

OCEAN WAVES

I. Introduction

The physical definition of a wave is a disturbance that transmits energy from one place to another. In the open ocean waves are formed when winds blowing across the water surface transfer energy to the water. This energy is then transmitted from the region of wave generation as a water wave. In a water wave the water particles travel in circular orbits (Figure 1). With depth the size of the orbits decreases, and at a depth equal to about one-half the wavelength, the orbital diameters are only about 1/25 of those at the surface. For all practical purposes we may consider this level as the maximum depth of wave motion. The distance between successive crests (or troughs) is the *wavelength*. The time it takes two crests (or troughs) to pass a point is the *wave period*. The displacement of the water surface from the rest position (flat surface) is the *amplitude* and the distance from wave trough to wave crest is the *wave height*.

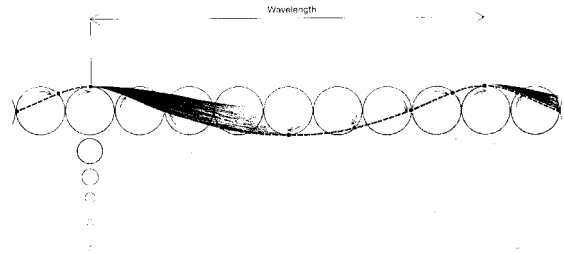


Figure 1. Cross-section of ocean wave traveling from left to right. The circles are orbits of water particles in the wave. At the surface their diameter equals the wave height. At a depth of half the wavelength the orbital diameter is only 4 percent of that at the surface. From Pipkin et al., 1987. *Laboratory Exercises in Oceanography, 2nd Ed.* New York: Freeman, p. 124.

When the waves are under the direct influence of the wind they tend to have round troughs and peaked crests. Such waves are referred to as *sea*. When the waves move out of the area of wave generation, and are no longer under the direct influence of the wind, they take on a more rounded (sinusoidal) shape. Such waves are referred to as *swell*. When waves enter shallow water they may begin to interact with the bottom. When this occurs the shape of the water particle orbitals change (Figure 2), the waves slow down and steepen. It is said that the waves “feel the bottom” and the depth at which this occurs is called the *wave base*. Under these conditions the waves can move bottom sediment.

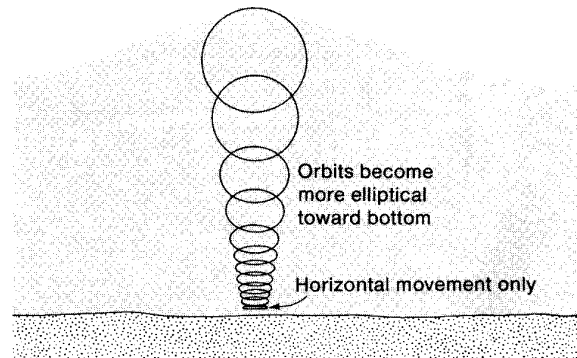


Figure 2. Orbits of water particles become elliptical as they approach a shallow bottom. At the bottom particles only move back and forth. From Pipkin et al., 1987. *Laboratory Exercises in Oceanography, 2nd Ed.* New York: Freeman, p. 131.

II. Deep water waves

When the water depth is greater than half the wavelength, the waves are considered to be deep-water waves, i.e. they do not interact with the bottom. Three factors are important in determining the size of deep-water waves: wind velocity, wind duration and the distance over which the wind acts (fetch). A *fully developed sea* is formed when for any given wind velocity the wind has enough open water and lasts long enough to produce the maximum wave height that can be maintained by the wind. Under these conditions the amount of energy transferred by the wind to the ocean surface is balanced by the amount of energy lost through friction effects in the wave. When a fully developed sea has been achieved the wave crests have

sharp peaks and water is blown off these peaks, i.e. the wave peaks are truncated by the wind. Table 1 lists the fetch and wind duration required to produce a fully developed sea for winds of different velocities, and gives the characteristics of the resulting waves.

Table 1. Conditions necessary for a fully developed sea as a function of wind speed and the characteristics of the resulting waves

Wind speed (knots)	Fetch (nautical miles)	Duration (hours)	Average height		Average length		Average period (Seconds)
			(feet)	(meters)	(feet)	(meters)	
10	10	2	0.9	0.27	28	8.5	3.0
12	18	4	1.4	0.43	40	12.2	3.4
14	28	5	2.0	0.61	55	16.8	4.0
16	40	7	2.8	0.85	71	21.6	4.6
18	55	8	3.8	1.2	90	27.4	5.0
20	75	10	4.9	1.5	111	33.8	5.7
22	100	12	6.3	1.9	135	41.2	6.3
24	130	14	7.8	2.4	160	48.8	7.0
26	180	17	9.5	2.9	188	57.3	7.4
28	230	20	11.4	3.5	218	66.4	8.0
30	280	23	13.6	4.1	251	76.5	8.6
32	340	27	16.0	4.9	285	86.9	9.0
34	420	30	18.6	5.7	322	98.2	9.7
36	500	34	21.4	6.5	361	110.1	10.3
38	600	38	24.5	7.5	402	122.6	10.9
40	710	42	27.9	8.5	446	136.0	11.4
42	830	47	31.5	9.6	491	149.7	12.0
44	960	52	35.4	10.8	540	164.6	12.6

1. What is the maximum wind that can set up a fully developed sea in a channel or strait 20 statute miles wide? Remember, 1 nautical mile = 1.15 statute miles.

2. The Cook Strait which separates the North and South Islands of New Zealand has some of the roughest seas in the world. When the wind blows from the NW across the Tasman Sea the fetch is in excess of 1300 statute miles. If the usual storm duration is 48 hours, what is the maximum wind speed that can form a fully developed sea?

What will be the average dimensions of the waves generated by this storm?

Wave height _____ Wavelength _____ Wave period _____

3. Typical afternoon breezes off southern California are 10 - 20 knots from the northwest. How long must they blow and over how much sea to produce a fully developed sea?

Duration _____ Fetch _____

4. Answer the following questions using Figure 3 which shows the characteristics of California waves coming from various directions in the course of a year.

- a. From what sector do the largest waves strike California during the winter?

- b. From what sector does the largest swell come in the summertime?

What is the range of potential periods and heights?

- c. Waves of what period (long, medium, short) produce the highest waves?

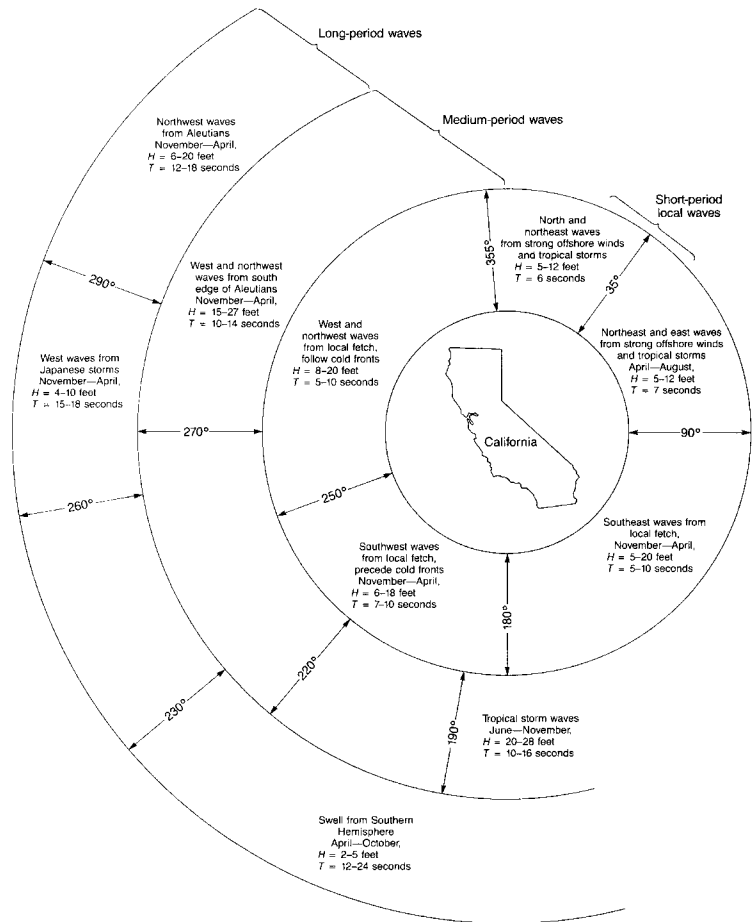


Figure 3. Diagram for the California area showing the characteristics of waves from different directions. H is the wave height and T is the wave period. From Pipkin et al., 1987. *Laboratory Exercises in Oceanography*, 2nd Ed. New York: Freeman, p. 126.

III. Shallow water waves

As noted above, when the depth of water is less than half the wavelength waves begin to interact with the bottom and become shallow-water waves. As the depth decreases the waves slow up and steepen. At a water depth of 1.3 times the wave height water supply is reduced and the particles of water in the crest have no room to complete their cycles. At this point the waves breaks. When waves move out of the wave generation area the wave period is conserved. This is an important observation since it enables us to predict when waves will begin to act as shallow-water waves (Figure 4). Note that given the average depth of the ocean, all waves with periods of greater than 80 seconds are shallow-water waves. The tides and tsunamis are shallow-water waves. Hence the velocity at which they travel through the ocean will be solely determined by the water depth. Thus if we know the shape of the ocean basin we can predict when tsunamis will arrive at any particular location. Since shallow-water waves interact with the bottom they can move sedimentary material and are important agents of erosion.

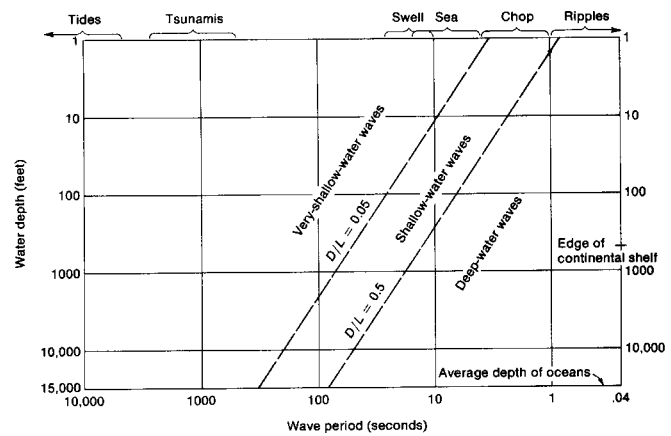


Figure 4. Relationship between period, water depth and wave type. From Pipkin et al., 1987. *Laboratory Exercises in Oceanography*, 2nd Ed. New York: Freeman, p. 132.

Waves can **reflect**, **refract**, **diffract** and **interfere**. For example waves striking a breakwater at an angle (angle of incidence) will reflect from the breakwater at the same angle (angle of reflection). **Refraction** occurs when a wave moves into shallow water at some angle other than parallel to the shoreline. The part of the wave that is in shallowest water travels slowest and the part of the wave in deepest water travels fastest. The mathematical relationship is $Wave\ velocity = [acceleration\ due\ to\ gravity \times water\ depth]^{1/2}$. The result is the bending of the wave crest and the concentration or dissipation of energy at the shoreline (Figure 5). The relative amount of concentration or dissipation of wave energy is determined by drawing lines, called **orthogonals**, perpendicular to the wave crests. By tracing the orthogonals shoreward on the crests of successive waves of selected periods or wavelengths we can determine how wave energy is concentrated or dissipated at the shore. The **wave energy coefficient**, e , the relative amount of concentration or dissipation of energy, is calculated by dividing the distance between two orthogonals at the shoreline by the distance between the same two orthogonals in deep water. When e is greater than 1 wave energy is dissipated and when e is less than 1 wave energy is concentrated. **Diffraction** occurs when waves move through an opening narrower than their wavelength. When this condition is met the waves spread

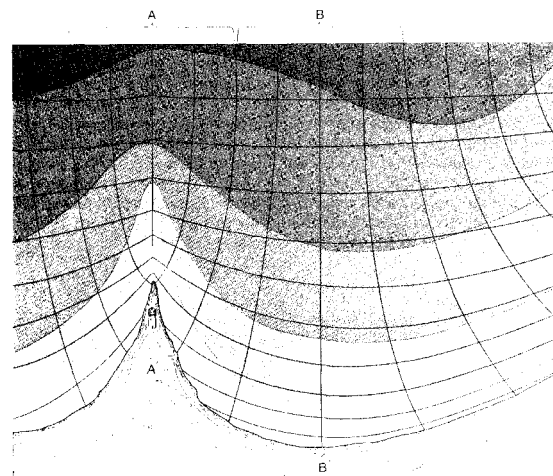


Figure 5. The wave refraction diagram shows how the energy of the wave front at A is concentrated by refraction at A' around the small headland area. The same energy at B enters a bay but is spread at the beach over a wide area B'. The horizontal lines are wave fronts, the vertical lines are orthogonals dividing the energy into equal units. From Pipkin et al., 1987. *Laboratory Exercises in Oceanography*, 2nd Ed. New York: Freeman, p. 134.

out on the other side of the opening. **Interference** occurs when waves pass through each other. If the crest of one wave and the trough of another interact wave amplitude is diminished and destructive interference occurs. If the crests of two waves, or the troughs of two waves, interact wave amplitude is increased and constructive interference occurs. One last empirical relationship of interest is that the **height of a breaker is approximately equivalent to 0.78 of its depth**. This type of approximation is important in determining the height that piers should be built above mean high water or some other datum.

Longshore currents form when waves approach the shoreline at an angle (Figure 6). Under these conditions there is a component of the wave velocity that runs parallel to the shoreline. This component is responsible for forming a current that moves parallel to the shoreline. This current can move sedimentary material. If an obstruction, such as a groin or jetty, is placed in the path of the current the current velocity is decreased and sediment is deposited. Since the longshore current is usually in equilibrium in terms of its sediment load, when the current passes an obstruction it becomes depleted in sediment and this sediment is replaced through erosion on the down current side of the obstruction. Hence long shore currents are important agents of coastal erosion and deposition. The direction of wave approach, and the resulting longshore current is not a constant. For example, reference to Figure 3 shows that wave approach to the California coast varies seasonally. When waves are approaching from the SW the longshore drift will be to the north and when waves approach from the NW the longshore drift will be to the south. Since sandspits build in the direction of longshore drift, the net longshore drift for a coastal region can be determined from the direction of sandspit growth. The other component of wave velocity that is perpendicular to the shoreline causes a net movement of water onto the shore. In order to maintain equilibrium this water must return to the open ocean. This return usually occurs as narrow, well defined currents referred to as **rip currents** (Figure 7). Since water moving onshore over a coastline length of hundreds of meters may be returning to the open ocean in a current that is only tens of meters wide, rip currents can have a high velocity. Swimmers caught in rip currents can be carried out to sea. To escape a rip current swim parallel to the coast line. Since the currents are narrow, it will take only a short time to escape the current.

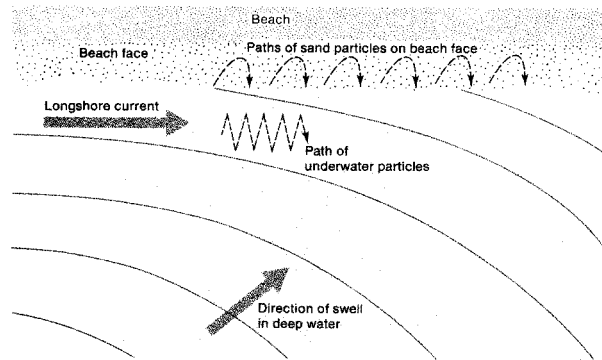


Figure 6. A longshore, or littoral, current is set up parallel to the shore when waves approach the shore at an angle. Sand is also transported parallel to the shore by the current. From Pipkin et al., 1987. *Laboratory Exercises in Oceanography*, 2nd Ed. New York: Freeman, p. 135.

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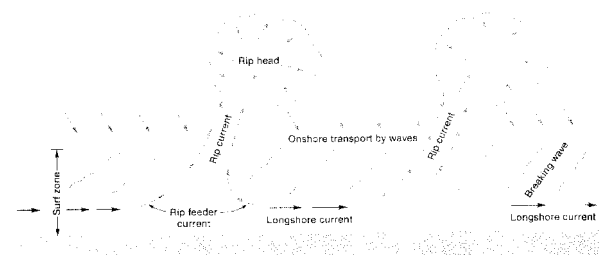


Figure 7. Diagram of the nearshore current system showing the longshore drift and the return of water to the open ocean via rip currents. From Pipkin et al., 1987. *Laboratory Exercises in Oceanography*, 2nd Ed. New York: Freeman, p. 136.

Tsunamis (seismic sea waves) are long wave length shallow-water waves that are generated by oceanic earthquakes, volcanic eruptions, etc. The velocity of these waves is controlled by the depth of the ocean. In the open ocean the waves are 80 to 100 miles long and can travel at velocities in excess of 400 miles per hour. When the waves enter shallow water their velocity and wavelength decrease and there is a substantial increase in the wave height. In low lying coastal regions these waves can inundate large areas and cause

substantial destruction and loss of life. Tsunamis are common in the Pacific Ocean because of the large number of earthquakes that occur in the Pacific basin. For this reason a tsunami alert network has been established which gives warning of impending tsunamis. With the advent of this network there has been a significant reduction in the loss of life, but property damage is still significant.

5. Figure 8 is a map view of the Santa Monica beach and breakwater. Indicate on this figure the distribution of wave energy at point A and B, using terms such as *high*, *low*, or *nil*.

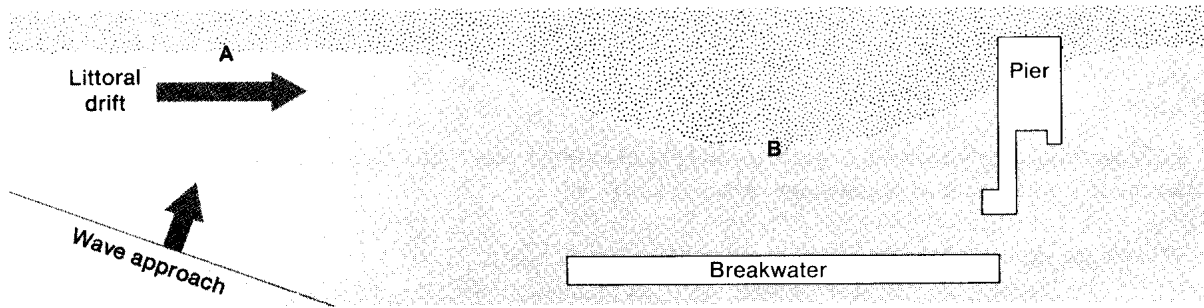


Figure 8. Diagram of a breakwater and beach at Santa Monica, California. From Pipkin et al., 1987. *Laboratory Exercises in Oceanography*, 2nd Ed. New York: Freeman, p. 141.

Where would sediment be deposited? Where would sediment be eroded?

6. a. Complete the wave-crest diagram (Figure 9). See Figure 5 for an example.
 b. Sketch in the orthogonals with a deep-water spacing as indicated.
 c. Calculate the wave energy coefficients for segments 1-4.

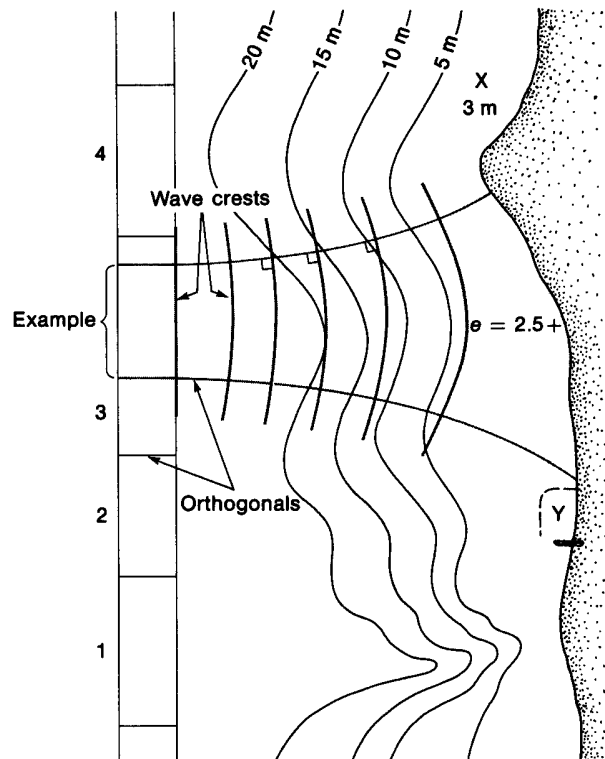


Figure 9. Wave refraction diagram. Numerals along the broken contours indicate the depth in meters. From Pipkin et al., 1987. *Laboratory Exercises in Oceanography*, 2nd Ed. New York: Freeman, p. 143.

- d. Indicate along the shore in the diagram several places at which you would expect a sand beach to be wider because of accretion, or narrower or nonexistent because of erosion.

b. What is the average velocity of the tsunami in its travel to:

Hawaii

Valparaiso, Chile

Give a rational explanation for this difference in velocity between the two stations.

c. Estimate the greatest height of the tsunami above still-water level for the stations shown in Figure 10.

Sitka, Alaska

Honolulu, Hawaii

San Luis Obispo, California

Valparaiso, Chile

Why would the wave be almost unnoticeable in Sitka even though it is much closer to the source area of the earthquake?

d. What was the first evidence of the arrival of the tsunami on the shoreline at Honolulu - low or high water?

Which crest in the series did the greatest damage?

d. Why do tsunamis occur so much less frequently in the Atlantic Ocean than in the Pacific Ocean?

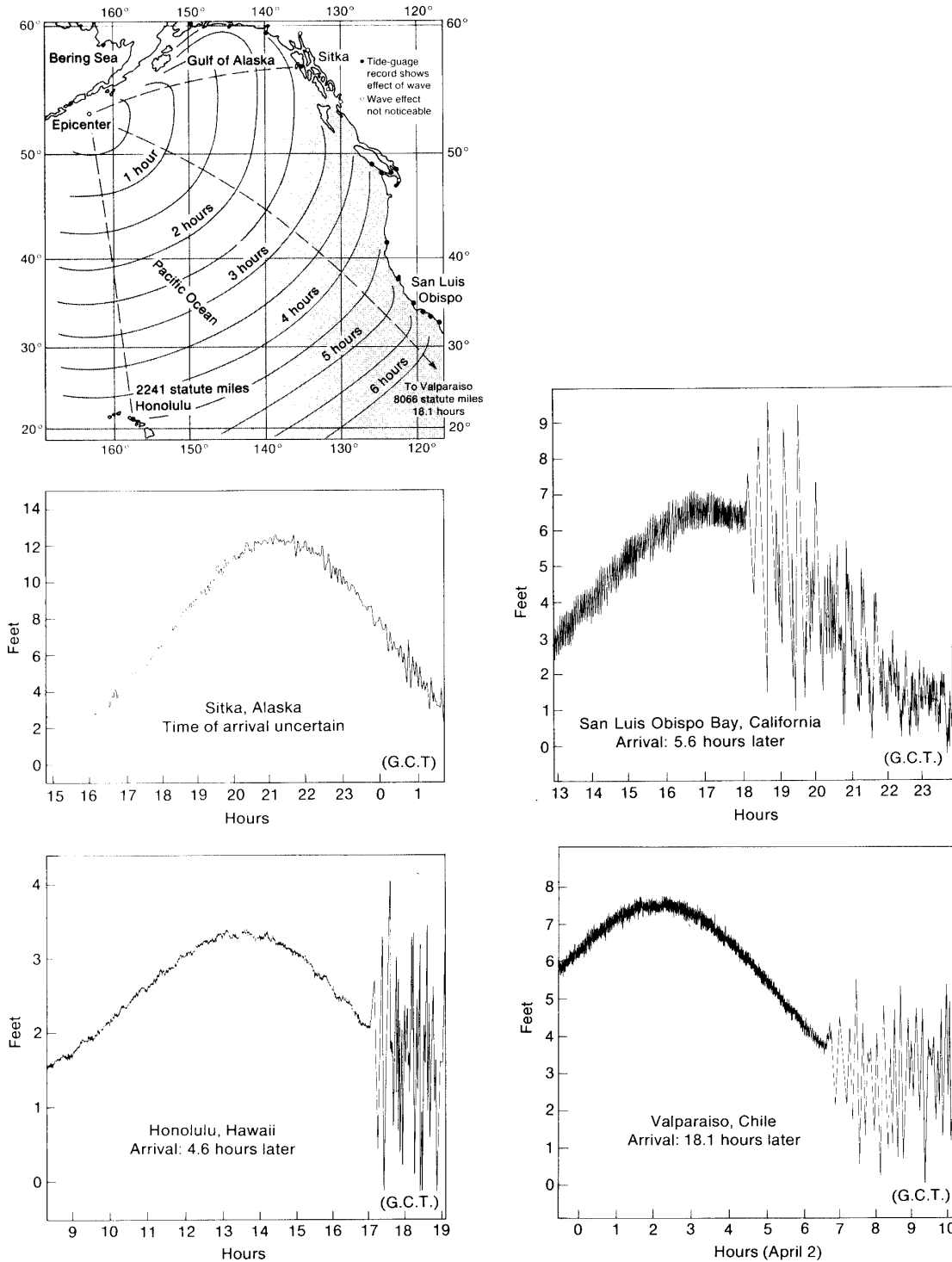


Figure 10. Records for the tsunami of April 1, 1946. Note that the tsunami arrived at different places at different stages of the tidal cycle, and that the first sign of its approach was a small rise followed by a larger fall in water level. The maximum height was not reached until the third or fourth crest, at least half an hour later. From Pipkin et al., 1987. *Laboratory Exercises in Oceanography, 2nd Ed.* New York: Freeman, p. 140.