Tsunami hazard and risk in Canada

John J. Clague
Simon Fraser University, Burnaby, BC, Canada

ABSTRACT
Tsunamis in Canada have been triggered by earthquakes, landslides, and a large chemical explosion. The Pacific coast is at greatest risk from tsunamis because of the high frequency of earthquakes and landslides in that region. The most destructive historical tsunamis, however, have been in Atlantic Canada – one in 1917 in Halifax Harbour, which was caused by an catastrophic explosion of a munitions ship, and another in 1929 in Newfoundland, caused by an earthquake-triggered landslide at the edge of the continental shelf. The tsunami risk along Canada's Arctic coast and along the shores of the Great Lakes is low in comparison to that of the Pacific and Atlantic coasts. The hazard is posed by landslides in fjords and inlets along the British Columbia coast is not fully appreciated.

RÉSUMÉ
Tsunamis au Canada ont été déclenchées par des tremblements de terre, glissements de terrain, et une grande explosion chimique. La côte Pacifique est le plus grand risque de tsunamis en raison de la fréquence élevée des tremblements de terre et glissements de terrain dans cette région. Les tsunamis historiques les plus destructrices, cependant, ont été dans le Canada atlantique - une en 1917 dans le port de Halifax, qui a été causé par une explosion catastrophique d'un navire transportant des munitions, et une autre en 1929 à Terre-Neuve, causé par un glissement de terrain le tremblement de terre déclenché à bord du plateau continental. Le risque de tsunami le long des côtes de l'Arctique canadien et sur les rives des Grands Lacs est faible par rapport à celle des côtes du Pacifique et de l'Atlantique. Le risque est posé par des glissements de terrain dans les fjords et anses le long de la côte de la Colombie-Britannique n'est pas pleinement apprécié.

1 INTRODUCTION

Canada has experienced many tsunamis, but few have caused damage. The most deadly tsunami in the country was triggered by the Grand Banks earthquake of November 18, 1929; it claimed 28 lives, all except one on Newfoundland's Burin Peninsula. Another deadly tsunami in Atlantic Canada resulted from the explosion of a munitions ship in Halifax Harbour on December 6, 1917. A third, large, destructive tsunami occurred in 1964 on the west coast of Vancouver Island following a great subduction zone earthquake in Alaska. A tsunami larger than any historical event could be triggered by a great earthquake at the Cascadia subduction zone, which underlies the seafloor of the eastern North Pacific Ocean. A landslide anywhere along a populated reach of the British Columbia coast also could generate a destructive tsunami. A large landslide at the Atlantic continental margin might trigger a tsunami like that in 1929 that would damage Canada's east coast. Finally, a landslide into a fjord or lake could produce a local destructive tsunami. This paper summarizes what is known about tsunami hazard and risk in Canada.

2 PHYSICAL BASIS FOR THE HAZARD

Tsunami is a Japanese word meaning *'harbour wave'*. The word has been adopted worldwide for long-period gravity waves generated by a sudden displacement of the water surface. The cause of this sudden displacement or release of energy is usually a submarine earthquake, but tsunamis can also be triggered by landslides, volcanic eruptions, human-made explosions, and the impact of bolides in the ocean. In deep water, tsunamis have amplitudes of less than 1 m, wavelengths of hundreds of kilometres, and move at velocities of up to 1000 km h^{-1}. Due to their long period, they behave as shallow-water gravity waves. Upon entering shallow water, a tsunami slows down and increases in height. Tsunamis may reach heights of 30 m or more at the shore, although most tsunamis arrive are less than 1 m high when they come ashore.

3 TSUNAMI TYPES IN CANADA

Canadian tsunamis can be subdivided into two groups for the purpose of hazard assessment. *Earthquake-triggered tsunamis* are generated by distant and local earthquakes. Distant sources are subduction zones bordering the Pacific Ocean, including the Cascadia subduction zone off the west coast of Vancouver Island and the Pacific coasts of Washington and Oregon. Local sources include active faults beneath the Canadian continental shelf. They affect a much smaller section of the coastline than tsunamis triggered by subduction zone earthquakes. *Landslide-triggered tsunamis* occur in lakes, fiords, inlets, and rivers.

4 TSUNAMI HAZARD

A popular misconception about tsunamis is that a single, very large wave breaks onto the shore. A tsunami, however, is not a single breaker, but rather a series of waves separated by minutes to an hour or more. The waves commonly are turbulent, onrushing surges (Figure 1) and not simple breakers, as is common with wind-generated waves. When one wave overtakes another, however, a steep wall of turbulent water, or *bore,* may be created. In some areas, a tsunami may be less energetic, with water levels rising rapidly, but no strong landward surge of turbulent water.

Tsunami hazard is normally evaluated from the maximum wave height or run-up. Run-up is the horizontal and vertical distance the wave floods inland (inundation). Because inundation depth depends on the height of the wave at the shore and local topography, vertical run-up is commonly used to quantify tsunami hazard. Hazard obviously increases with increasing vertical run-up. Any run-up exceeding 1 m is considered dangerous.

Figure 1. Tsunami of the 2011 Tohoku earthquake arriving at the shore in Natori, Japan. Note the strong landward surge of turbulent seawater. (Newscom/Kyodo/ WENN.com.)

The shallow water dynamics of tsunamis are complex and not fully understood. Wave amplitude and run-up are dependent (1) on the size, spatial extent, and speed of the perturbation that sets the waves in motion; (2) offshore bathymetry; (3) shoreline orientation and shape; and (4) onshore topography. Gentle bottom slopes are conducive to wave breaking, whereas steep slopes produce strong wave reflection with little or no breaking. Other topographic effects include focusing, attenuation, formation of edge waves, formation of bores, and resonance in harbours, bays, and inlets. Because topography varies along most coasts, run-up may differ considerably over even short distances, making it difficult to assess local hazard. For example, the 1993 Hokkaido Nansei-Oki tsunami ranged in height from 5 to 30 m over a 500 m length of coast on Okushiri Island in Japan. In general, however, run-up is small on steep shorelines and is higher at the heads of shallow broad bays and some long inlets, and along straight shorelines fronting broad shallow offshore areas.

5 HISTORIC TSUNAMIS

5.1 Pacific Coast

The west coast of Canada is located along the Pacific *Ring of Fire* and is vulnerable to tsunamis generated by earthquakes beneath the Pacific Ocean (Figure 2). The largest tsunamis in British Columbia result from great (magnitude 8 or larger) earthquakes at the Cascadia subduction zone where the oceanic Juan de Fuca plate moves underneath North America. The British Columbia coast is also affected by tsunamis of more distant Pacific earthquakes. In fact, the largest tsunami to strike British Columbia in historical time was generated by the great (magnitude 9.2) Alaska earthquake of March 27, 1964.

The 1964 Alaska earthquake triggered primary and secondary tsunamis that killed 130 people, some as far away as California. The primary tsunami caused extensive damage on Vancouver Island – it sank a fishing boat and damaged log booms at Ucluelet, damaged wharf facilities at Tofino, breached the municipal water pipeline that crosses the sea floor near Tofino, destroyed an Indian village at Hot Springs Cove, and swept buildings off their foundations at Zeballos. Damage was greatest, however, at Port Alberni, located at the head of Alberni Inlet. The sea surged up Somass River at a velocity of about 50 km h^{-1} and spilled onto the land, inundating whole neighbourhoods with chest-deep water. The second and most destructive wave in the wave train splintered the ground floor of the Barclay Hotel, located 1 km from the river. As the water subsided, some buildings were dragged seaward. Two hundred and sixty homes in Port Alberni were damaged by this tsunami, sixty extensively, and the total economic loss in the town was about $5 million (1964 Canadian dollars).

Tsunamis of more local extent, triggered by landslides and shallow crustal earthquakes also pose a hazard to people and property on the west coast of British Columbia and Alaska, especially in steep-walled fiords and inlets that indent the coast. The 1964 Alaska earthquake triggered a large (~75 000 000 m^3) submarine slump near Valdez, Alaska, which produced a local tsunami that destroyed waterfront facilities and the fishing fleet. The slide and accompanying tsunami were responsible for the loss of 30 lives, nearly 25% of all the casualties of the earthquake. More recently, in November 1994, a submarine landslide at the head of Taiya Inlet, just outside Skagway, Alaska, triggered a local tsunami with waves up to 9-11 m high at the shoreline. The tsunami killed one person and destroyed more than 300 m of a cruise ship dock that was under construction at the time.

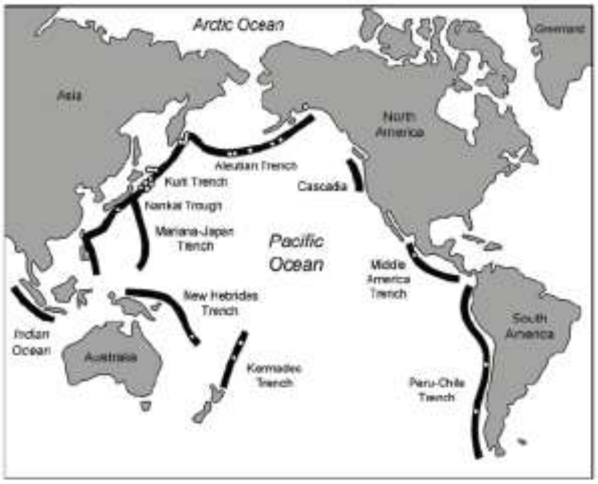

Figure 2. Most large tsunamis in the Pacific Ocean have been triggered by great earthquakes at the subduction zones (black bands) shown in this figure. Circles locate the sources of tsunamis larger than 10 cm in height that were recorded at the Tofino tide gauge on the west coast of Vancouver Island between 1905 and 1981. (Clague, 2001, fig. 3.)

Several submarine landslides in Kitimat Inlet, a fiord on the northern British Columbia coast, triggered tsunamis between 1952 and 1968 and also in 1971 and 1974. The largest historic tsunami in the area, however, occurred on the morning of April 27, 1975. Two or possibly three large waves were generated by the 1975 landslide; the largest had a peak height from crest to trough of 8.2 m. The waves moved rapidly to the head of the inlet and into connecting bays and inlets. The landslide occurred about one hour after low tide, suggesting that an ephemeral decrease in buoyancy and yield stress triggered the event. The underlying cause of the landslide, however, is the presence of unstable, late Quaternary glaciomarine and deltaic sediments at the sides and head of Kitimat Inlet. The 1975 event involved two major, contemporaneous failures – a landslide in sensitive glaciomarine clay on the west wall of the fiord and a larger failure of sediments on the slope of the Kitimat River delta. Similar unstable sediments are present in most fiords on the British Columbia coast; thus local, landslide-triggered tsunamis are possible in many areas other than Kitimat Inlet.

Fortunately, most people on the west coast of Canada live around the Strait of Georgia, an area of low tsunami risk (Figure 3). The greatest risk is to small communities on western Vancouver Island (e.g., Tofino, Ucluelet, Port Alberni), but the total population at risk in these communities is about 5000, which is much smaller than the number of people living within the tsunami inundation zone on the Pacific coasts of Oregon and Washington.

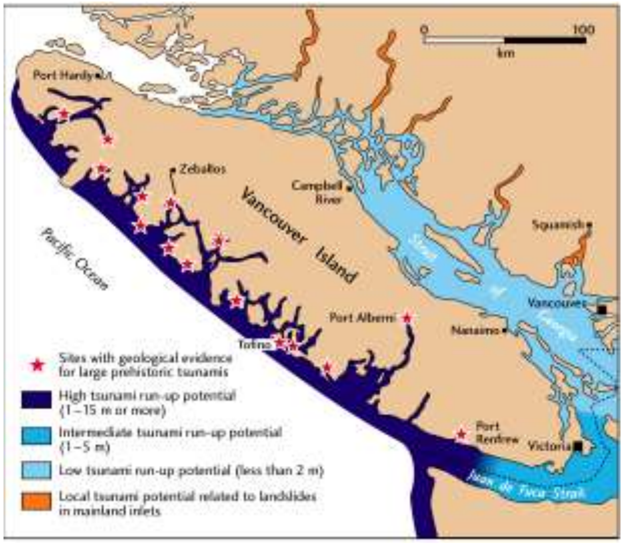

Figure 3. Tsunami hazard map, southwestern British Columbia. The map shows four generalized hazard zones, as well as sites with evidence for large prehistoric tsunamis, the location of the 1975 Kitimat tsunami (inset), and maximum wave heights of the 1964 Alaska tsunami. Details on four important recent tsunamis are given at the bottom. Southwestern British Columbia is the only part of the Canadian coast where sufficient information exists to produce a map like this. (Clague *et al.*, 1999, fig. 13.)

5.2 Atlantic Coast

A large crustal earthquake or a submarine landslide at the edge of the Atlantic continental shelf could generate a tsunami that might damage the east coast of Canada. Most Atlantic tsunamis are destructive only near their source, but a distant, huge submarine landslide could generate a very large tsunami with wide impact.

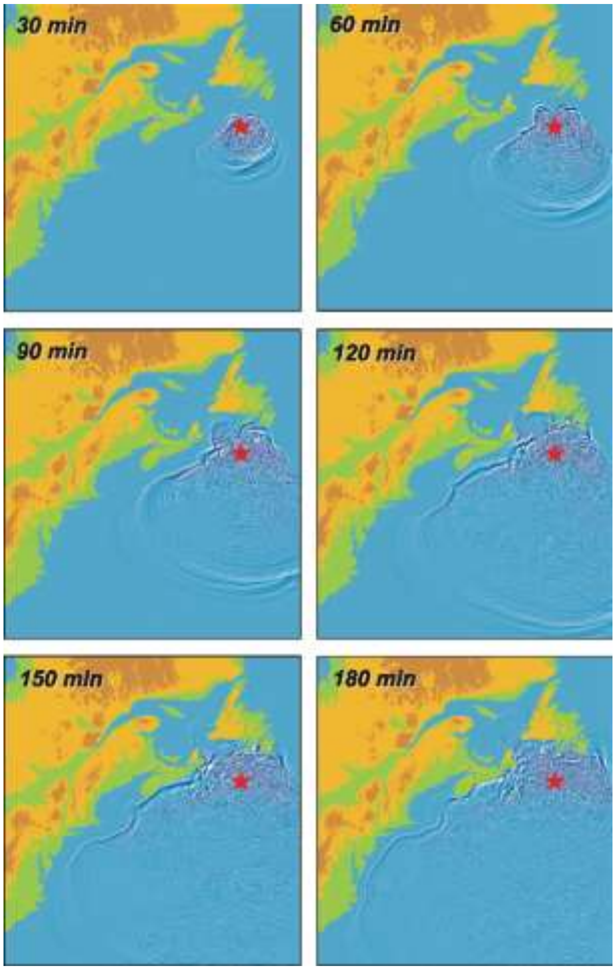

Figure 4. Snapshots of the simulated tsunami of the 1929 Grand Banks earthquake 30, 60, 90, 120, 150, and 180 minutes after the earthquake-triggered landslide. The star shows the location of the earthquake epicentre. (Fine *et al.*, 2005, fig. 5.)

There have been only two destructive historical tsunamis in Atlantic Canada – one in 1917 in Halifax Harbour and the other in 1929 in Newfoundland. The Halifax Harbour tsunami was triggered by a massive chemical explosion and thus was not a natural event. Shortly before 9 a.m. on December 6, 1917, the munitions ship *Mont Blanc* collided with the relief ship *Imo* in the Narrows of Halifax Harbour. The *Mont Blanc* was carrying the equivalent of about 2630 tonnes of TNT. A fire broke out on the *Mont Blanc*, and the crew abandoned the ship, which then drifted onto the Halifax side of the harbour and grounded. A short time later, the cargo exploded, devastating a large section of the city. Nearly 2000 people were killed and 9000 injured. Some of the deaths and injuries are attributable to the tsunami that immediately followed the explosion.

On Monday, November 18, 1929, a magnitude-7.2 earthquake occurred about 20 km beneath the sea floor at the southern edge of the Grand Banks, 250 km south of Newfoundland (Figure 4). The shaking triggered a huge submarine slump. The slump, in turn, set off a tsunami that propagated across the Atlantic Ocean, registering on tide gauges as far away as South Carolina and Portugal. Burin Peninsula of Newfoundland was hardest hit by the tsunami. Three main waves swept up narrow channels and into bays over a half-hour period. The first wave was preceded by an unusual withdrawal of water, which left anchored boats in coastal communities high-and-dry. In some areas, this withdrawal was followed by a turbulent onrush of water, probably a bore. The tsunami lifted small boats and schooners 5 m high, snapping anchor chains and tossing the craft onshore or engulfing them. Houses floated from their foundations; some were splintered, whereas others were swept back and forth by the flooding and ebbing waters (Figure 5). The tsunami damaged more than 40 coastal communities on Burin Peninsula and claimed 27 lives in Newfoundland and one in Nova Scotia.

Figure 5. Coastal communities on Burin Peninsula bore the brunt of the 1929 tsunami. This photograph shows buildings in Lord's Cove that were tossed and smashed by the tsunami. (Photo by Harris M. Mosdell, from the collection of W.M. Chisholm; provided by A. Ruffman.)

The recurrence interval for an earthquake of the size of the 1929 event is probably between a few hundred years and 1000 years. Even if an earthquake of this size were to occur off Canada's east cost, it might not trigger a tsunami unless it vertically displaced a large area of the sea floor. There is a greater hazard that such an earthquake could indirectly generate a destructive tsunami by triggering a submarine landslide, as happened in 1929. A large tsunami-generating landslide could also occur independently of an earthquake, although there is no historical precedent for such an event.

5.3 Arctic Coast

Little is known about the tsunami hazard in Arctic Canada. No significant tsunamis have been reported in this region, and no geological evidence has been found for prehistoric tsunamis. Although moderate and large earthquakes occur in some parts of the Arctic, for example Baffin Bay and Beaufort Sea, the presence of extensive sea ice greatly reduces the possibility of a large tsunami any- where in the region.

5.4 Lakes and Rivers

Some lakes or rivers bordered by steep, unstable slopes or lakes containing actively growing deltas could experience landslides that trigger tsunamis. In August 1905, millions of cubic metres of Pleistocene glaciolacustrine sediments slid into the Thompson River at Spences Bridge in southwest British Columbia. The landslide produced a wave 5-6 m high that rushed more than 1.5 km upstream, destroying 20 buildings and drowning 15 people. Three years later, in 1908, a landslide occurred suddenly on the Liève River in western Quebec. It generated a displacement wave that overwhelmed part of the village of Notre-Dame-de-la Salette, killing 27 people. In December 2007, 2-3 Mm^3 of rock plunged into Chehalis Lake in the southern Coast Mountains of British Columbia and triggered a tsunami that stripped forest up to 25 m above the lake surface and impacted the entire 18 km perimeter of the lake (Figures 6 and 7). Three campsites, which fortunately were unoccu- pied at the time of the event, were destroyed.

Figure 6. Scar of landslide that entered Chehalis Lake on December 4, 2007, triggering a tsunami that affected the entire perimeter of the lake. (Photo by John J. Clague.)

6 PREHISTORIC TSUNAMIS

Sand sheets deposited by prehistoric tsunami have been found in mud and peat deposits in protected tidal marshes at many sites on western Vancouver Island, Washington, and Oregon (Figure 8). They are evidence that large tsunamis have struck the Pacific coast repeatedly during the Holocene. The sand sheets thin, fine, and rise in a landward direction, and commonly contain marine microfossils, indicating that they were deposited by landward surges of water. Some of the sand sheets directly overlie buried peaty or forest soils that subsided during large earthquakes. The earthquakes that generated the tsunamis occurred on the large thrust fault separating the subducting oceanic Juan de Fuca plate and the overriding continental North America plate (a region referred to as the Cascadia subduction zone). Analogues for these prehistoric subduction earthquakes include the great earthquakes in Chile in 1960 and Japan in 2011, both of which produced widespread crustal subsidence in the source areas and destructive tsunamis that crossed the Pacific Ocean.

Figure 7. Tsunami trimline along the shore of Chehalis Lake; landslide scar in the middle distance. Photo panorama by Nick Roberts),

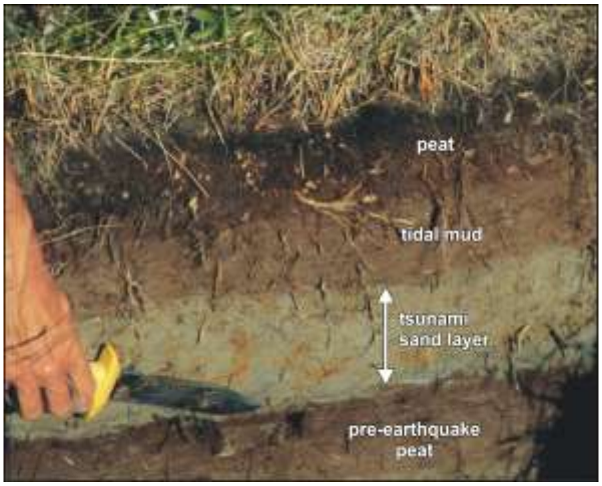

Figure 8. Tsunami sand in a tidal wetland near Tofino, British Columbia. The tsunami was triggered by the most recent great earthquake at the Cascadia subduction zone in January 1700. The sand sharply overlies brown peat that represents a former tidal marsh surface that subsided during the earthquake. (Photo by John J. Clague.)

Tsunami deposits also have been found in low-lying coastal lakes in Oregon and on western Vancouver Island. Tsunamis enter coastal lakes by surging up outlet streams or by crossing sand dunes that lie between some of the lakes and the sea. The most complete record found to date is from Bradley Lake in Oregon, where there are 14 tsunami layers in a sequence spanning the last 7500 years.

So far, evidence for prehistoric tsunamis has been found only on Canada’s west coast, but similar evidence possibly exists in Atlantic Canada. A layer of 8000-yearold sand, which has been found in coastal areas of eastern Scotland, western Norway, and Iceland, was deposited by a large tsunami triggered by a gigantic submarine landslide in the North Atlantic Ocean. On the basis of the known extent and character of the deposit, the tsunami may have been large enough to leave a trace on the far side of the Atlantic, in Canada. It is also possible that other submarine landslides or large earthquakes, like the Lisbon, Portugal, earthquake of AD 1755, triggered large tsunamis that have struck Atlantic Canada.

7 RISK TRENDS

Hazard can be defined as the probability that a harmful event of a particular type and size will occur within a specified period of time. Tsunami hazard probably does not change systematically over timescales of centuries and longer. Although hazard non-stationarity is possible on shorter scales due to non-random recurrence of earthquakes and landslides, temporal randomness is likely on long timescales.

Tsunami risk, on the other hand, is increasing in Canada. Risk is a function, not only of hazard, but also social and economic factors, including vulnerability and coping capacity. Vulnerability can be defined as the latent state of an element of value (i.e., people and societal infrastructure), representing their susceptibility to a hazard. Coping capacity is the ability to respond to, and reduce the negative impacts of, a hazardous event.

Tsunami risk is increasing on both the Pacific and Atlantic coasts of Canada due to the increase in population along shorelines that could be impacted by tsunamis and, more importantly, to the rapid growth in fixed property (residential, commercial, and industrial) along these shorelines. Although, as discussed in the following sections, the risk of injury and loss of life from tsunamis can be reduced, the economic risk cannot easily be lessened. Although Canada's coastlines are not at risk from the huge losses that Japan suffered from the tsunami of the 2010 Tohoku earthquake (over US $200 billion) (Figure 9), possible losses are increasing due to continued development of shorelines that are within potential tsunami run-up zones. Likely large-scale industrial development on British Columbia's north coast related to exports of oil and natural gas must take into account the possibility of earthquake- and landslide-triggered tsunamis.

8 PREPAREDNESS AND MITIGATION

Tsunamis cannot be prevented, but the damage they cause can be reduced through a variety of actions. Hazard reduction measures are of two types: *non-structural*, which include land-use controls (zoning, relocation, and property acquisition), emergency preparedness, and public education; and *structural*, which include dyking, barrier construction, flood proofing, and tsunami-resistant construction. An essential first step in any tsunami hazard reduction program is an assessment of the nature and level of risk for each coastal community.

Figure 9. Damage from the 2011 Tohoku tsunami in Japan (yaeyaminippo.busness.com).

8.1 Tsunami Hazard Assessment

Tsunami prediction is not possible, but risk to coastal communities can be assessed by estimating the frequency, size, and probable impacts of tsunamis. Historical records and geological data provide information on tsunami frequency and size. Maximum possible tsunami heights along a reach of the coast are estimated using numerical models and the distribution of historic and prehistoric tsunami deposits. Maps can then be produced showing areas likely to be inundated by tsunamis with various return periods. These maps can be used to guide or restrict development in tsunami-prone areas and to educate people living in these areas about the risk they face. Numerical models also provide estimates of tsunami arrival times, currents, and forces on structures,

8.2 Land-Use Controls

The first objective of any hazard reduction program is protection of life. Public safety may require that certain uses of land in high-hazard areas be restricted through zoning regulations or by relocating property owners to higher ground; however, as a rule, these types of action are strongly resisted by residents who would be affected by them.

8.3 Warning Systems

Protection of life also requires that there be an effective system in place to warn people of an approaching tsunami and to provide timely evacuation. The principle objective of a tsunami warning system is to provide accurate and timely notification of an impending tsunami in order to protect life and property, A secondary objective is to inform and educate people living within tsunami risk zones so that they are prepared to respond when warnings are issued.

Warning systems, however, are useful only when the source of the tsunami is far from populated shores. The travel times of far-field tsunamis are sufficiently long that threatened low-lying areas in British Columbia could be evacuated following alerts. Where the source of the tsunami is less than about 100 km away, there is insufficient time to warn and safely evacuate people, and no warning is possible when local landslides trigger near-source tsunamis. In any case, property within the inundation zone that cannot be quickly moved is likely to be damaged or destroyed.

There are three types of tsunami warming systems in the Pacific Ocean: a Pacific-wide system (the Pacific Tsunami Warning Center) located in Hawaii and operated by the U.S. Government; regional systems, including the West Coast and Alaska Tsunami Warning System, located in Alaska; and local systems in Chile and Japan. All three systems use earthquake magnitude and location to trigger warnings and coastal tidal stations to verify tsunamis.

Emergency Management BC is the agency designated by the British Columbia Government to disseminate tsunami bulletins issued by the Pacific Tsunami Warning Center and the West Coast and Alaska Tsunami Warning Center. It is responsible for evaluating tsunami information received from the warning centres and for deciding on appropriate follow-up action in British Columbia. The Canadian Hydrographic Service (CHS) provides Emergency Management BC with information on tsunamis in real time based on data transmitted from warning stations (Langara Island, Winter Harbour, and Tofino) and from the Pacific and Alaska tsunami warning centers.

CHS also provides forecast information based on numerical modeling. Maximum wave heights and current velocities have been estimated for 185 sites on the British Columbia coast for simulated tsunamis originating from Alaska, Chile, the Aleutian Islands, and Kamchatka. The most vulnerable regions are the outer coast of Vancouver Island, the west coast of Haida Gwaii, and the central mainland coast.

Although useful, tsunami warning systems have rarely provided reliable measurements of wave heights. A large local earthquake and tsunami can damage tide gauges or communication systems, limiting the usefulness of real-time tsunami observing systems. In the case of Pacific-wide tsunami warnings, it is difficult to tell from a few tide gauge recordings what the wave heights will be at other, more distant locations. Depending on their locations with respect to earthquake source, tide gauges may provide misleading information about the tsunami. A tsunami in Japan in October 1997 produced high waves near the source, leading to a warning for the entire Pacific coast of North America. The waves that reached British Columbia, Washington, Oregon, and California, however, proved to be insignificant. The costs of such false alarms can be considerable; for example, a tsunami warning that triggered the evacuation of Honolulu on May 7, 1986, cost Hawaii more than $30 million in lost salaries and business revenues.

How well tide gauge data represent a tsunami depends on the design and location of the gauges. The stilling wells of tide gauges filter out the wind waves and swell that commonly ride on top of tsunami waves. They also limit the highest and lowest tsunami heights that can be measured by the gauge. Many tide gauges are located in harbours where waves may be attenuated or amplified. Ideally, a tsunami-observing network should include gauges that record the full range of possible waves, are shock-hardened, independently powered, report in real time, and are located at exposed coastal and offshore sites.

Wave measurement devices now record the passage of tsunamis in deep water. NOAA operates a network of deep-ocean reporting stations that can track tsunamis and report them in real time. The network comprises sensitive ocean-bottom sensors that detect the increased pressure from the additional volume of water produced when a tsunami wave passes overhead (Figure 10). The sensors transmit the pressure measurements to a buoy at the ocean surface, which then relays the information to a ground station via satellite.

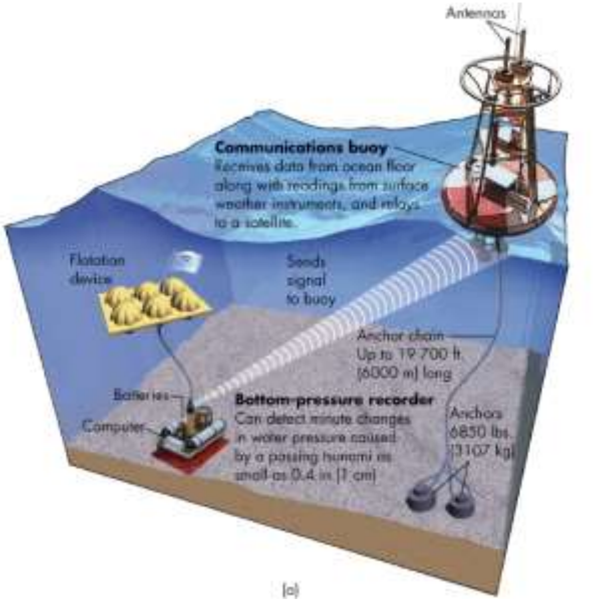

Figure 10. The Deep Ocean Assessment and Reporting of Tsunamis (DART) Project is an ongoing effort by NOAA to detect and report tsunamis in the open ocean. DART stations are located in regions with a history of destructive tsunamis to ensure early detection and to acquire data essential for real-time forecasts. A DART system consists of an anchored seafloor bottom pressure recorder, which can detect tsunamis as small as 1 cm in height on the open ocean, and a companion moored surface buoy for real-time data communication. The data are relayed via a satellite link from the buoy to ground stations, where they are processed and disseminated to NOAA's Tsunami Warning Centers. (Clague et al. 2007, p. 150.)

8.4 Education

Even the most reliable tsunami warning system is ineffective if people do not respond appropriately. Because tsunamis are infrequent, their recollection, as with any rare natural hazard, fades with time, leading some communities into a false sense of security. This fact was tragically illustrated during the catastrophic tsunami in the Indian Ocean in December 2004. Over 230,000 people in 14 countries perished in this tsunami; a large percentage of the victims failed to heed the warning provided by the sudden unprecedented withdrawal of water from the shore prior to the arrival of the wave. Education is therefore essential if communities are to become more resilient to tsunamis. In this context, public awareness of the nature of tsunamis, the chance of one occurring, areas likely to be affected, and correct response to tsunami warnings, are important.

8.5 Structural and Other Measures

Structural hazard reduction measures provide protection from tsunamis either by preventing them from inundating low-lying areas or by lessening their impact on buildings. Dykes and walls can be constructed to prevent waves from reaching threatened residential and commercial areas, although these structures are expensive and should be built to the highest possible level that can be reached by a tsunami. In some cases, offshore barriers can deflect tsunami waves or lessen their energy before they reach the shore. Again, these structures are expensive structures and may provide only limited protection. They are economically feasible only where large populations are at risk, where the threatened shoreline is at the head of a bay or inlet, and only in wealthy developed countries.

In areas of high tsunami hazard, buildings can be designed or protected to reduce water damage. Elevation of buildings and other types of flood proofing (e.g., installation of seals for basement windows, bolting houses to their foundations) provide protection where water depths are 1 m or less. Structures can be elevated to higher levels to provide greater protection, but costs may be prohibitive. Some houses near the shoreline on the Hawaiian Islands, for example, have been built on piers, their floors elevated 2-3 m above ground level.

8.6 Response and Recovery

With adequate warning, emergency personnel will evacuate people in areas threatened by an approaching tsunami. It is questionable, however, whether people with little or no understanding of tsunamis will respond to an order to evacuate. Past experience with tsunamis suggests that many people remain in, or return to, their homes in order to remove possessions, only to be caught in the onrushing waters. In any case, some tsunamis reach the shore with insufficient advance warning to effect an evacuation.

Unlike earthquakes, tsunami damage is restricted to the coastal zone. Aid thus is quick to arrive in affected communities served by roads and airports. The response may be much slower in remote communities, especially in developing countries with little capacity to deal with natural disasters. Damaged areas may be reoccupied and rebuilt with little or no appreciation of the fact that similar tsunamis may recur in the future. Where the loss of life is large, however, governments may restrict or prevent development in tsunami inundation zones.

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