows how waves coming toward an irregular shoreline refract so that they, too, nearly align with the shore. However, the refraction of waves along an irregular shoreline distributes wave energy unevenly along the shore.

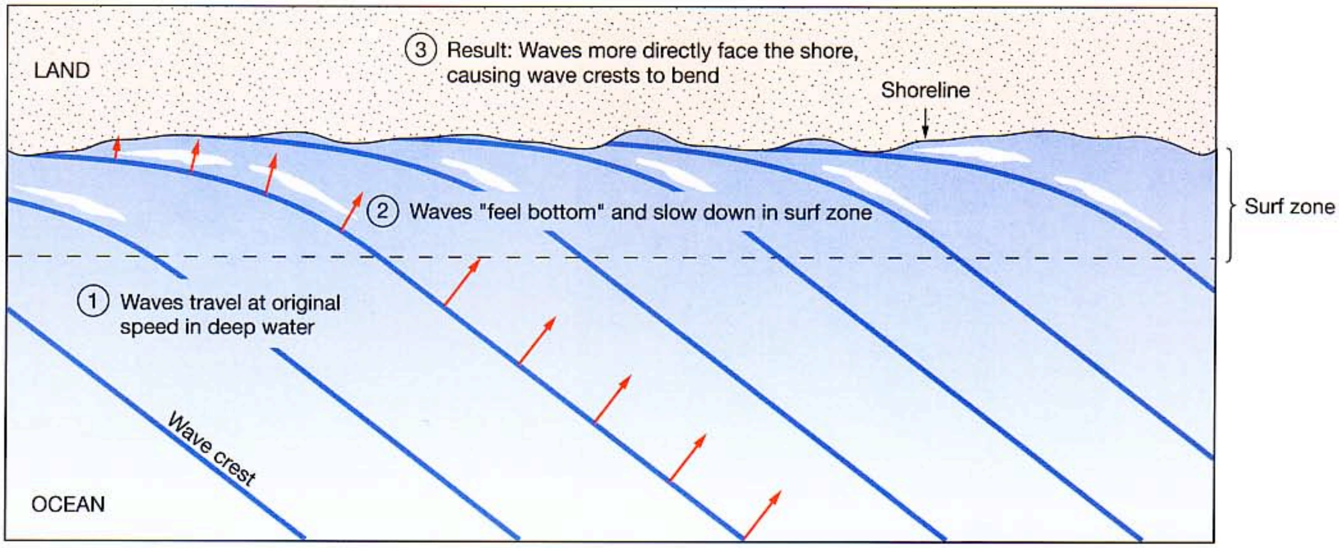


Figure 8–17 Refraction along a straight shoreline. Waves approaching the shore at an angle first "feel bottom" close to shore. This causes the segment of the wave in shallow water to slow, causing the crest of the wave to refract or bend so that the waves arrive at the shore nearly parallel to the shoreline. Red arrows represent direction and speed of the wave.

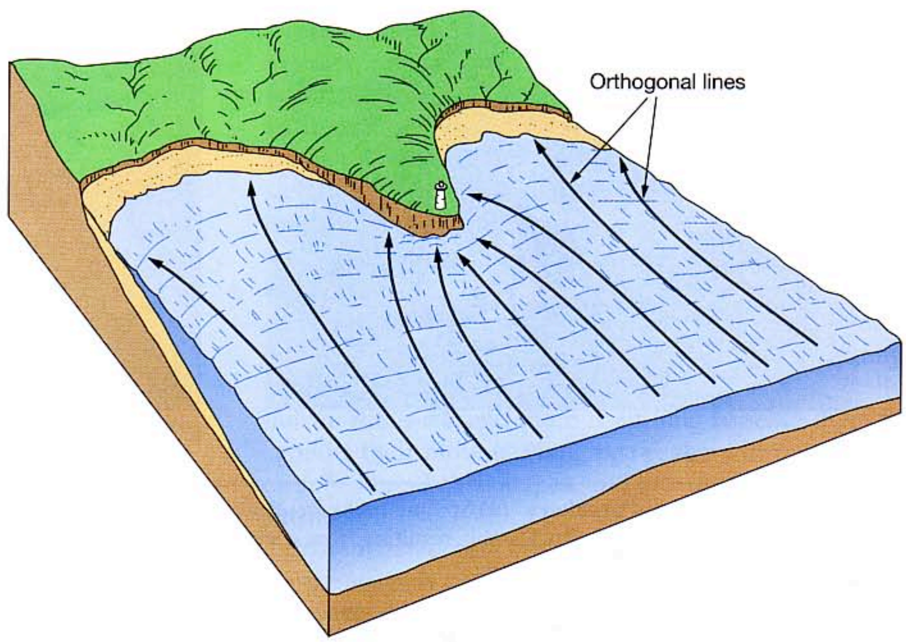


Figure 8–18 Refraction along an irregular shoreline. As waves first "feel bottom" in the shallows off the headlands, they are slowed, causing the waves to refract and align nearly parallel to the shoreline. Evenly spaced orthogonal lines (*black arrows*) show that wave energy is concentrated on headlands (causing erosion) and dispersed in bays (resulting in deposition).

The long black arrows in Figure 8–18 are called **orthogonal** (*ortho* = straight, *gonia* = angle) **lines**. Orthogonal lines are drawn perpendicular to the wave fronts (so they indicate the direction that waves travel) and are spaced so that the energy between lines is equal at all times. They help determine how energy is distributed along the shoreline by breaking waves.

The orthogonals in Figure 8–18 are equally spaced far from shore. As they approach the shore, however, the orthogonals *converge* on headlands that jut into the ocean, and *diverge* in bays. This means that wave energy is concentrated against the headlands, but dispersed in bays. The result is heavy erosion of headlands and deposition of sediment in bays. The greater energy of waves breaking on headlands is reflected in an increased wave height.[6] Conversely, the smaller waves in bays provide areas for good boat anchorages.

Wave Reflection

Not all of the energy of waves is expended as they rush onto the shore. A vertical barrier, such as a seawall or a rock ledge, can reflect waves back into the ocean with

[6]Sailors have long known that "the points draw the waves." Surfers also know how wave refraction causes good "point breaks."

little loss of energy—a process called **wave reflection** (*reflecten* = to bend back), which is similar to how a mirror reflects (bounces) back light. If the incoming wave strikes the barrier at a right (90-degree) angle, the wave energy is reflected back parallel to the incoming wave, often interfering with the next incoming wave and creating unusual waveforms. More commonly, waves approach the shore at an angle, causing wave energy to be reflected at an angle equal to the angle at which the wave approached the barrier.

An outstanding example of wave reflection occurs in an area called "The Wedge," which develops west of the jetty that protects the harbor entrance at Newport Harbor, California (Figure 8–19). The jetty is a solid man-made object that extends into the ocean 400 meters (1300 feet) and has a near-vertical side facing the waves. As incoming waves strike the vertical side of the jetty at an angle, they are reflected at an equivalent angle. Because the original waves and the reflected waves have the same wavelength, a constructive interference pattern develops, creating plunging breakers that may exceed 8 meters (26 feet) in height (Figure 8–19, *inset*). Too dangerous for board surfers, these waves present a fierce challenge to the most experienced body surfers. The Wedge has crippled or even killed many who have come to try it.

Standing waves (or *stationary waves*) can be produced when waves are reflected at right angles to a barrier. Standing waves are the sum of two waves with the same wavelength moving in opposite directions, resulting in no net movement. Although the water particles continue to move vertically and horizontally, there is none of the circular motion that is characteristic of a progressive wave.

Figure 8–20 shows the movement of water during the wave cycle of a standing wave. Lines along which there is no vertical movement are called *nodes* (*node* = knot), or nodal lines. *Antinodes*, crests that alternately become troughs, are the points of greatest vertical movement within a standing wave.

No particle motion exits when an antinode is at its greatest vertical displacement, and the maximum particle movement occurs when the water surface is level. At this time, the maximum movement of the water is in a horizontal direction directly beneath the nodal lines. The movement of water particles beneath the antinodes is entirely vertical.

We consider standing waves further when we discuss tidal phenomena in Chapter 9, "Tides." Under certain conditions, the development of standing waves significantly affects the tidal character in coastal regions.

Wave refraction is the bending of waves caused when waves slow in shallow water; wave reflection is the bouncing back of wave energy caused when waves strike a hard barrier.

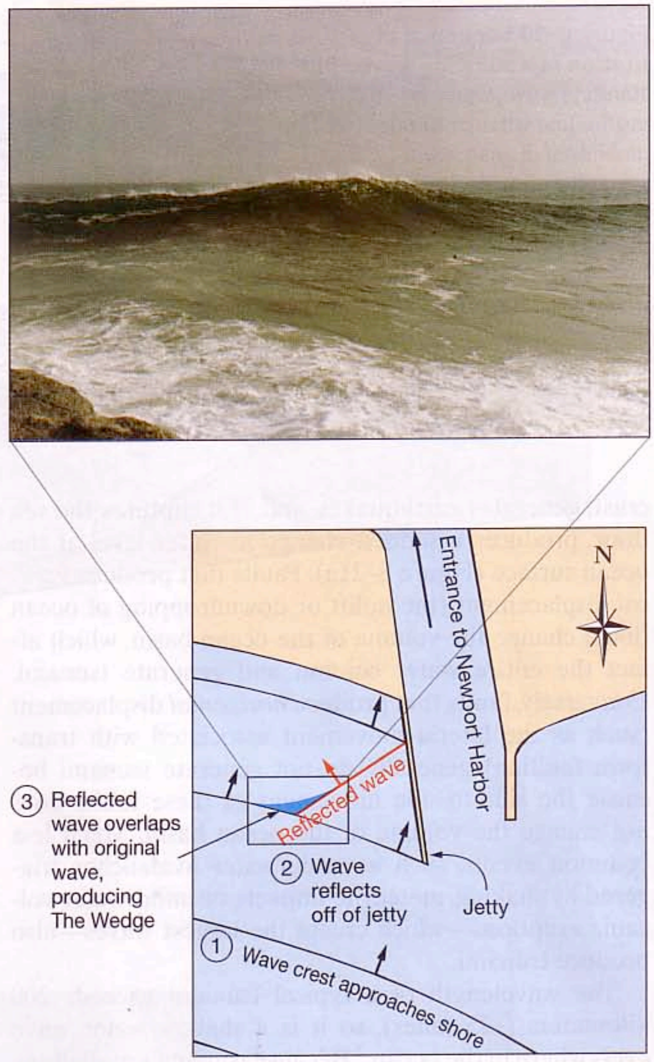


Figure 8–19 Wave reflection at The Wedge, Newport Harbor, California. As waves approach the shore (1), some of the wave energy is reflected off the long jetty at the entrance to the harbor (2). The reflected wave overlaps and constructively interferes with the original wave (3), resulting in a wedge-shaped wave (*dark blue triangle*) that may reach heights exceeding 8 meters (26 feet). Photo of The Wedge (*inset*) shows three dots in front of the wave that are the heads of body surfers.

Tsunami

The Japanese term for the large, sometimes destructive waves that occasionally roll into their harbors is **tsunami** (*tsu* = harbor, *nami* = wave). Tsunami originate from sudden changes in the topography of the sea floor caused by slippage along underwater faults, underwater avalanches, or underwater volcanic eruptions. Many people mistakenly call them "tidal waves," but tsunami are unrelated to the tides. The mechanisms that trigger tsunami are typically seismic events, so tsunami are *seismic sea waves*.

The majority of tsunami are caused by *fault movement*. Underwater fault movement displaces Earth's

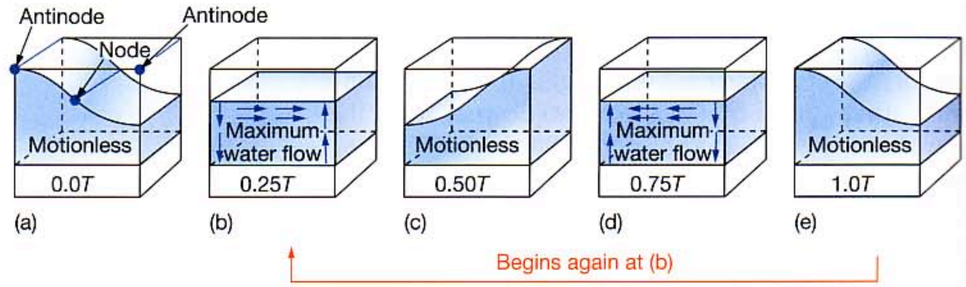


Figure 8–20 Sequence of motion in a standing wave. In a standing wave, water is motionless when antinodes reach maximum displacement (*a, c,* and *e*; *a* and *e* are identical). Water movement is at a maximum (*blue arrows*) when the water is horizontal (*b* and *d*). Movement is vertical beneath the antinodes, and maximum horizontal movement occurs beneath the node. After *e,* cycle begins again at *b.*

crust, generates earthquakes, and, if it ruptures the sea floor, produces a sudden change in water level at the ocean surface (Figure 8–21a). Faults that produce *vertical* displacement (the uplift or downdropping of ocean floor) change the volume of the ocean basin, which affect the entire water column and generate tsunami. Conversely, faults that produce *horizontal* displacement (such as the lateral movement associated with transform faulting) generally do not generate tsunami because the side-to-side movement of these faults does not change the volume of the ocean basin. Much less common events, such as underwater avalanches triggered by shaking, meteorite impacts, or underwater volcanic eruptions—which create the largest waves—also produce tsunami.

The wavelength of a typical tsunami exceeds 200 kilometers (125 miles), so it is a shallow-water wave everywhere in the ocean.[7] Because tsunami are shallow-water waves, their speed is determined only by water depth. In the open ocean, tsunami move at well over 700 kilometers (435 miles) per hour—they could easily keep pace with a jet airplane—and have heights of only about 0.5 meter (1.6 feet). Even though they are fast, tsunami are small in the open ocean and pass unnoticed in deep water until they reach shore, where they slow in the shallow water, and the water begins to pile up.

Coastal Effects

A tsunami does not form a huge breaking wave at the shoreline. Instead, it is a strong flood or surge of water that causes the ocean to advance (or, in certain cases, retreat) dramatically. In fact, a tsunami resembles a sudden, *extremely* high tide, which is why they are misnamed "tidal waves." It takes several minutes for the tsunami to express itself fully, during which time sea level can rise up to 40 meters (131 feet) above normal, with normal waves superimposed on top of the higher sea level. The strong surge of water can rush into low-lying areas with destructive results (Figure 8–21b).

As the trough of the tsunami arrives at the shore, the water will rapidly drain off the land. In coastal areas, it will look like a sudden and *extremely* low tide, where sea level is many meters lower than even the lowest low tide. Because tsunami are typically a series of waves, there are often an alternating series of dramatic surges and withdrawals of water, separated by only a few minutes. The first surge may not always be the largest; the third, fourth, or even seventh surge may be the largest, instead.

In some cases, the trough of a tsunami arrives at the coast first, exposing parts of the lowermost shoreline that are rarely seen. For people at the shoreline, the temptation is to explore these newly exposed areas and catch stranded fish. Within a few minutes, however, a strong surge of water (the crest of the tsunami) is due to arrive.

The alternating surges and retreats of water by tsunami can severely damage coastal structures. Tsunami can be deadly as well. The speed of the advance—up to 4 meters (13 feet) per second—is faster than a person can run. Those who are trapped by tsunami are often drowned or crushed by floating debris (Figure 8–22).

Historic Tsunami

Many small tsunami are created each year, and go largely unnoticed. On average, 57 tsunami occur every decade, with a large tsunami occurring somewhere in the world every two to three years and an extremely large and damaging one occurring every 15 to 20 years. About 86% of all great waves are generated in the Pacific Ocean because large-magnitude earthquakes occur along the series of trenches that ring its ocean basin where oceanic plates are subducted along convergent plate boundaries. Volcanic activity is also common along the Pacific "Ring of Fire," and the large earthquakes that occur along its margin are capable of producing extremely large tsunami (Box 8–2).

One of the most destructive tsunami ever generated came from the eruption of the volcanic island of

[7]Recall that the depth of the wave base is equal to one-half a wave's wavelength. Thus, tsunami can typically be felt to depths of 100 kilometers (62 miles), which is deeper than even the deepest ocean trenches.

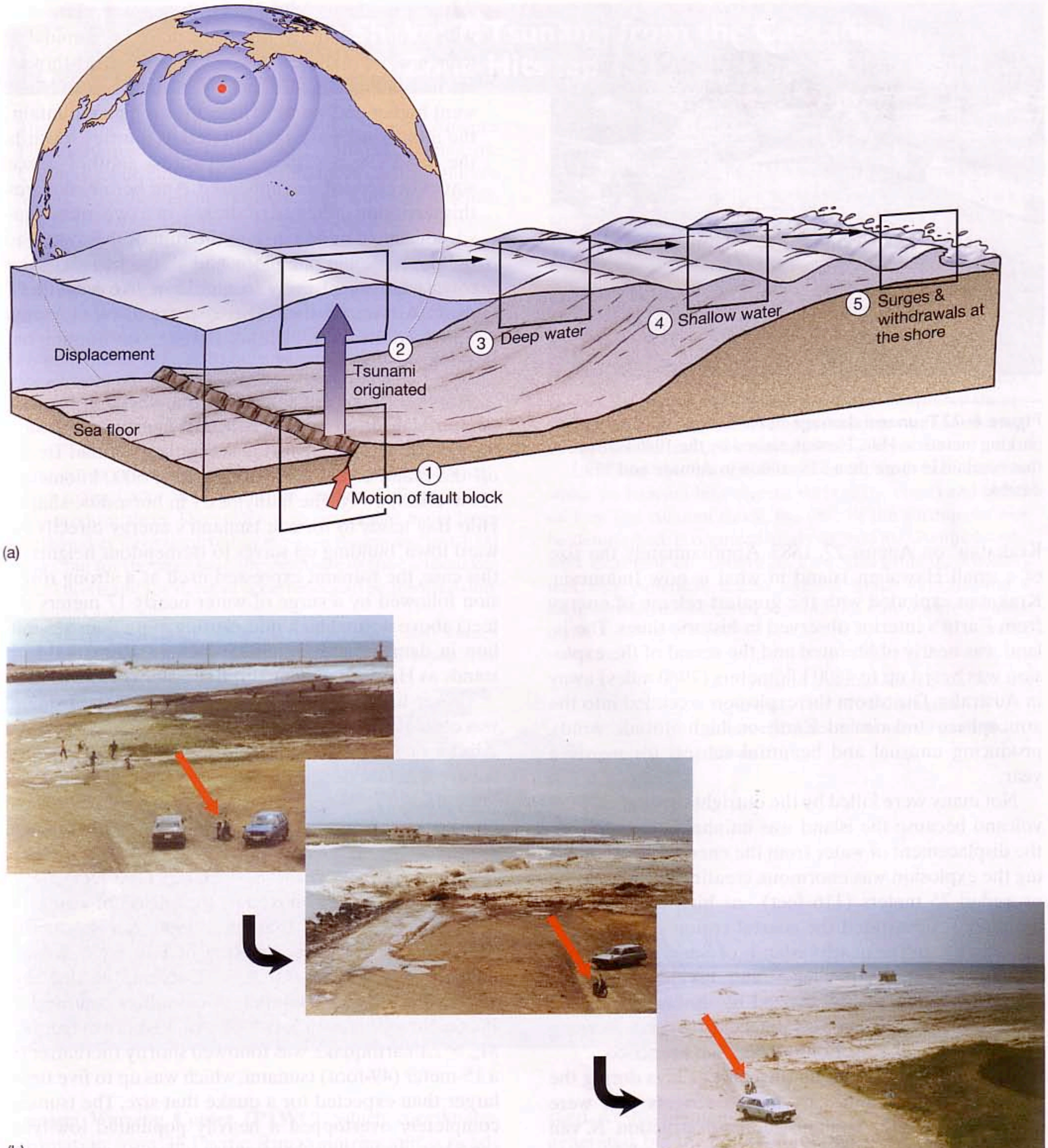


Figure 8–21 Origin of a tsunami. **(a)** Abrupt vertical movement along a fault on the sea floor raises or drops the ocean water column above a fault, creating a tsunami that travels from deep to shallow water where it is experienced as alternating surges and withdrawals of water at the shore. **(b)** Sequence of photos of a 1983 tsunami in northern Japan that surges toward fleeing spectators in a harbor. Red arrows show stationary motorcycle.

Figure 8–22 Tsunami damage in Hilo, Hawaii. Flattened parking meters in Hilo, Hawaii, caused by the 1946 tsunami that resulted in more than $25 million in damage and 159 deaths.

Krakatau[8] on August 27, 1883. Approximately the size of a small Hawaiian Island in what is now Indonesia, Krakatau exploded with the greatest release of energy from Earth's interior observed in historic times. The island was nearly obliterated and the sound of the explosion was heard up to 4800 kilometers (2980 miles) away in Australia. Dust from the explosion ascended into the atmosphere and circled Earth on high-altitude winds, producing unusual and beautiful sunsets for nearly a year.

Not many were killed by the outright explosion of the volcano because the island was uninhabited. However, the displacement of water from the energy released during the explosion was enormous, creating a tsunami that exceeded 35 meters (116 feet)—as high as a 12-story building. It devastated the coastal region of the Sunda Strait between the nearby islands of Sumatra and Java, drowning over 1000 villages and taking more than 36,000 lives. The energy carried by this wave reached every ocean basin, and was detected by tide recording stations as far away as London and San Francisco.

Several ships were along the coast of Java during the eruption of Krakatau, carrying passengers that were eyewitnesses to the tsunami and its destruction. N. van Sandick, an engineer aboard the Dutch vessel *Loudon*, gave the following account:

> Suddenly we saw a gigantic wave of prodigious height advancing from the sea-shore with considerable speed. Immediately the crew set to under considerable pressure and managed after a fashion to set sail in face of the imminent danger; the ship had just enough time to meet with the wave from the front. After a moment, full of anguish, we were lifted up with a dizzy rapidity. The ship made a formidable leap, and immediately afterwards we felt as though we had plunged into the abyss. But the ship's blade went higher and we were safe. Like a high mountain, the monstrous wave precipitated its journey towards the land. Immediately afterwards another three waves of colossal size appeared. And before our eyes this terrifying upheaval of the sea, in a sweeping transit, consumed in one instant the ruin of the town; the lighthouse fell in one piece, and all the houses of the town were swept away in one blow like a castle of cards. All was finished. There, where a few moments ago lived the town of Telok Betong, was nothing but the open sea.

Another strong tsunami was experienced in the port of Hilo, Hawaii, on April 1, 1946. The tsunami was from a magnitude $M_w = 7.3$ earthquake in the Aleutian Trench off the island of Unimak, Alaska, over 3000 kilometers (1850 miles) away. The bathymetry in horseshoe-shaped Hilo Bay tends to focus a tsunami's energy directly toward town, building up waves to tremendous heights. In this case, the tsunami expressed itself as a strong recession followed by a surge of water nearly 17 meters (55 feet) above normal high tide, causing more than $25 million in damage and killing 159 people. Remarkably, it stands as Hawaii's worst natural disaster (Figure 8–22).

Closer to the source of the earthquake, the tsunami was considerably larger. The tsunami struck Scotch Cap, Alaska, on Unimak Island, where a two-story reinforced concrete lighthouse stood 14 meters (46 feet) above sea level at its base. The lighthouse was destroyed by a wave that is estimated to have reached 36 meters (118 feet), killing all five people inside the lighthouse at the time. Vehicles on a nearby mesa 31 meters (103 feet) above water level were also moved by the onrush of water.

Figure 8–23 shows that since 1990, ten destructive tsunamis along the Pacific Ring of Fire have claimed more than 4000 lives. Of these tsunami, the one that caused the greatest number of casualties occurred in Papua New Guinea in July 1998. An offshore magnitude $M_w = 7.1$ earthquake was followed shortly thereafter by a 15-meter (49-foot) tsunami, which was up to five times larger than expected for a quake that size. The tsunami completely overtopped a heavily populated low-lying sand bar, destroying three entire villages and resulting in at least 2200 deaths. Researchers who mapped the sea floor after the tsunami discovered the remains of a huge underwater landslide, which was apparently triggered by the shaking and generated the deadliest tsunami in 65 years.

Tsunami Warning System

In response to the tsunami that struck Hawaii in 1946, a tsunami warning system was established throughout the Pacific Ocean. It led to what is now the **Pacific**

[8]The volcanic island Krakatau (which is *west* of Java) is also called Krakatoa.

Box 8–2 The Big Shake: A Tsunami from the Cascadia Subduction Zone Hits Japan

The Juan de Fuca Plate slides beneath the North America Plate offshore of the U.S. Pacific Northwest, creating the Cascadia subduction zone. The February 28, 2001, magnitude $M_w = 6.8$ Seattle Earthquake is a reminder that the Cascadia subduction zone is capable of producing large, damaging earthquakes.

Paleo-earthquake and paleo-tsunami evidence suggest that much larger earthquakes have occurred along the Cascadia subduction zone in the past. The paleo-earthquake evidence consists of offshore turbidity current deposits, accumulations of organic matter including entire forests that were buried during sudden coastal downdropping, and sediments that have liquefied on land due to ground shaking. The paleo-tsunami evidence consists of sand layers deposited in low-lying coastal areas. The Cascadia subduction zone is the presumed source of the earthquakes, although other major faults on land (such as the Seattle Fault) might also produce them. The evidence indicates that many large earthquakes have occurred in the area during the last 1000 years, but for the most part, the exact size of the earthquakes is unknown and the dates of occurrence can be resolved only to within a decade.

Evidence for large Cascadia earthquakes also comes from the historic records of tsunami damage in Japan. The records indicate that a tsunami of unknown origin hit the coast of Japan on January 27–28 in 1700. Based on the time of arrival and the height of the tsunami in different locations in Japan, other Pacific Rim regions (South America, Alaska, and the Kamchatka Peninsula in Russia) can be eliminated as potential sources. Even a locally generated tsunami does not fit the reported effects, leaving the Cascadia subduction zone as the most likely source (Figure 8C). Because Japan received tsunami heights of 2 to 3 meters (6.5 to 10 feet), the earthquake must have been magnitude $M_w = 9.0$. Only two earthquakes of this size have ever been recorded: one along the coast of Chile in 1960, and the other in southern Alaska in 1964. An earthquake this large must have ruptured the entire length of the Cascadia subduction zone and is estimated to have a recurrence interval of 300 to 700 years.

Based on the historic records in Japan (which indicate when the tsunami hit different parts of the coast) and based on how fast tsunami travel, the time of the earthquake can be determined: it occurred at about 9:00 P.M. Pacific Northwest local time on January 26, 1700. This estimate is consistent with American Indian legends, which indicate that a large earthquake occurred at about this date during a winter night.

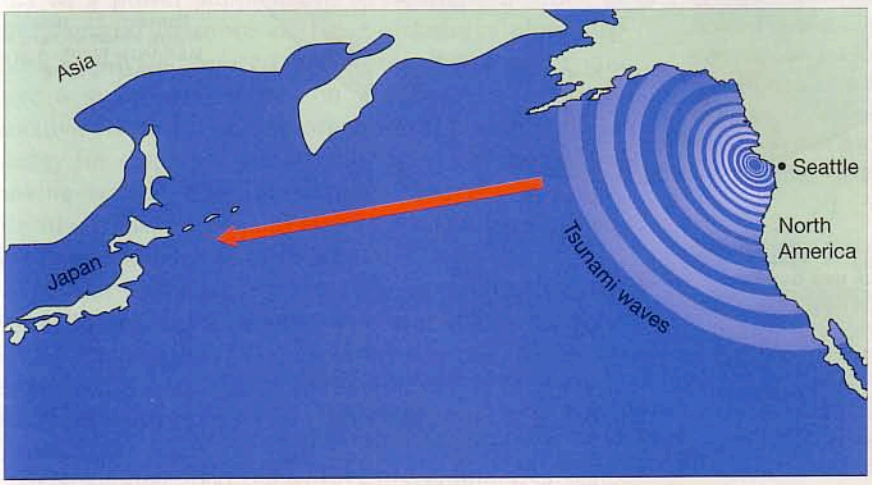


Figure 8C The 1700 Cascadia subduction zone tsunami reached Japan.

Tsunami Warning Center (PTWC), which coordinates information from 25 Pacific Rim countries and is headquartered in Ewa Beach (near Honolulu), Hawaii. In the open ocean, tsunami have small wave heights and are difficult to detect, so the tsunami warning system uses seismic waves—some of which travel through Earth at speeds 15 times faster than tsunami—to forecast destructive tsunami.[9] When a seismic disturbance occurs beneath the ocean surface that is large enough to be tsunamigenic (capable of producing a tsunami), a *tsunami watch* is issued. At this point, a tsunami may or may not have been generated, but the potential for one exists.

The PTWC is linked to over 50 tide-measuring stations throughout the Pacific, so the recording station nearest the earthquake is closely monitored for any indication of unusual wave activity. If unusual wave activity is verified, the tsunami watch is upgraded to a *tsunami warning*. Generally, earthquakes smaller than magnitude $M_w = 6.5$ are not tsunamigenic because they lack the duration of ground shaking necessary to initiate a tsunami. Additionally, transform faults do not usually produce tsunami because lateral movement does not offset the ocean floor and impart energy to the

[9] A new method of tracking tsunami that is currently being tested uses a series of sensitive pressure sensors on the ocean floor that can detect the passage of tsunami in the open ocean.

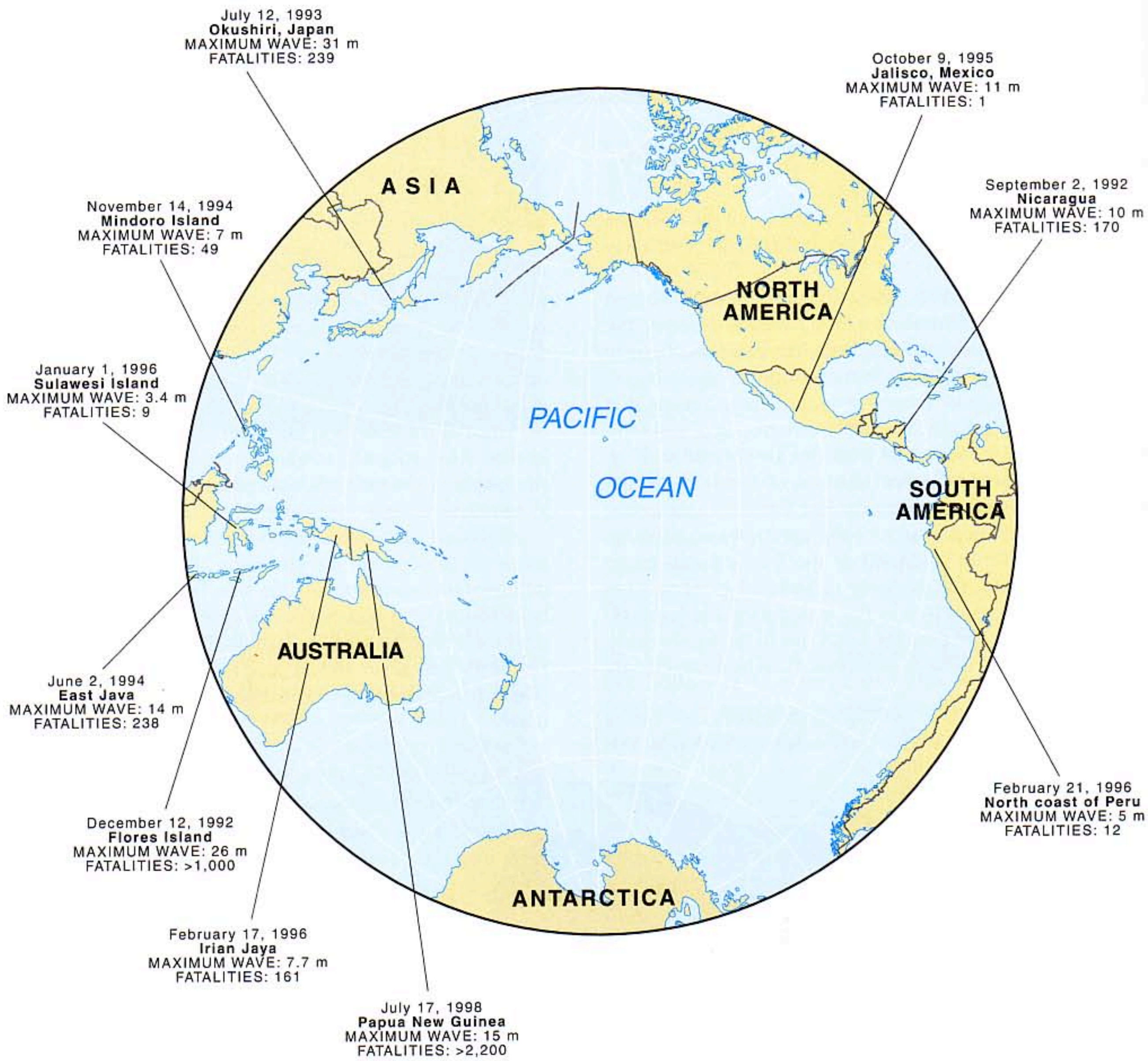


Figure 8–23 Tsunamis since 1990. Ten destructive tsunamis have claimed more than 4000 lives since 1990. These killer waves are most often generated by earthquakes along colliding tectonic plates of the Pacific Rim, although the deadly 1998 Papua New Guinea tsunami that killed more than 2200 was generated by an underwater landslide.

water column in the same way that vertical fault movements do.

When a tsunami is detected, warnings are sent to all the coastal regions that might encounter the destructive wave, along with its estimated time of arrival. This warning, usually just a few hours in advance of the tsunami, makes it possible to evacuate people from low-lying areas and remove ships from harbors before the waves arrive. If the disturbance is nearby, however, there is not enough time to issue a warning because a tsunami travels so rapidly. Unlike hurricanes, whose high winds and waves threaten ships at sea and send them to the protection of a coastal harbor, a tsunami washes ships from their coastal moorings into the open ocean or onto shore. The best strategy during a tsunami warning is to get ships out of coastal harbors and into deep water, where tsunami are not easily felt.

Since the PTWC was established in 1948, it has effectively prevented loss of life due to tsunami when people have heeded the evacuation warnings. Property damage, however, has increased as more buildings have been constructed close to shore. To combat the damage caused by tsunami, countries that are especially prone to tsunami like Japan have invested in shoreline barriers, seawalls, and other coastal fortifications.

Perhaps one of the best strategies to limit tsunami damage and loss of life is to restrict construction projects in low-lying coastal regions where tsunami have frequently struck in the past. However, the long time interval between large tsunami can lead people to forget past disasters.

Most tsunami are generated by underwater fault movement, which transfers energy to the entire water column. When these fast and long waves surge ashore, they can do considerable damage.

Power from Waves

Moving water has a huge amount of energy, which is why there are so many hydroelectric power plants on rivers. Even greater energy exists in ocean waves, but significant problems must be overcome for the power to be harnessed efficiently. The most likely locations for power generation are where waves refract and converge, focusing wave energy, such as around headlands (see Figure 8–18). Using this advantage, a wave power plant might extract up to 10 megawatts of power[10] per kilometer (0.6 mile) of shoreline.

One of the disadvantages of wave energy is that the system produces significant power only when large storm waves break against it, so the system could serve only as a power supplement. In addition, a series of one hundred or more of these structures along the shore would be required. Structures of this type could have a significant impact on the environment, with negative effects on marine organisms that rely on wave energy for dispersal, transporting food supplies, or removing wastes. Also, harnessing wave energy might alter the transport of sand along the coast, causing erosion in areas deprived of sediment.

Internal waves are a potential source of energy, too. Along shores that have favorable ocean floor topography for focusing wave energy, internal waves may be effectively concentrated by refraction. This energy could power an energy-conversion device that would produce electricity.

In November 2000, the world's first commercial wave power plant began generating electricity. The small plant, called **LIMPET 500** (Land Installed Marine Powered Energy Transformer), is located on Islay, a small island off the west coast of Scotland. The plant was constructed at a cost of about $1.6 million and allows waves to compress air in a chamber that, in turn, rotates a turbine for the generation of power. Under peak operating capacity, the facility is capable of producing 500 kilowatts of power, which is capable of lighting about 400 homes. Economic conditions in the future may lead to the construction of larger wave plants that are capable of using this renewable source of energy.

Figure 8–24 shows the average wave height experienced along coastal regions and indicates the sites most favorable for wave energy generation (*red areas*). The map shows that west-to-east movement of storm systems in the mid-latitudes between 30 and 60 degrees north or south latitude causes the western coasts of continents to be struck by larger waves than eastern coasts. Thus, more wave energy is generally available along western than eastern shores. Furthermore, some of the largest waves (and greatest potential for wave power) are associated with the prevailing westerly wind belt in the mid-latitude Southern Hemisphere.

Students Sometimes Ask...

Do waves always travel in the same directions as currents?

Not always. Surface currents and most waves are created by winds blowing across the ocean surface, so it seems logical that they should move in the same direction, too. Most surface waves do travel in the same direction as the wind blows, but waves radiate outward in all directions from the disturbance (release of energy) that creates them. In addition, as waves move away from the sea area where they were generated, they enter areas where other currents exist. Consequently, the direction of wave movement is often unrelated to that of currents. Fundamentally, movement of waves is independent of currents, so wave trains can travel in various directions relative to currents. In fact, waves can even travel in a direction *completely opposite* to that of a current. A rip current, for example, moves away from shoreline, opposite to the direction of incoming waves.

Can internal waves break?

Internal waves do not break in the way that surface waves break in the surf zone. When internal waves approach the edges of continents, however, they do undergo similar physical changes as waves in the surf zone. This causes the waves to build up and expend their energy with much turbulent motion, in essence "breaking" against the continent.

Can a wave break twice?

Certainly. This is commonly seen anywhere offshore obstacles such as coral reefs, rock reefs, or sand bars are shallowly submerged. Waves approaching these obstacles undergo physical changes just as breaking waves do in the surf zone, expending some of their energy by breaking. Some of the energy moves over the top of the obstacle, however, and the wave—now diminished in size—continues to move toward shore. The wave will expend the last of its energy against the shore, effectively breaking twice.

I know that swell is what surfers hope for. Is swell always big?

Not necessarily. Swell is defined as waves that have moved out of their area of origination, so these waves do not have to

[10] Ten megawatts of power is comparable to the electricity consumed by 20,000 average U.S. households.

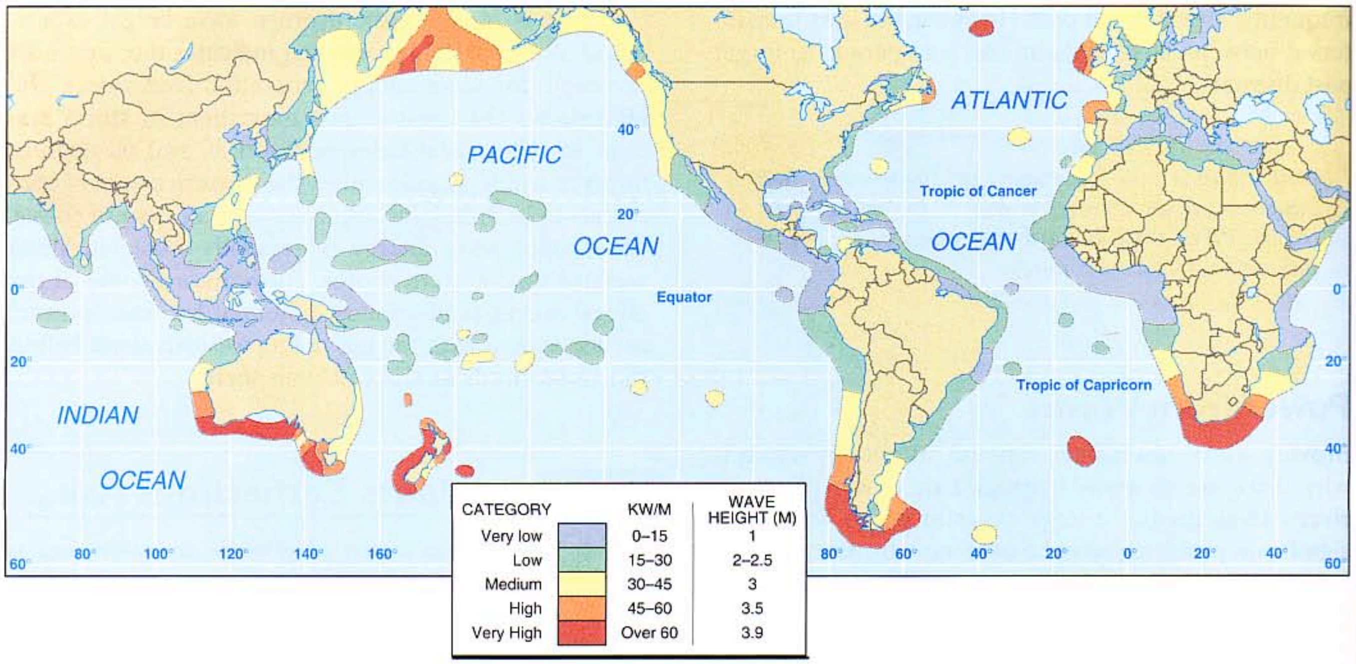


Figure 8–24 Global coastal wave energy resources. Distribution of coastal wave energy shows that more wave energy is available along western shores of continents, especially in the Southern Hemisphere. KW/M is kilowatts per meter (for example, every meter of "red" shoreline is a potential site for generating over 60 kilowatts of electricity); average wave height is in meters.

be a certain wave height to be classified as swell. It is true, however, that the uniform and symmetrical shape of most swell delights surfers.

In your opinion, where is the best surfing?

The answer to that question is highly subjective, with each surfer claiming his or her own favorite spot—often revealed to very few others. Some of the factors that determine an ideal surfing location must include size and regularity of waves, climate, cost, accessibility, and seclusion (not necessarily in that order). Figure 8–10, which compares worldwide wave height, shows that some of the largest waves are found in the south Indian and South Pacific Oceans. Because the Pacific Ocean has the greatest fetch (which allows for the possibility of bigger waves to develop), continents and islands in the South Pacific seem like ideal locations if wave size is the most important factor.

Surfing can often be enhanced, however, when waves have been sorted into swell, so locations a bit farther from the Southern Hemisphere might have slightly smaller waves but ones that are more regular. In this case, some of the tropical Pacific islands (such as Hawaii, Fiji, and some of the more remote Indonesian islands) might offer better surfing. Besides their location in warm climates, they also have the advantage of being exposed to North Pacific Ocean swell.

If seclusion is the highest priority—and you don't mind donning a full wetsuit—some coastal locations with large waves in Alaska have recently been surfed, and surfing in Antarctica can't be far behind!

Why is surfing so much better along the west coast of the United States than along the east coast?

There are three main reasons why the west coast has better surfing conditions:

- The waves are generally bigger in the Pacific. The Pacific is larger than the Atlantic, so the fetch is larger, allowing bigger waves to develop in the Pacific (see Figure 8–24).
- The beach slopes are generally steeper along the west coast. Along the east coast, the gentle slopes often create spilling breakers, which are not as favorable for surfing. The steeper beach slopes along the west coast cause plunging breakers, which are better for surfing.
- The wind is more favorable. Most of the United States is influenced by the prevailing westerlies, which blow toward shore and enhance waves along the west coast. Along the east coast, the wind blows away from shore.

What is the record height of a tsunami?

Japan holds the record because Japan's proximity to subduction zones causes it to endure more tsunami than any other place on Earth (followed by Chile and Hawaii). The largest documented tsunami occurred in the Ryukyu Islands of southern Japan in 1971, when one raised normal sea level by 85 meters (278 feet). In low-lying coastal areas, such an enormous vertical rise can send water many kilometers inland, causing flooding and widespread damage. The most deadly tsunami was probably the one that hit Aura, Japan, in 1703 and was responsible for an estimated 100,000 deaths.

Since 5-foot surf is common at the beach where I live, why should I be worried about a 5-foot tsunami?

A tsunami is quite different from a normal ocean wave, even though both may have the same wave height. A tsunami carries much more energy than a normal ocean wave because a tsunami influences the *entire* column of water, while an ocean wave is confined to surface waters. A tsunami has a much greater wavelength than a wave, so it will reach much farther ashore, too. The biggest storm breakers expend their energy within the surf zone while a tsunami can reach several kilometers inland in low-lying areas. Five-foot surf may be fun to play in, but a 5-foot tsunami can knock down the building you are in, drag you out to sea, and batter you to death.

If there is a tsunami warning issued, what is the best thing to do?

The *smartest* thing to do is to stay out of coastal areas, but people often want to see a tsunami for themselves. For instance, when an earthquake of magnitude $M_w = 7.7$ occurred offshore of Alaska in May 1986, a tsunami warning was issued for the west coast of the United States. In southern California, people flocked to the beach to observe this natural phenomenon. Fortunately, the tsunami was only a few centimeters by the time it reached southern California, so it went unnoticed.

If you must go to the beach to observe the tsunami, expect crowds, road closings, and general mayhem. It would be a good idea to stay at least 30 meters (100 feet) above sea level. If you happen to be at a remote beach where the water suddenly withdraws, evacuate immediately to higher ground (Figure 8D). And, if you happen to be at a beach where an earthquake occurs and shakes the ground so hard that you can't stand up, *RUN*—don't walk—for high ground as soon as you *can* stand up!

Figure 8D Warning sign advises residents to evacuate low-lying areas during a tsunami.

After the first surge of the tsunami, stay out of low-lying coastal areas for several hours because several more surges (and withdrawals) can be expected. There have been many documented cases where curious people have been killed when they are trapped by the third or fourth surge of a tsunami.

Chapter in Review

• All ocean waves begin as disturbances caused by releases of energy. The releases of energy include wind, the movement of fluids of different densities (which create internal waves), mass movement into the ocean, underwater sea floor movements, the gravitational pull of the Moon and the Sun on Earth, and human activities in the ocean.

• Once initiated, waves transmit energy through matter by setting up patterns of oscillatory motion in the particles that make up the matter. Progressive waves are longitudinal, transverse, or orbital, depending on the pattern of particle oscillation. Particles in ocean waves move primarily in orbital paths.

• Waves are described according to their wavelength (L), wave height (H), wave steepness (H/L), wave period (T), frequency (f), and wave speed (S). As a wave travels, the water passes the energy along by moving in a circle, called circular orbital motion. This motion advances the waveform, not the water particles themselves. Circular orbital motion decreases with depth, ceasing entirely at wave base, which is equal to one-half the wavelength measured from still water level.

• If water depth is greater than one-half the wavelength, a progressive wave travels as a deep-water wave with a speed that is directly proportional to wavelength. If water depth is less than $^1/_{20}$ wavelength ($L/20$), the wave moves as a shallow-water wave with a speed that is directly proportional to water depth. Transitional waves have wavelengths between deep- and shallow-water waves, with speeds that depend on both wavelength and water depth.

• As wind-generated waves form in a sea area, capillary waves with rounded crests and wavelengths less than 1.74 centimeters (0.7 inch) form first. As the energy of the waves increases, gravity waves form, with increased wave speed, wavelength, and wave height. Factors that influence the size of wind-generated waves include wind speed, duration (time), and fetch (distance). An equilibrium condition called a fully developed sea is reached when the maximum wave height is achieved for a particular wind speed, duration, and fetch.

• Energy is transmitted from the sea area across the ocean by uniform, symmetrical waves called swell. Different wave trains of swell can create either constructive, destructive, or mixed interference patterns. Constructive interference produces unusually large waves called rogue waves or superwaves.

• As waves approach shoaling water near shore, they undergo many physical changes. Waves release their energy in the surf zone when their steepness exceeds a 1:7 ratio and break. If waves break on a relatively flat surface, they produce spilling breakers. The curling crests of plunging breakers, which are the best for surfing, form on steep slopes and abrupt beach slopes create surging breakers.

• When swell approaches the shore, segments of the waves that first encounter shallow water are slowed. The parts of the waves in deeper water move at their original speed, causing each wave to refract, or bend. Refraction concentrates wave energy on headlands, while low-energy breakers are characteristic of bays.

• Reflection of waves off seawalls or other barriers can cause an interference pattern called a standing wave. The crests of standing waves do not move laterally as in progressive waves but alternate with troughs at antinodes. Between the antinodes are nodes, where there is no vertical movement of the water.

• Sudden changes in the elevation of the sea floor, such as from fault movement or volcanic eruptions, generate tsunami, or seismic sea waves. These waves often have lengths exceeding 200 kilometers (125 miles) and travel across the open ocean with undetectable heights of about 0.5 meter (1.6 feet) at speeds in excess of 700 kilometers (435 miles) per hour. Upon approaching shore, a tsunami produces a series of rapid withdrawals and surges, some of which may increase the height of sea level by over 30 meters (100 feet). Most tsunami occur in the Pacific Ocean, where they have caused millions of dollars of coastal damage and taken tens of thousands of lives. The Pacific Tsunami Warning Center (PTWC) has dramatically reduced fatalities by successfully predicting tsunami using real-time seismic information.

• Ocean waves can be harnessed to produce hydroelectric power, but significant problems must be overcome to make this a practical source of energy.

Key Terms

Atmospheric wave (p. 238)
Capillary wave (p. 244)
Circular orbital motion (p. 241)
Constructive interference (p. 246)
Crest (p. 240)
Decay distance (p. 245)
Deep-water wave (p. 241)
Destructive interference (p. 246)
Frequency (p. 240)
Fully developed sea (p. 244)
Gravity wave (p. 244)
Interference pattern (p. 245)
Internal wave (p. 238)
LIMPET 500 (p. 259)
Longitudinal wave (p. 238)
Mixed interference (p. 247)
Ocean wave (p. 238)
Orbital wave (p. 240)
Orthogonal line (p. 252)
Pacific Tsunami Warning Center (PTWC) (p. 256)
Plunging breaker (p. 250)
Refraction (p. 251)
Restoring force (p. 244)
Rogue wave (p. 249)
Sea (p. 244)
Shallow-water wave (p. 242)
Shoaling (p. 248)
Spilling breaker (p. 250)
Splash wave (p. 236)
Standing wave (p. 253)
Still water level (p. 240)
Superwave (p. 249)
Surf beat (p. 247)
Surf zone (p. 247)
Surging breaker (p. 250)
Swell (p. 245)
Transitional wave (p. 243)
Transverse wave (p. 239)
Trough (p. 240)
Tsunami (p. 253)
Wave base (p. 241)
Wave dispersion (p. 245)
Wave height (p. 240)
Wave period (p. 240)
Wave reflection (p. 253)
Wave speed (p. 242)
Wave steepness (p. 240)
Wave train (p. 245)
Wavelength (p. 240)

Questions and Exercises

1. How large was the largest wave ever authentically recorded? Where did it occur, and how did it form?

2. Discuss several different ways in which waves form. How are most ocean waves generated?

3. Why is the development of internal waves likely within the pycnocline?

4. Discuss longitudinal, transverse, and orbital wave phenomena, including the states of matter in which each can transmit energy.

5. Draw a diagram of a simple progressive wave. From memory, label the crest, trough, wavelength, wave height, and still water level.

6. Can a wave with a wavelength of 14 meters ever be more than 2 meters high? Why or why not?

7. What physical feature of a wave is related to the depth of the wave base? On the diagram that you drew for Question 5, add the wave base. What is the difference between the wave base and still water level?

8. Explain why the following statements for deep-water waves are either true or false:

a. The longer the wave, the deeper the wave base.

b. The greater the wave height, the deeper the wave base.

c. The longer the wave, the faster the wave travels.

d. The greater the wave height, the faster the wave travels.

e. The faster the wave, the greater the wave height.

9. Calculate the speed (S) in meters per second for deep-water waves with the following characteristics:

a. $L = 351$ meters, $T = 15$ seconds
b. $T = 12$ seconds
c. $f = 0.125$ wave per second

10. Using the information about the giant waves experienced by the USS *Ramapo*, what were the waves' wavelength and speed?

11. Define swell. Does swell necessarily imply a particular wave size? Why or why not?

12. Waves from separate sea areas move away as swell and produce an interference pattern when they come together. If Sea A has wave heights of 1.5 meters (5 feet) and Sea B has wave heights of 3.5 meters (11.5 feet), what would be the height of waves resulting from constructive interference and destructive interference? Illustrate your answer (see Figure 8–13).

13. Describe the physical changes that occur to a wave's wave speed (S), wavelength (L), height (H), and wave steepness (H/L) as a wave moves across shoaling water to break on the shore.

14. Describe the three different types of breakers and indicate the slope of the beach that produces the three types. How is the energy of the wave distributed differently within the surf zone by the three types of breakers?

15. Using examples, explain how wave refraction is different from wave reflection.

16. Using orthogonal lines, illustrate how wave energy is distributed along a shoreline with headlands and bays. Identify areas of high and low energy release.

17. Define the terms *node* and *antinode* as they relate to standing waves.

18. Why is it more likely that a tsunami will be generated by faults beneath the ocean along which vertical rather than horizontal movement has occurred?

19. While shopping in a surf shop, you overhear some surfing enthusiasts mention that they would really like to ride the curling wave of a tidal wave at least once in their life, because it is a single breaking wave of enormous height. What would you say to these surfers?

20. Explain what it would look like at the shoreline if the trough of a tsunami arrives there first. What is the impending danger?

21. What ocean depth would be required for a tsunami with a wavelength of 220 kilometers (136 miles) to travel as a deep-water wave? Is it possible that such a wave could become a deep-water wave any place in the world ocean? Explain.

22. Explain how the tsunami warning system in the Pacific Ocean works. Why must the tsunami be verified at the closest tide recording station?

23. Describe the different types of evidence used to support the idea that a large earthquake along the Cascadia subduction zone produced a tsunami in 1700 that was felt in Japan.

24. Discuss some environmental problems that might result from developing facilities for conversion of wave energy to electrical energy.

References

Bascom, W. 1980. *Waves and beaches: The dynamics of the ocean surface* (revised edition). New York: Anchor Books (Doubleday).

Bowditch, N. 1958. *American practical navigator*, rev. ed. H.O. Pub. 9. Washington, DC: U.S. Naval Oceanographic Office.

Brown, J. 1989. Rogue waves. *Discover* 10:4, 47–52.

Folger, T. 1994. Waves of destruction. *Discover* 15:5, 66–73.

Furbish, D. J., and Parker, W. C. 2000. Corks, buoyancy, and wave-particle orbits. *Journal of Geoscience Education* 48:4, 500–507.

Gill, A. E. 1982. *Atmosphere-ocean dynamics*. International Geophysics Series, Vol. 30. Orlando, FL; Academic Press.

Kinsman, B. 1965. *Wind waves: Their generation and propagation on the ocean surface*. Englewood Cliffs, NJ: Prentice-Hall.

Knamori, H., and Kikuchi, M. 1993. The 1992 Nicaragua earthquake: A slow tsunami earthquake associated with subducted sediments. *Nature* 361:6414, 714–716.

McCredie, S. 1994. When nightmare waves appear out of nowhere to smash the land. *Smithsonian* 24:12, 28–39.

Melville, W., and Rapp, R. 1985. Momentum flux in breaking waves. *Nature* 317:6037, 514–516.

Miller, D. J. 1960. *Giant waves in Lituya Bay, Alaska*. U. S. Geological Survey Professional Paper 354-C.

Pickard, G. L. 1975. *Descriptive physical oceanography: An introduction*, 2nd ed. New York: Pergamon Press.

Satake, K., Shimazaki, K., Tsuji, Y., and Ueda, K. 1996. Time and size of a giant earthquake in Cascadia inferred from Japanese tsunami records of January 1700. *Nature* 379: 6562, 246–249.

Schneider, D. 1995. Tempest on the high sea: The Ocean Drilling Program narrowly averts catastrophe. *Scientific American* 273:6, 14–16.

Stewart, R. H. 1985. *Methods of satellite oceanography*. Berkeley, CA: University of California Press.

Sverdrup, H. U., Johnson, M. W., and Fleming, R. H. 1942. Renewal 1970. *The oceans: Their physics, chemistry, and general biology*. Englewood Cliffs, NJ: Prentice-Hall.

Tappin, D. R., et. al. 1999. Sediment slump likely caused 1998 Papua New Guinea tsunami. *Eos Trans. AGU* 80:30, 329–334.

van Arx, W. S. 1962. *An introduction to physical oceanography*. Reading, MA: Addison-Wesley.

Suggested Reading in Scientific American

Bascom, W. 1959. Ocean waves. 201:2, 89–97. An informative discussion by a renowned expert of the nature of wind-generated waves, tsunami, and tides.

Greenberg, D. A. 1987. Modeling tidal power. 257:5, 44–55. Examines what effect a dam to extract tidal power would have in upper New England.

González, F. I. 1999. Tsunami! 280:5, 56–65. One of the world's leading tsunami researchers examines the physics and results of these killer waves, with special attention to descriptions of recent tsunami.

Hyndman, R. D. 1995. Giant earthquakes of the Pacific Northwest. 273:6, 68–75. A review of the evidence that supports the idea that the Cascadia subduction zone can produce extremely large earthquakes, with special attention to the January 1700 tsunami felt in Japan.

Koehl, M. A. R. 1982. The interaction of moving water and sessile organisms. 274:6, 124–135. A discussion of the adaptations of benthic shore-dwelling animals to the stresses of strong currents and breaking waves.

Oceanography on the Web

Visit the *Essentials of Oceanography* home page for on-line resources for this chapter. There you will find an on-line study guide with review exercises, and links to oceanography sites to further your exploration of the topics in this chapter. *Essentials of Oceanography* is at: **http://www.prenhall.com/thurman** (click on the Table of Contents menu and select this chapter).