Chapter 9. Tsunamis (Tidal Waves)

On March 27, 1964, at 7:36 p.m., Pacific Standard Time, an intense earthquake originated near the western side of Unakwik Inlet approximately 102 km east of Anchorage (Fig. 9.1). It was one of the strongest earthquakes ever recorded on the North American continent, and registered a magnitude of 8.5 on the Richter Scale[1]. A massive uplift over 250,000 km^2 of the seafloor adjacent to the Alaska coast accompanied the tremor, which sent a series of "tidal waves" at high speed toward all corners of the Pacific Ocean. Less than 4 h later, the first waves reached the outer coast of Vancouver Island where they produced abnormally large and rapid changes in sea level (Fig. 9.2). Although the villages of Hot Springs Cove and Zeballos suffered major wave and flood damage, Port Alberni was the hardest hit when a 7-m wave swept up Alberni Inlet. It was the largest wave of its kind recorded in British Columbia and, though it caused no deaths, was responsible for $10 million damage to ships, residential property, and industry (Fig. 9.3, 9.4). The USA was less fortunate. In Alaska, tidal waves surged onto the land and killed 107 people, while in California and Oregon, nearly 2000 km from the source, 15 people were killed. Damage exceeded $104 million and many were left injured and homeless.

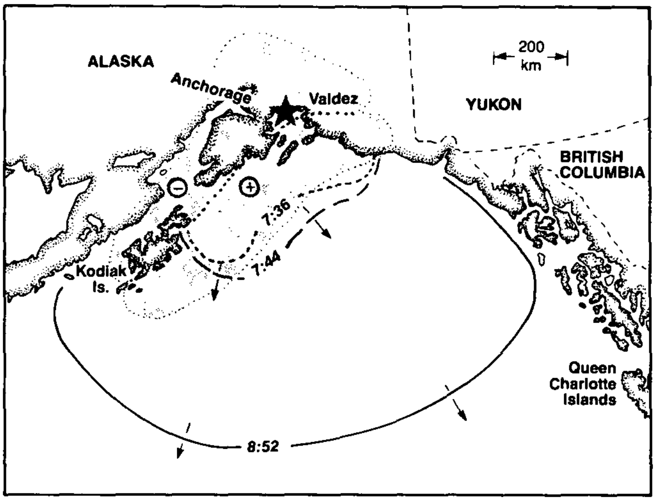

FIG. 9.1. Leading edge of 1964 Alaska tsunami beginning with inception around 7:36 p.m. 27 Mar. Star marks earthquake epicenter in Unakwik Inlet at northern end of Prince William Sound. Shaded area delineates area of crustal uplift (+) and subsidence (−) that accompanied the earthquake. Maximum uplift was about 9 m, maximum subsidence about 1½ m. (Adapted from Spaeth and Berkman 1967)

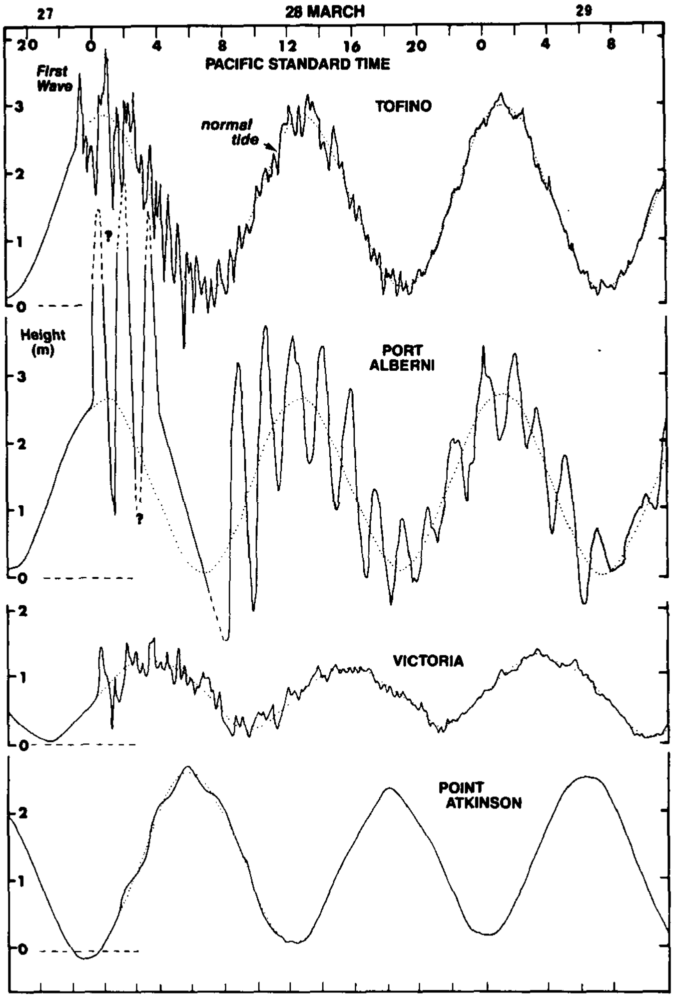

FIG. 9.2. Sea level records from four British Columbia locations, Mar. 27–29, 1964. First tsunamic waves arrived around midnight and caused rapid fluctuations in water levels with respect to normal tide heights (dotted lines). At Port Alberni, larger waves forced tide gage off-scale. Initial values are reconstructed from flood levels in city. (Adapted from Wigen and White 1964)

Waves of the magnitude generated by the Alaska earthquake are rare. Of the 176 instances recorded between 1900 and 1970 in the Pacific, 35 caused damage near their source but only 9 created widespread destruction. Nevertheless, it is important to be familiar with the nature of such waves. How are they generated and what factors determine their destructiveness? Is the first wave the highest? What effect would a tidal wave have on a ship at sea?

[1] Richter Scale: A logarithmic scale that expresses the intensity of a seismic disturbance in terms of the energy it dissipates. A unit (1) increase in the scale implies a 10-fold increase in energy. Thus, an earthquake that measures 4 on the Richter Scale is 10 times more energetic than an earthquake that measures 3, and 100 times more energetic than one measuring 2. The smallest disturbance that can be felt on land has a scale reading of 1.5; an earthquake of 4.5 causes slight damage; a reading of 8.5 means a devastating earthquake. A seismic disturbance of 8 on the Richter Scale has the equivalent energy of a 250-megaton thermonuclear bomb. In comparison, the atom bomb dropped on Hiroshima in 1945 was only 0.02 megatons, a factor of 12,500 less powerful.

FIG. 9.3. Property damage in Port Alberni from 1964 Alaska tsunami. (*Vancouver Sun* photo)

FIG. 9.4. Property damage in Port Alberni by 1964 Alaska tsunami. (*Vancouver Sun* photo)

Generation

The formation of so-called tidal waves has absolutely nothing to do with the tide, the vertical rise and fall of sea level produced by the sun and moon. For this reason, a tidal wave is now more properly referred to as a tsunami. Meaning "harbor wave" in Japanese, it is a recognition of that country's pioneering work on the subject, and the unparalleled destruction such events have wreaked on its inhabitants throughout history. Universal acceptance of the name tsunami has also replaced terms like seismic sea wave and seaquake, which were in common use until recently. Seaquake now has a specialized meaning related to earthquake shock vibrations transmitted through the water. (Two B.C. mariners reported noticing such brief vibrations when anchored in the Gulf Islands during a calm day, at the time of a small earthquake in the area.)

Essentially, tsunamis appear to be associated with earthquakes generated beneath the seafloor with magnitudes greater than 6.5 on the Richter Scale and centers not deeper than about 100 km below the seabed. However, even if such a tremor occurs it rarely generates a tsunami. This is because the great majority of earthquakes in the Pacific cause a sideways slipping of the seafloor rather than an upward or downward displacement, which is needed to cause distortion of the ocean surface (Fig. 9.5). Nevertheless, such faults do form across large areas of the seafloor. When they do, a tsunami is created and spreads outward as a series of waves, somewhat analogous to the pattern

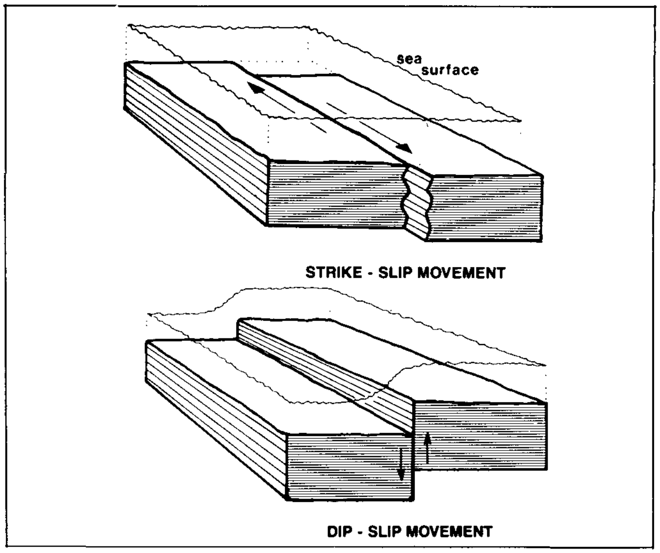

FIG. 9.5. Two types of seafloor crustal faults (highly exaggerated in scale). Tsunamis are generated by vertical dip-slip dislocations that lead to rapid deformation of sea level.

formed by a stone cast into a pond. For the most part, tsunami generation is confined to the rim of the Pacific Ocean where shifts of the oceanic crust relative to the continental land masses have created highly active earthquake zones (Chapter 1). Statistically, 62% of all tsunamis occur in the Pacific Ocean, 20% in the Indian Ocean, and the remaining 18% in the Mediterranean Sea and the North Atlantic Ocean. The South Atlantic is relatively aseismic and tsunami-free.

Not all tsunamis are directly attributable to seafloor motions. Most damage along the Alaska coast in 1964 was, in fact, due to locally derived waves formed by underwater landslides and shoreline slumps that were triggered by the land-centered earthquake. Because tsunamis of this type are usually generated in confined areas like inlets, they can be highly destructive. Near Valdez, Alaska, an underwater slide created a tsunami that deposited driftwood 52 m above the low water mark and splashed sand to a height of 67 m. A massive rockfall at the head of Lituya Bay, Alaska, on July 9, 1958, precipitated a giant wave in narrow Gilbert Inlet, which ascended 518 m up the opposite headland. A similar but much less dramatic event occurred in British Columbia in 1975. On April 27, a large underwater slide down-inlet from Kitimat sent waves "boiling ashore." After an initial fall of 4.6 m below low tide, the sea level near the Kitimat waterfront rose by 7.6 m in only a matter of minutes and then surged back and forth for about an hour before returning to its normal state. Damage from these events and others in the same week was light, however, as they occurred near the time of low tide. Tsunamis may also be generated by the explosion of submarine volcanoes. When Krakatoa erupted on Aug. 27, 1883, in the East Indies, it created waves 30 m high that crashed over neighboring islands and drowned more than 36,500 people in nearby Java and Sumatra. The atmospheric shock waves from the volcanic blasts induced sea level oscillations that were detected by tide gages as far away as the English Channel. Conceivably a large meteorite crashing into the ocean would produce a tsunami, although there are no records of such an event.

It is postulated that about 1% of the seismic energy of submarine earthquakes goes into the generation of tsunamic waves, and that heights of the waves at a coast within a range of 800 km of the earthquake's origin are proportional to the square root of the earthquake energy. On this basis, a submarine earthquake of magnitude 7 on the Richter Scale would cause wave heights of around 2 m at the coast and an earthquake of magnitude 8 would cause wave heights of 10 m (Fig. 9.6). Within the generat-

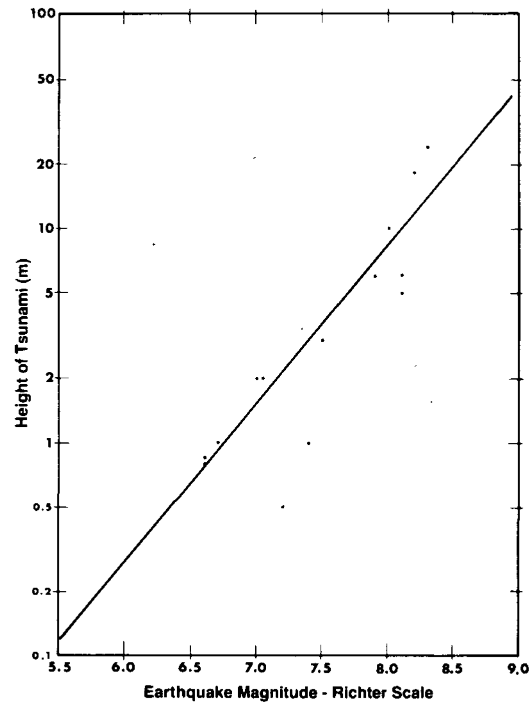

FIG. 9.6. Heights of tsunamis expected at coasts within 900 km of submarine earthquake. Based on data collected near Japan 1923–1957. Dots give measured wave heights for various earthquake magnitudes. (Modified after Wilson 1964)

ing region itself, tsunamis are thought to begin as a complex system of waves with a broad spectrum of periods, heights, and wavelengths. Eventually the waves sort themselves out through dispersive effects with longer waves leading the way out of the generating region, though present knowledge regarding the types of initial waves and the transformations they undergo is still lacking. In reality, there is often more than one group of waves because of aftershocks and readjustments of the seabed following the initial upheaval.

Away from the generating region, tsunamis, as other wave phenomena, are affected by refraction, shoaling, dissipation, diffraction, resonance, and reflection. These factors, together with those that produce the waves in the first place, lead to a convoluted wave pattern whose behavior at a coast is extremely difficult to predict or even to reconstruct. Table 9.1 gives some indication of the complexity of the problem by illustrating the considerable variability in maximum wave heights at, and between, various locations in the Pacific for the five most recent ocean-wide tsunamis.

TABLE 9.1. Maximum waves (rise or fall) recorded for five recent tsunamis within the Pacific Ocean (heights in metres). Where maximum wave exceeded gage limit (+ sign), values may be misleading. Hilo, Hawaii, for example was devastated by the 1960 tsunami yet only suffered minor flooding from the 1964 tsunami despite its greater recorded height. Heading gives year and origin of tsunamis. (Adapted from Spaeth and Berkman 1967)

Location	1946 Aleutian Islands	1952 Kamchatka Peninsula	1957 Aleutian Islands	1960 Chile	1964 Alaska Peninsula
Sitka, Alaska	0.79	0.46	0.79	0.91	4.36
Tofino, B.C.	0.60	0.61	–	1.40	2.47
Neah Bay, Wash.	0.37	0.46	0.30	0.73	1.43
Crescent City, Calif.	1.80	2.07	1.31	3.32	3.96+
Talcahuano, Chile	–	3.66+	1.40	5.06	1.65
Hilo, Hawaii	–	2.41	2.71	2.93+	3.81+
Honolulu, Hawaii	1.25	1.34	0.98	1.68+	0.82
Wake Island	–	0.52	0.73	1.01	0.15
Kushimoto, Japan	–	–	–	3.20	0.79

Wave Travel

Once generated, a tsunami consists of a series of waves that spread rapidly away from their source. In the deep ocean, waves attain speeds of over 900 km/h. The crest-to-crest separation between each wave in the series is typically around 100–400 km so that even at their fantastic speeds it usually takes 10–60 min for successive crests to pass a given point. Because their wavelength is appreciably greater than the depth of the ocean, tsunamis fall into the category of shallow-water waves (Chapter 6, 8). As a consequence, they behave in midocean somewhat like ordinary wind waves that propagate through knee-high water, in that their speed, C, depends only on the local water depth, D, through the simple formula $C = \sqrt{gD}$. According to this equation, for example, tsunamis would travel at a speed of 620 km/h or 335 kn in water 3050 m deep.

Because tsunamis continually feel the presence of the bottom, they must always adjust their speed according to the depth. They decelerate in shoaling regions and accelerate in deepening regions. As a result, the concentric wavefronts begin to distort as different parts of the front move across areas of different depth in the ocean. The part of a wavefront over the shallow continental shelf will move appreciably slower than the part of the wavefront over an ocean abyss, and, therefore, lag behind (Fig. 9.1). For this reason, it took the first wave of the 1964 tsunami 3 h, 24 min to travel the 1800 km (973 nm) over relatively shallow water from Alaska to Tofino, for an average speed of 530 km/h (286 kn). On the other hand, it took only 5 h, 17 min for this wave to cross the 4386 km (2368 nm) to Honolulu, for an average speed of 830 km/h (448 kn). Obviously, a detailed knowledge of the ocean depths is essential for accurate predictions of arrival times around the Pacific rim.

Height at Sea

Contrary to what one might think, the height of a tsunami at sea is always small, rarely exceeding 1 m from crest to trough. And, because the crest-to-crest separation is so large, the profile of these waves at sea is extremely low. A ship would not detect their passage as any possible effect would be lost in the confusion of sea and swell. During the April 1946 tsunami at Hawaii, ships standing off the coast observed tremendous waves breaking on the shore but detected no unusual motion at their offshore locations.

Height Near Shore

When it arrives at a shore, a tsunami may take several forms. It may cause nothing more than a series of gentle rises and falls of the water level over periods of 10–60 min, somewhat like a time-lapse version of the tide. Alternatively, the sea level may rise and fall more quickly, and produce swift floodlike currents. Withdrawals may be rapid and destructive and sweep all before them. Or if conditions are right, a tsunami may manifest itself as a cresting wall of water tens of metres high that crashes ashore with devastating force.

The first wave of a tsunami is usually not the highest. In fact, the approach of a tsunami is often heralded by a slight rise in the water level as the first small crest arrives, followed some time later by a much larger ebb associated with the first trough. At Kodiak, Alaska, the first wave from the 1964 tremor produced nothing more than a gentle rise in sea level followed by a gradual fall. The second wave, however, was a 10-m high monster that pushed 100 t boats over a breakwater and then carried them three blocks into the city.

Tsunamis do not affect all areas equally. Figure 9.2 illustrates that Tofino, on the west coast of Vancouver Island, is only moderately susceptible to these waves, whereas Port Alberni, some 65 km inland, is highly susceptible. In Crescent City, Calif., the 1964 tsunami killed 11 people but in Hilo, Hawaii, no deaths were reported, despite the fact that the waves at both places reached heights of 4 m. Clearly, there are other factors that determine the overall effect of a tsunami aside from the original amount of energy put into it at the generating region.

Proximity

The force of a tsunami is most likely to be extreme if the waves are generated nearby. Japan suffers considerably in this respect and coastal communities in Alaska were hard-hit in 1964 because of their proximity to the wave-generation area.

Tsunamis lose energy as they propagate. A fraction of this energy is lost directly through friction as the waves "rub against the bottom." In addition, there is a decrease in the wave energy as the initial impulse given to the tsunami in the generation region becomes spread over an ever-increasing area of the ocean. The latter is similar to the way sound diminishes as it spreads away from its source, but with an important difference. Whereas sound intensity diminishes inversely as the square of the distance, the energy in tsunamis diminishes inversely as the distance alone. Therefore, tsunamis weaken very slowly and distance alone is not a guarantee of immunity. Often it is more important to be out of the direct "line of sight" to the generation region as most tsunamis tend to be highly directional. But, the best protection is an obstacle course of straits, passages, islands, shoals, and sharp corners through which the waves effectively dissipate their energy. At Point Atkinson in the well-protected Strait of Georgia region, the 1964 tsunami caused only a 25-cm (10 in.) rise in sea level, while at the more exposed Argentine Islands in Antarctica, 13,000 km and 16 h later, a 60-cm (24 in.) rise was recorded.

Shoaling

As with other sea waves, tsunamis steepen as they move from the deep ocean into shallow water. The greatest amplification of the wave takes place near shore. If the slope of the shore or beach is gradual over many kilometres, much of the wave power is dissipated before it reaches the land. Reefs like those around the Fijian Islands are particularly helpful in this regard. Where the beach is small compared to the distance between crests, however, the waves may grow to a large swell that breaks at its crest. The shoreward run-up of the waves can then carry them over low-lying areas as a flood whose turbulent crest will quickly subside once it is ashore. On the other hand, if a tsunami encounters a steep, abrupt shore, the wave will slosh up the beach but its run-up height will be no higher than the height at which it is breaking. Under such circumstances, most damage will be due to flooding, not direct wave force. Underwater ridges near the shore will tend to focus the wave energy, and make it significantly higher than normally expected. There is some evidence that Crescent City, Calif., received large waves in 1964 partly because Cobb Seamount, 740 km northwest, acted like a lens and focused the tsunami toward the city. (Submarine canyons, of course, have the opposite effect and tend to lower the wave height.)

If a tsunami propagates into a narrowing embayment, it may be funneled to much greater heights than if it encounters a straight shoreline. The tsunami from the Sanriku earthquake in Japan, June 15, 1896, amplified into devastating 30-m waves at the head of Kamaishi Bay where it claimed over 27,000 lives. But every tsunami appears to be different, and quite often embayments are no more affected than other localities as the structure of the bottom outside of the bay apparently also affects the behavior of waves inside the bay.

At abrupt continental margins, a considerable portion of the energy associated with an approaching tsunami may be reflected back to sea, and effectively reduce the impact of the waves at the coast. Alternatively, the waves may be guided by the bathymetry in such a way that they become trapped near the coast. Trapping of this kind can take place around islands, along coastlines, or over undersea ridges and escarpments with the waves slowly "radiating" their energy back to sea over a period of time (see Fig 8.7).

State of the Tide

The higher the tide at the time a tsunami arrives ashore, the greater the likelihood of flooding. The worst set of circumstances in this regard is a high spring tide during a period of strong onshore winds. Waves of the 1964 Alaska earthquake first arrived at the shores of Vancouver Island about the time of a normal high water so, although sea levels rose above higher high water in many locations (Fig. 9.7), conditions were not extreme given the possible heights tides can attain in these areas.

Natural Oscillations

Despite a distance of 65 km from the coast, the twin cities of Alberni–Port Alberni suffered widespread damage from the Alaska tsunami. Its arrival at these cities, moreover, was atypical in that the 97-min delay between the first and second crests was much longer than usual. (This, and the fact that the first wave was smaller, allowed people time to evacuate the area.) Why these peculiarities? It seems that the combination of Trevor Channel and Alberni Inlet, which leads to the cities, had a natural resonant frequency that matched that of the tsunami, and allowed the waves to amplify (Fig. 9.2). In other words, the series of oceanic waves was able to make the water in the inlet slosh back and forth near its natural "sloshing frequency" just as water in a bathtub can be made to surge higher and higher by the appropriate rhythmic motion of one's hand. The relatively large tsunamic waves at Crescent City also appear mainly to have been the result of resonant conditions brought about by the bowl-like bathymetry of the adjacent continental shelf.

Ignorance

In San Francisco, 10,000 people jammed the beach areas to watch the Alaska tsunami wash ashore. Fortunately, for them, the waves were small! In contrast, the beaches in Chile, Japan, and Hawaii were deserted after the warning was issued; people had learned from previous experience the power of tsunamis. Most deaths in Crescent City from these waves were due to ignorance. The owners of a tavern that had suffered damage from the first two waves, returned with friends to remove money from the building. As everything appeared normal, they stayed to have a beer and were caught by the third wave, the largest of the series, and five were drowned. In 1960, the Chile tsunami killed 61 people in Hawaii who had failed to heed the warning to get to higher ground.

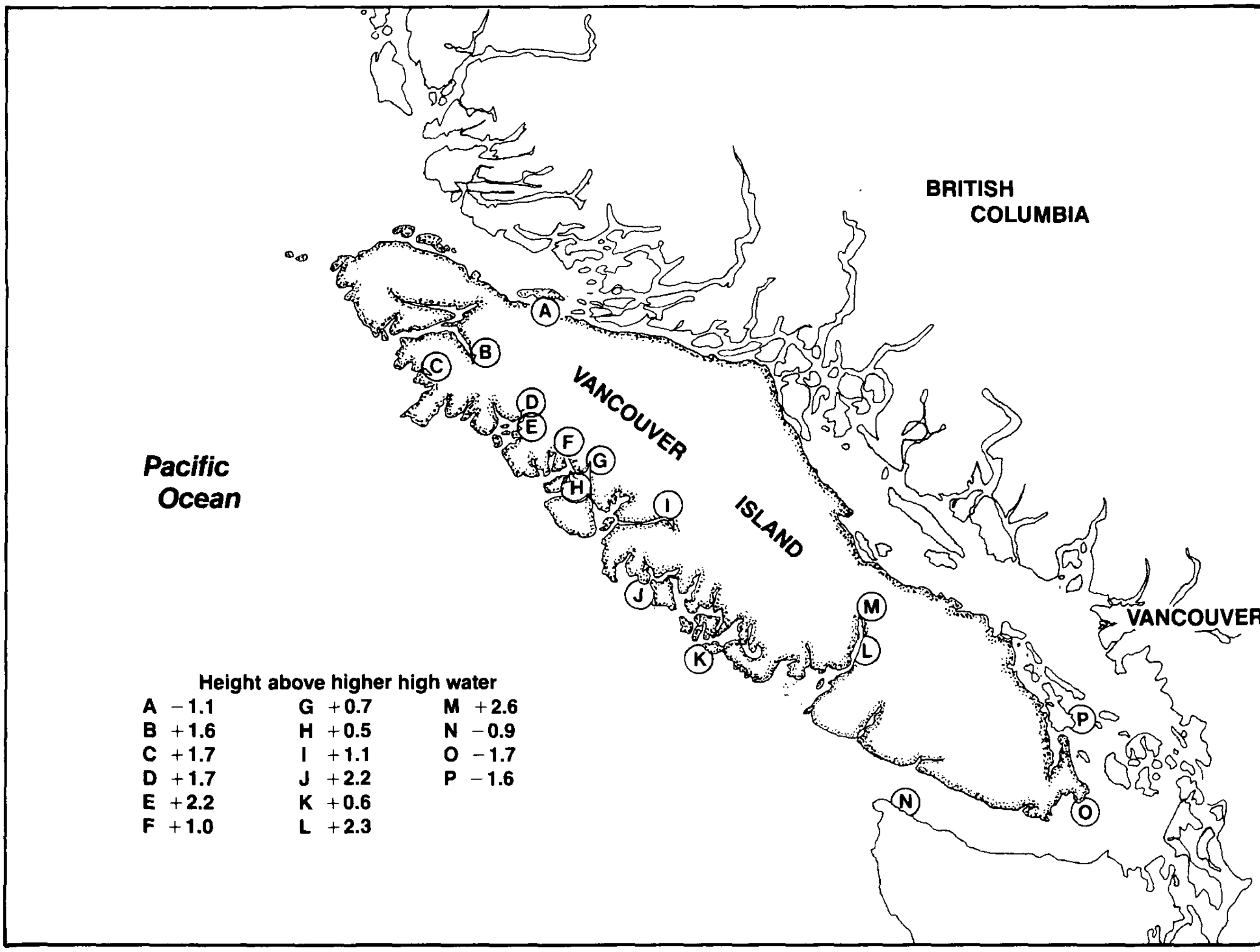

FIG. 9.7. Locations in southwestern British Columbia that reported significant tsunami activity Mar. 27–29, 1964. Numbers give height in metres of maximum wave crest above HHW, large tide (negative values indicate less than HHW). A, Alert Bay; B, Port Alice; C, Klaskino; D, Fair Harbour; E, Amai Inlet; F, Zeballos; G, Esperanza; H, Tahsis; I, Gold River; J, Hot Springs Cove; K, Tofino; L, Franklin River; M, Port Alberni; N, Neah Bay; O, Victoria; P, Fulford Harbour. (Adapted from Wigen and White 1964)

Population

The population of an area has a lot to do with the destructiveness of a tsunami. The highest waves reported in British Columbia in 1964, for example, were at Shields Bay on the west coast of the Queen Charlotte Islands. One wave was estimated to be over 9 m above the low-tide level. Damage was light compared to Alberni–Port Alberni as only a logging camp was there at the time.

Tsunami Warning System

After the devastating Aleutian tsunami of April 1, 1946, and its widespread damage to Hawaii, officials in the United States began to push for the formation of an early warning system in the Pacific Ocean. To do this, it was necessary to design tide gage stations capable of detecting abnormal changes in sea level and to have a communication network linked via a central dissemination center. With the engineering problems overcome, the system of tide gages (and seismic gages) in U.S. territory went into operation 2 yr later. Japan added gages in 1949. Canada waited until after the disastrous Chile tsunami of May 1960 to join the network, as did other nations like Chile, Taiwan, New Zealand, and the Philippines. No major tsunami occurred in the next few years so Canada withdrew in 1963 and, therefore, received no prior warning of the 1964 Alaska tsunami. Needless to say, Canada is a member again!

To date, Canada maintains two special tide gage stations within the Pacific network of 30 odd stations. Located at Tofino and Langara Island on the northwest tip of the Queen Charlottes, these stations are capable of direct telephone contact with the warning center in Honolulu. If an abnormal change in the water elevation occurs at these stations over a period of 5 min, the machine immediately switches to "warning mode," then dials Honolulu and repeats the message . . . *Warning Tsunami.* If such gages determine that a "tidal wave" is headed toward B.C., the Honolulu Observatory first contacts the Civil Defense Preparedness Agency in Bothwell, Wash., which in turn telephones (collect) to RCMP "E" Division Headquarters in Victoria, B.C. They then contact the Provincial Emergency Programme Co-ordinator (PEPC), the RCMP Duty Officer, and the Department of National

Defense. Based on the known epicenter of the earthquake and other gages in the network, a time of arrival is determined from specially prepared charts. Provided there is more than 2½ h, the above group, together with the Regional Tidal Superintendent, evaluate the information and determine the likely damage to low-lying areas. If there is a possibility the waves will reach the coast, people in these areas are evacuated by local civil defense authorities. On the other hand, if there is less than 2½ h notice because of the proximity of the earthquake, the PEPC contacts Broadcast News in Vancouver, which then issues a warning via special broadcasts over TV and radio.

The probability that a large tsunami from the ocean will propagate far into Juan de Fuca Strait or the Strait of Georgia is very low. It is also unlikely that the occurrence of a major earthquake off the coast will generate a tsunami because faulting in this geographical location is mostly of the sideways slip type. "Unlikely," however, does not mean impossible. In fact, there is a documented case of tsunamic waves generated by just such an occurrence. According to Murty (1977), the earthquake of June 23, 1946, that originated on the east coast of Vancouver Island was sufficiently strong to break telegraph cables on the seafloor and to cause the water level at Franklin River in Alberni Inlet to rise 6.1–9.1 m above average. At Sisters Rock near Texada Island in the Strait of Georgia, the tsunami attained an amplitude of over 2 m. A second wave in the Strait had an amplitude of 1.2–1.5 m and was responsible for the death of one person near Mapleguard Point opposite the southern end of Denman Island.