

Tsunami Hazard to North and West Vancouver, British Columbia

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Summary

We evaluated the possibility that people and property at shorelines in North Vancouver and West Vancouver are at risk from tsunamis. The main sources for these waves are:

- great earthquakes at the Cascadia subduction zone, located off the west coast of Vancouver Island, Washington, and Oregon
- great earthquakes at other subduction zones around the Pacific Rim
- large, shallow earthquakes on **faults**¹ beneath the Strait of Georgia
- a landslide at the front of the Fraser River **delta** west of Richmond
- a landslide into Howe Sound or Indian Arm

In order to assess this risk, we examined historical records, native oral traditions, and simulation models of tsunami behaviour. Most importantly, evidence of tsunami inundation was sought in geological archives of the Fraser River delta in Richmond, Delta, and Surrey. Sites such as marshes and bogs that are most likely to record and preserve tsunami deposits were targeted for coring. The 33 cores collected in the summer of 2005 preserve sediments dating as far back as 4000 years ago. Analysis of the sediment sequences in the cores was supplemented by a re-evaluation of the sediment sequences in the Fraser River delta marshes and bogs described in the scientific literature.

A computer simulation model indicates that a great earthquake at the local plate boundary (Cascadia subduction zone) would generate tsunami waves 1 – 2 m high in Boundary Bay south of Delta, but only 0.5 m high at the western shore of the delta bordering Richmond and even less at the shorelines of North Vancouver and West Vancouver. The last great earthquake occurred in AD 1700. No deposits from the tsunami generated by this event, or those generated by earlier plate-boundary earthquakes, were found in the bogs in Delta and Richmond municipalities, or in the tidal marshes of Boundary Bay, Mud Bay, and the Campbell River estuary. The absence of deposits suggests that the threat to North Vancouver and West Vancouver by tsunamis from this source is very low.

Historical records show that earthquakes at plate boundaries elsewhere in the Pacific Ocean (such as the Alaska tsunami of 1964) do not represent a threat to North Vancouver and West Vancouver.

Ruptures on suspected upper-plate faults underlying the southern Strait of Georgia might generate tsunami waves at the North Vancouver and West Vancouver shorelines. The lack of evidence of tsunami inundation around Boundary Bay and in western Richmond, however, indicates that no significant tsunamis have been generated from this source in the last 4000 years.

Computer models of large subaqueous block slides on the western foreslope of the Fraser delta indicate that waves about 2 metres high would strike adjacent shorelines shortly after the landslide. No evidence of such waves was detected in the geological record, suggesting that such waves, if they occur, are extremely rare.

¹ Bolded technical words are defined in the Glossary.

1 Scope of report

The first section of the report provides an overview of tsunamis – what they are, how they are generated, their characteristics, and their impacts. We then detail the record of historic tsunamis in British Columbia. We then provide an assessment of the tsunami hazard to North and West Vancouver (hereafter, the ‘North Shore’) by evaluating (1) the potential threat from distant and local tsunami sources, (2) the geological history of tsunami inundation of low-lying areas along the shores of the southern Strait of Georgia and (3) the inundation risk for the North Shore using GIS generated maps. We provide a list of recommendations for preparedness, mitigation, and response strategies for the North Shore municipalities. These recommendations are based on generic mitigation strategies that other communities in the Pacific Northwest use to reduce the impact of tsunamis on their population and coastline.

2 Anatomy of a tsunami

Tsunamis are waves in the ocean or lakes generated by the sudden vertical displacement of the seafloor or lake floor by earthquakes (Fig. 1), volcanic eruptions, or underwater landslides. Tsunamis can also be produced by large landslides into the sea and, much more rarely, by asteroid impacts. Earthquake-triggered tsunamis are also called seismic sea waves and, erroneously, ‘tidal waves,’ as they have nothing to do with tides.

Tsunamis are very different from waves generated by winds. Tsunamis are ‘body waves,’ where energy is propagated by wave forms that involve the entire body of water through which they move. In contrast, wind-generated waves involve only the uppermost few tens of metres of the sea and even less of the water column in a lake. This distinction explains the huge difference in the amount of energy expended when the tsunami and storm-driven waves reach the shore.

Tsunamis generated by submarine earthquakes, which are the most common type, travel at speeds of up to 1000 kilometres per hour across the ocean with minimal loss of energy. In the open ocean, the waves are generally only a few tens of centimeters high and many tens of kilometres apart, but as they enter shallow water and approach the shore the distance between wave crests decreases and the waves may grow to heights of 10 metres or more (Fig. 2). Because of this, they can cause fatalities and destroy property around the entire margin of the ocean basin. Unlike earthquake-triggered tsunamis, waves created by landslides, whether triggered by earthquakes or not, have only a local impact.

The tsunami hazard at a particular location depends on the tsunami potential of the local area, the exposure of the shoreline to tsunamis traveling from distant sources, and the onshore and offshore topography of the coastal zone. All other things being equal, the larger the tsunami, the greater the damage and loss of life. The exposure of the shoreline, however, is equally important. In general shores that face in the direction the tsunami waves are traveling will be more severely impacted than shores oriented parallel to the tsunami travel direction. Another important factor is the steepness of the backshore area. Inundation will be restricted along shorelines that rise rapidly inland, whereas large tsunamis can run many kilometres inland on low-lying coastal plains. The tsunami in South Asia in 2004 reached up to seven kilometres inland in Aceh province in Sumatra. Tsunami waves can also grow in height in some bays and inlets. The city of Hilo on Hawaii is particularly vulnerable to tsunamis because Hilo Bay amplifies the waves. The 1964 Alaska tsunami was amplified by a factor of three as it moved up Alberni Inlet to Port Alberni. Finally, vegetation may lessen tsunami run-up and thus reduce risk. Forests at mid-

latitudes around the Pacific Ocean and mangroves in subtropical latitudes expend some of the energy of waves as they run inland.

Most tsunamis occur in the Pacific Ocean, which is bordered by the 'Ring of Fire,' a zone of earthquakes and volcanoes marking the boundaries between huge crustal plates that form the outer shell of earth (Fig. 3). The main sources of destructive Pacific tsunamis are large earthquakes at the Nankai Trough and Kurile Trench east of Japan, the Aleutian Trench south of Alaska and the Peru-Chile Trench west of South America.

Two examples serve to illustrate the devastation that can be wrought in the Pacific by earthquake-triggered tsunamis. In 1896, waves up to 35 m high struck the east coast of Japan, destroying more than 100,000 houses and drowning 27,000 people. A magnitude 7.3 earthquake in Alaska in 1946 generated a tsunami that was strong enough to wipe out both a lighthouse situated almost 10 m above sea level and a nearby radio antenna 35 m above the sea (Fig. 4). One of the most destructive tsunamis to ever strike the Hawaiian Islands, it killed 159 people and caused millions of dollars in damage.

Even these events, however, are dwarfed by the tsunami in the Indian Ocean in December 2004. At 7:58 am local time on December 26, 2004, the fault separating the India and Burma plates ruptured over a distance of 1200 kilometres along the Sunda Trench west of Thailand and Indonesia. As the Burma plate was thrust upward along the fault, it produced a giant **magnitude 9.3** earthquake, triggering a tsunami that radiated from the source at a velocity of over 700 kilometres per hour and left staggering human casualties and economic damage in its wake. Less than 30 minutes after the earthquake, the first waves reached the outer shores of northern Sumatra, drowning more than 100,000 people. Seawater surged up to 7 km inland and, at one site, reached up to 35 m above sea level. About one hour later, the tsunami devastated communities and tourist resorts of Thailand, Sri Lanka and southern India. Nearly 300 people died in waves 3 m high in Somalia, 5,000 km from the earthquake epicenter. With casualty estimates ranging from 150,000 to 300,000, the South Asian tsunami is by far the worst tsunami disaster in human history and one of the most lethal natural catastrophes of the last 100 years.

3 Past tsunamis in British Columbia

3.1 1964 Alaska tsunami

The only tsunami to cause damage in British Columbia during the historic period resulted from a great earthquake in southern Alaska on March 27, 1964. The earthquake was the third largest in history and triggered tsunamis that killed 130 people, some as far away as California. The main tsunami swept southward across the Pacific Ocean at a velocity of over 800 kilometres per hour and reached Port Alberni on Vancouver Island in six and one-half hours. Waves grew in size as they moved up Alberni Inlet and were two and one-half times larger at Port Alberni at the head of the inlet than at Tofino and Ucluelet on the open coast.

Three main waves struck Port Alberni between 12:20 AM and 3:30 AM on March 28. The first wave arrived at or near high tide. The sea surged up Somass River at a velocity of about 50 kilometres per hour and spilled onto the land, inundating neighbourhoods in chest-deep water (Fig. 5). This first wave peaked at 3.7 metres above mean sea level and knocked out the Port Alberni tide gauge. The second and most destructive wave arrived less than two hours later, at 2 AM. Logs and debris crashed into buildings, and houses were swept off their foundations and transported inland. As the water subsided, some buildings were dragged seaward. The second wave crested at 4.3 metres above mean sea level. The third wave, which arrived at about 3:30

AM, was the largest of all, but because the tide had fallen it crested at 3.9 metres and did little further damage. Other waves oscillated in Alberni Inlet, with decreasing strength for another two days.

Two hundred and sixty homes in Port Alberni were damaged by this tsunami and the total economic losses here and elsewhere on Vancouver Island were estimated at about \$50 million (2005 dollars).

Fortunately, tsunamis of this destructiveness are rare. Of the 176 tsunamis recorded in the Pacific Ocean between 1900 and 1970, only nine resulted in widespread destruction, and none other than the 1964 event significantly damaged British Columbia (Table 1).

3.2 1700 Cascadia tsunami

The last great earthquake and tsunami at the **Cascadia subduction zone**, where the **Juan de Fuca plate** is moving beneath the **North America plate**, occurred in 1700. Analogues for this event include the great **subduction earthquakes** in Chile in 1960 and Alaska in 1964, both of which produced destructive tsunamis that crossed the Pacific Ocean (Plafker, 1969, 1972; Plafker and Savage, 1970).

Japanese writings provide an exact age for the event. Tsunami waves up to 5 m high damaged sites along a 1000-km length of the east coast of Honshu on January 27-28, 1700 (Satake *et al.*, 1996; Tsuji *et al.*, 1998). The waves were not the result of a local earthquake, and there are no accounts of a great earthquake elsewhere in the Pacific Ocean that conceivably could be the source of the tsunami. Japanese researchers thus argued, by a process of elimination, that the tsunami was produced by a great earthquake off the west coast of North America. They further reasoned, from the size of the waves and the distance from the source, that the earthquake had a moment magnitude close to 9. After correcting for the travel time to Japan and the time zone difference, they concluded that the earthquake occurred on January 26, 1700, at about 9 p.m. local time. This conclusion agrees with oral traditions of North American coastal native peoples who describe the shaking and tsunami of a large earthquake at night in winter (Clague, 1995; McMillan and Hutchinson, in press).

The deposit of the 1700 tsunami is present in many tidal marshes and some low-elevation coastal lakes on Vancouver Island. In most areas, the 1700 deposit is coarser and thicker than the 1964 deposit, suggesting that the older tsunami was the larger of the two events at Vancouver Island.

4 Potential sources of tsunamis that might affect the North Shore

There are four possible sources of tsunamis at the North Shore: (1) great earthquakes at subduction zones bordering the North Pacific Ocean, (2) a large shallow earthquake on a fault beneath the Strait of Georgia, (3) a large landslide at the front of the Fraser River delta west of Richmond, where the delta slopes down into deep waters of the Strait of Georgia, and (4) a large landslide into Howe Sound or Indian Arm.

4.1 Subduction zone earthquakes

The **crustal plates** that underlie the Pacific Ocean are being subducted beneath continents around the perimeter of the ocean basin (Fig. 3). At each subduction zone the interface between the converging oceanic and continental plates is locked for long periods of time, and the accumulating strain compresses and deforms the continental margin. The accumulated strain is released every few decades or centuries in great (magnitude (M) ≥ 8) plate-boundary earthquakes.

During these earthquakes the sea floor above the locked zone abruptly rises, generating a tsunami, and the coastal zone suddenly subsides, with flooding of low-lying areas. After the earthquake the plate interface relocks, and the cycle begins again. The great ($M = 9.3$) earthquake that occurred off the coast of Sumatra in 2004 exemplifies the rupture process.

4.1.1 Earthquakes at the Cascadia subduction zone

Prior to 1987, assessments of tsunami hazard on the west coast of North America were based on the impact of distant Pacific-wide tsunamis, but in the last two decades scientists have recognized that the west coast of North America is also vulnerable to tsunamis generated at the Cascadia subduction zone

Studies of tidal marshes on the Pacific coast of North America that suddenly subsided during great ($M > 8$) earthquakes show that the Cascadia subduction zone ruptured five times in the last 2600 years (Atwater and Hemphill-Haley, 1997). Sheets of tsunami-deposited sand that record these, and earlier, plate-boundary earthquakes are widespread beneath marshes along the Pacific coasts of Oregon, Washington and British Columbia (Clague et al., 2000), at sites at the eastern end of the Strait of Juan de Fuca (Williams et al., 2005), and in some low-lying coastal lakes (Hutchinson et al., 2000; Kelsey et al., 2005).

Are tsunamis triggered by a great plate-boundary earthquake at the Cascadia subduction zone a threat to lives and property in the coastal lowlands of the Strait of Georgia? The last great earthquake at this plate boundary occurred in AD 1700 (Satake et al., 1996), and although there are no written records of the size or impacts of these waves, their devastating impact on coastal settlements on the outer coast of Vancouver Island is recorded in Native oral histories (McMillan and Hutchinson, 2002). As far as we are aware, however, there are no equivalent oral traditions of tsunamis from this event in the Strait of Georgia.

A computer model² showing the propagation of tsunami waves from a great earthquake at the Cascadia subduction zone has recently been developed by oceanographers at the Institute of Ocean Sciences in Sidney, British Columbia. The computer model provides a useful surrogate for direct evidence. Their computer simulation forecasts wave heights on the outer (west) coast of southern Vancouver Island and adjacent areas of Washington State, Juan de Fuca Strait, and neighbouring inland waters.

The simulation model predicts that a great earthquake at the plate boundary will generate tsunami waves about 5–10 metres high on the outer coast. These large waves gradually diminish in height as they move through Juan de Fuca Strait and the narrows between the San Juan and Gulf Islands (Fig. 6). The leading edge of the first wave is forecast to reach Vancouver about two hours and thirty minutes after the earthquake. Because Boundary Bay is oriented at right angles to the direction of wave travel, this wave grows to a height of about 1 metre. The second wave, which is approximately the same size as the first, arrives at about three hours and thirty minutes. A third, slightly smaller, wave arrives at about four hours and thirty minutes. By six hours this wave grows to almost two metres in height.

Note, however, that the magnitude of the waves generated by the computer model depends on assumptions about the size of the submarine earthquake and the deformation of the seafloor at the boundary between the two plates. In addition, because of data limitations the model does not estimate the extent and depth of tsunami inundation on land.

If these model predictions are valid, areas of the North Vancouver and West Vancouver foreshores might experience waves one to two metres high about two hours after a great

² http://www-sci.pac.dfo-mpo.gc.ca/osap/projects/tsunami/tsunamimodel_e.htm (note their disclaimer).

earthquake. Wave run-up would depend on the arrival time of the tsunami; it would be higher if it coincided with a high tide and lower if it arrived at a low tide. Wave run-up would also differ according to the orientation of the shore; north-facing shorelines would experience smaller waves than south-facing shorelines.

4.1.2 Earthquakes at other Pacific subduction zones

Of the subduction zones that surround the North Pacific (with the important exception of our local subduction zone), only the Alaska-Aleutian margin represents a significant tsunami threat to the west coast of Canada. Great earthquakes have ruptured this subduction zone six times in the last 4000 years. As mentioned above, tsunami waves up to six metres high devastated several communities on the outer coast of Vancouver Island on March 28, 1964, following the great Alaska earthquake. The island archipelagos at the northern and southern ends of the Strait of Georgia, however, effectively excluded the tsunami from these inland waters. Whereas at the eastern end of Juan de Fuca Strait the largest wave from the 1964 Alaska tsunami was one to two metres high (Williams et al., 2005), in the southern Strait of Georgia it diminished to less than 0.5 metre (Spaeth and Berkman, 1967). We conclude therefore that tsunamis triggered by distant plate-boundary earthquakes do not constitute a significant source of hazard to North Shore communities (Fig. 7).

4.2 Shallow local earthquakes

Earthquakes on faults within the North America plate represent an additional tsunami hazard to coastal communities of the Pacific Northwest. Faults in central and northern Puget Sound are known to have ruptured in large (M 7) earthquakes in the last few millennia. Some low-lying areas around Puget Sound were flooded by the tsunamis generated by these earthquakes. For instance, a sand sheet beneath the coastal marshes of Puget and Possession Sounds in northwest Washington State records inundation by a tsunami generated by an earthquake on the Seattle fault about AD 900-930 (Atwater and Moore, 1992; Bourgeois and Johnson, 2001). Other submarine upper-plate faults in northern Puget Sound have also possibly produced large earthquakes and tsunamis in the last few thousand years (Williams et al., 2005). The narrow, winding passages of this inland sea, however, cause rapid loss of tsunami wave energy, and we consider it highly unlikely that tsunamis generated by submarine earthquakes in Puget Sound or Juan de Fuca Strait have ever inundated the lowlands of the Fraser River delta.

What is less certain, however, is the tsunami potential posed by submarine faults beneath the Strait of Georgia? A number of east-west lineaments that have been identified on the sea floor of the Strait of Georgia may be fault-controlled, but the status of these faults remains unknown. If any of these faults are active, and if vertical displacement of the sea floor occurs during a future earthquake, then the ensuing tsunami would likely represent a significant hazard to coastal areas in the Strait that are oriented parallel to the fault zone.

4.3 Landslides at the front of the Fraser delta

In addition to the hazard represented by seismic tsunamis generated by plate-boundary earthquakes or upper plate earthquakes beneath the Strait of Georgia, seismic shaking may also cause subaqueous slides at the Fraser River delta front, which in turn may generate tsunamis. The unconsolidated sediments forming the delta front may also fail without a seismic trigger, and yet still produce a tsunami.

Landslide-induced tsunamis are particularly dangerous because the waves may locally be very large and the warning time very short. For example, in November 1994 a submarine slide in

Taiya Inlet (perhaps initiated by construction activities in the harbour) created a wave that reached a height of 9-11 metres at the shoreline in Skagway, Alaska, causing one fatality and over \$20 million of damage (Cornforth and Lowell, 1996).

It has long been recognized that the western slope of the Fraser delta is at high risk from submarine landslides (Terzaghi, 1956). The Fraser River discharges about 17 million tonnes of sediment into the Strait of Georgia each year (Currie and Mosher, 1996), and much of this sediment accumulates on the steep frontal slope of the delta. Small slides are common in this unconsolidated material. For example, between 1970 and 1985 five flow slides are known to have occurred on the western delta slope. These were likely all shallow slides that moved down the delta front over a period of hours and consequently did not produce tsunami waves (McKenna et al., 1992).

Rabinovitch et al. (2003) investigate two potential modes of failure at the southwestern delta front. They conclude that a large slide could generate tsunami waves up to 18 m high on the eastern shores of Galiano and Mayne Island, but that waves at the shorelines of North and West Vancouver would likely not exceed a few metres, even if they coincided with high tide.

4.4. Landslides in Howe Sound or Indian Arm

A large, sudden landslide from a steep slope bordering Howe Sound or Indian Arm, or from the delta front at the mouth of Squamish or Indian Rivers, could trigger a tsunami that would travel south along these **fiords** and possibly damage Sunset Beach, Horseshoe Bay, or parts of Deep Cove. The waterfronts of North and West Vancouver, however, are not at risk from such a tsunami. Perhaps the most spectacular landslide-generated tsunami in recent time occurred in Lituya Bay, southeast Alaska, in 1958. A landslide triggered by a large earthquake plunged into the head of the bay and generated a huge displacement wave that surged up to 525 metres up the opposite valley wall and was still more than 10 metres high at the bay mouth, 8 kilometres from its source (Miller, 1960). Similar, although much smaller tsunamis claimed xx lives in fiords in Norway in the twentieth century.

The probability of a landslide-triggered tsunami in Howe Sound or Indian Arm is very low, although not zero. No such event has occurred since the time of European settlement more than 150 years ago, and no slopes bordering the fiords are known to be unstable. In the unlikely event of such a tsunami, its size at Sunset Beach, Horseshoe Bay, or Deep Cove would depend on the size and character of the triggering landslide and on the distance of these communities from the tsunami. A large (>10 million cubic metres) landslide in southern Howe Sound or Indian Arm might produce damaging waves several metres high in Sunset Beach, Horseshoe Bay, or Deep Cove. Landslide-triggered tsunamis, however, decrease in size rapidly as they move away from their source, thus a landslide at the head of Howe Sound or Indian Arm might not damage these communities.

5 Documenting past tsunamis from the geological record

In the previous section we documented sources of potential tsunamis that might affect North Shore communities. In this section we suggest that these sources can only be realistically evaluated if telltale tsunami deposits are found in the sediments of neighbouring lowlands.

This geological approach to tsunami hazard assessment is based on the observation that when tsunami waves recede, the inundated area can be determined by mapping the sediments they have left behind. If new sediments are quickly deposited on top of the tsunami sediment, the tsunami event is archived in the geological record. If these tsunami deposits can be identified and

dated, then it becomes possible to reconstruct the history of tsunamis at that location. This approach has been used to determine the incidence of tsunamis on the outer coast of Vancouver Island (Clague *et al.* 2000), in Puget Sound (Atwater and Moore, 1992), Juan de Fuca Strait (Williams *et al.*, 2005), and the Fraser River delta south of Vancouver (Clague *et al.*, 2005).

5.1 2005 field work

One of the authors of this report (Clague) and Dr. Ian Hutchinson completed a survey of sites on the Fraser River delta and adjacent low-lying areas in the summer of 2005. This area was targeted for detailed study because it lies at sea level and because wetlands such as Burns Bog and Serpentine Fen contain a continuous sequence of organic sediments (peats and carbon-rich silts) that extend back several thousand years. Any large tsunami in the Strait of Georgia would leave a landward-thinning layer of sand in these wetlands.

A total of 33 cores were retrieved from sites where the likelihood of tsunami deposit preservation was highest. Cores were retrieved using an Eijkelpamp hand-coring device with a 1 m long barrel and a 4 centimeter barrel diameter. Extensions were added to the coring barrel to reach coring depths of up to 5 metres. On retrieval, cores were measured and described. Core logs were drafted from these field descriptions.

Results of the field survey are summarized in Clague *et al.* (2005). The key result, of relevance to North Shore communities, is that no tsunami deposits were found in Richmond, Delta, or other areas of the Fraser River delta. Clague *et al.* (2005) could not completely rule out the possibility that tsunamis have inundated portions of the Fraser River delta in the past. They could safely say, however, that the tsunami threat to the Fraser delta lowlands, and by extension the North Shore, is very small.

6 Tsunami inundation risk maps

The maximum predicted run-up data from the model discussed in Section 4.1.1, was used to generate 10 maps showing tsunami inundation risk for North and West Vancouver (Figs. 8 to 17). The maps were generated in ArcGIS Version 9.0 and ArcView 3.2 using digital elevation data and photographs supplied by the municipalities. All of the maps are at a scale of 1:13 000. For display purposes, the North Vancouver and West Vancouver waterfront areas were arbitrarily divided into three and seven zones, respectively.

6.1 North Vancouver

The North Vancouver tsunami inundation risk maps were produced using a raster digital elevation model (DEM) with a 2 x 2 m cell resolution supplied by the District of North Vancouver. The DEM was overlain with ortho-rectified aerial photographs with 0.1 x 0.1 m cell resolution, also supplied by the District of North Vancouver. Inundation risk is expressed using four, conservative categories:

1. Moderate risk - areas between 0 and 1.5 m above mean sea level
(approximate annual probability of inundation = 0.005-0.01)
2. Low risk for areas between 1.5 and 2.5 m above mean sea level
(approximate annual probability of inundation = 0.0001-0.005)
3. Very low risk for areas between 2.5 and 3.0 m above mean sea level
(approximate annual probability of inundation = <0.0001)
4. No risk for areas higher than 3.0 m above mean sea level

The categories were plotted using the elevation data contained within the DEM. As a result, inaccuracies and artifacts within the DEM determine the reliability of the inundation risk zones, particularly in areas where contour lines are close.

6.2 West Vancouver

The West Vancouver tsunami inundation risk maps were produced using a different procedure from that used to produce of the North Vancouver maps. The GIS data were supplied as 1 m and 5 m ESRI Shape files, and it was necessary to produce a rasterized DEM to complement the data presented for North Vancouver. A DEM of 4 x 4 m resolution was produced by rasterizing the 1 m contour data. A 50 m coastal slice was then extracted from the DEM using elevations of 1 m and 50 m as limiting bounds. The ESRI shape files were supplied without a 0 contour, thus several offshore artifacts were produced during the DEM interpolation phase. These artifacts were removed by creating a 5 m buffer on the sides of the 1 m contour line and an auto-closing polygon on the seaward side of the 5 m buffer zone. This closed polygon was set to 'not data' and used to clip the DEM. By this procedure, we were able to extend the DEM classification to mean sea level (0 m).

Inundation risks are expressed using the same four, conservative categories as for the North Vancouver waterfront:

1. Moderate risk - areas between 0 and 1.5 m above mean sea level
(approximate annual probability of inundation = 0.005-0.01)
2. Low risk for areas between 1.5 and 2.5 m above mean sea level
(approximate annual probability of inundation = 0.001-0.005)
3. Very low risk for areas between 2.5 and 3.0 m above mean sea level
(approximate annual probability of inundation = <0.001)
4. No risk for areas higher than 3.0 m above mean sea level

These categories were plotted using the elevation data contained within the DEM and overlain on 0.75 x 0.75 m resolution ortho-rectified images of West Vancouver supplied by the City of West Vancouver. Errors are probably higher for the West Vancouver DEM than for the North Vancouver DEM, because the accuracy of the former is based primarily on the accuracy of the contour line data supplied and the ArcGIS interpolation algorithms. Nevertheless, the maps show excellent accordance between the interpolated DEM and the coastline on the overlain imagery.

7 North Shore tsunami risk

Based on the foregoing field and GIS based analyses, we conclude that the likelihood of North or West Vancouver being struck by a damaging tsunami is very low. It is difficult to quantify "very low," but the absence of tsunami evidence in geological archives bordering the southern Strait of Georgia and spanning more than 4000 years suggests that the annual probability of a tsunami with waves greater than 2.5 metres high is no greater than 1 in 1000 (i.e., one tsunami every 1000 years, on average) and more likely 1 in 5000 or less (one tsunami every 5000 years). A tsunami with 1.5-2.5 metre waves has a somewhat higher annual probability, but probably no greater than 1 in 200 (one such tsunami every 200 years), and perhaps much less.

Even though tsunamis pose little risk to North Shore communities, we adopt a conservative approach in displaying areas on the accompanying maps (Figs. 8 through 17) that are within the run-up zone of hypothetical 1.5-m and 2.5-m tsunamis that occur at high tide. Even in the unlikely, worst-case scenario, damage would be restricted to small areas.

The small risk to Lions Bay, Sunset Beach, and parts of Deep Cove derives entirely from local, landslide-triggered tsunamis in Howe Sound and Indian Arm. As mentioned previously, this risk is very low. The risk to the North and West Vancouver waterfronts derives largely from tsunamis triggered by large, shallow earthquakes beneath the Strait of Georgia. The largest possible tsunami of this type could produce run-ups of more than 2 metres on the North Shore, but this is a worst-case scenario with a very low likelihood of occurrence. Tsunamis triggered by great earthquakes at distant North Pacific subduction zones pose no risk to North Shore communities. Tsunamis triggered by great earthquakes at the Cascadia subduction zone would result in run-ups of less than 2 metres on the North Shore.

Although not within the mandate of our study, we conclude that severe storms pose a greater risk to North Shore coastal infrastructure than tsunamis. A severe winter storm in the 1990's caused nearly \$1 million damage to the Ambleside seawall. Wind-generated waves overtopped the seawall and, in a few places, eroded the adjacent bed of the BC Railway tracks. The waves reached up to 2 metres above mean sea level, similar to the maximum expected run-up of a tsunami in this area. The maximum size of wind-generated waves on the North Shore is a function of the maximum **fetch**, or distance of water over which the waves can be generated. In the case of Ambleside and Dundarave, the maximum fetch for southwesterly winds, which pose the greatest risk to the seawall, is 45 kilometres. The maximum run-up for waves generated by hurricane-force southwestern winds is 3 metres. Only the Ambleside, Dundarave and Erwin Park shorelines are at risk from storm-generated waves. The maximum fetch in Howe Sound, Indian Arm, and the inner harbour is too small to produce damaging waves.

8 Preparedness, mitigation, and response strategies

In this section, we explore strategies for tsunami preparedness, mitigation, and response that would allow North Shore municipalities to reduce economic losses in the event of an unlikely damaging tsunami. Based on the inundation risk maps, areas most likely to suffer damage are the Erwin Park shoreline, the seawall in the Ambleside and Dundarave areas, and localized areas in Deep Cove. Visitors to Caulfield Park might also be being swept off the rocks during a tsunami or storm surge. Infrastructure in these areas, including BC Rail rail line, is also at risk from inundation or erosion by a tsunami or, in the case of West Vancouver waterfront, storm-driven waves. Much of North Vancouver's waterfront is industrial. Only an extraordinarily rare tsunami would flood this area, but a smaller one could still damage boats, wharves, and the BC TransLink Sea Bus ferry terminal.

We recommend the following preparedness, mitigation, and response strategies for tsunamis.

8.1 Preparedness

1. **Waterfront access routes:** North and West Vancouver should identify access routes to higher risk waterfront areas, and all emergency personnel should be made aware of these routes. Municipalities should make plans to restrict use to waterfront access routes to emergency response personnel and vehicles in the event of a tsunami. This recommendation pertains not only to tsunamis and storms, but also to other, more common emergencies that might occur (waterfront fires, ship collisions).
2. **Training:** Emergency and city personnel should receive basic information on earthquakes and tsunamis.

3. **Monitoring:** We recommend that the municipalities subscribe to the tsunami warning email system operated by the US based Pacific Tsunami Warning System (<http://www.prh.noaa.gov/ptwc/>). The Pacific Tsunami Warning system provides tsunami alerts and warnings via email for the Pacific Coast of North America, including British Columbia.
3. **Emergency protocol:** Although outside the mandate of this report, we recommend that each municipality develop a tsunami response protocol in the event that a large earthquake occurs at the Cascadia subduction zone or in the Strait of Georgia.
4. **Public education:** We suggest that North and West Vancouver follow the lead of the Oregon Department of Geology and Mineral Industries, which has produced tsunami awareness brochures for municipalities along the Oregon coast. The brochures provide information on locally generated and far-traveled tsunamis, and appropriate responses. The warning time for locally generated tsunamis is short, thus coastal residents and visitors must recognize that strong ground shaking followed by a sudden change in sea level may be the signal of an imminent tsunami and that they should seek higher ground immediately. Far-traveled tsunamis are accompanied by longer warning times that allow emergency personnel to evacuate high risk areas if deemed necessary. We would be happy to prepare a brochure, flyer, or website material providing basic tsunami information if North or West Vancouver wishes.

8.2 Mitigation

1. **Warning signs:** North and West Vancouver may wish to place signs in higher risk areas indicating that those areas could be flooded during a tsunami or storm surge.
2. **Warning system:** Tsunami emergency sirens are used extensively along the Pacific coast of Oregon and Washington to alert residents and visitors of approaching tsunamis and to send all-clear signals. However, given the low probability of a damaging tsunami on the North Shore, we do not feel a tsunami emergency siren system is warranted.

8.3 Response strategies

In view of the low probability of a tsunami striking the North Shore, the most effective response strategy is to ensure that the tsunami access routes mentioned in Section 8.1 are identified and kept clear. Any large tsunami generated in the Pacific Ocean will take at least 3 hours to reach the North Shore, allowing sufficient time for emergency response if an appropriate plan is in place. In contrast, the warning time for a locally generated tsunami will be very short. In such a case, the most effective response strategy is to ensure that emergency crews have immediate access to risk areas.

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10 Glossary

Cascadia subduction zone: A 1000-kilometre-long zone off the coasts of northern California, Oregon, Washington, and Vancouver Island, where the *Juan de Fuca plate subducts*, beneath the *North America plate*.

Crustal or (tectonic) plate: One of the large, nearly rigid fragments that form the *crust* and upper *mantle* of the earth. Plates are 5 to 250 kilometres thick.

Delta: A low, nearly flat, triangular- or fan-shaped feature near the mouth of a stream or river. A delta is composed of sediment carried by a stream or river into the sea or a lake.

Fault: A fracture within the earth's crust along which rocks have moved past one another.

Fetch: The maximum distance across open water that winds can travel in a particular direction.

Fiord (or fjord): A deep, long, narrow, steep-walled inlet or arm of the sea along a mountainous coast. A fjord is the seaward end of a glacially eroded valley. Local examples are Howe Sound and Indian Arm.

Juan de Fuca plate: One of the plates forming the outer shell of the earth, located between the Pacific and North America plates west of northern California, Oregon, Washington, and Vancouver Island.

Magnitude: A measure of the amount of energy released during an earthquake. Numerous scales and measures of magnitude have been devised for different purposes, including the Richter scale and modern moment magnitude scale. Moment magnitude, favoured by seismologists, is a logarithmic measure of earthquake size, obtained by multiplying the rupture area of a fault by the amount of slip and the shear strength of the rocks.

North America plate: One of the large plates that forms the outer shell of the earth. It includes North America, part of Siberia, Greenland, and the western half of the Atlantic Ocean.

Subduction earthquake: An earthquake caused by the sudden slippage of one crustal plate over another at a subduction zone. Subduction earthquakes can be very large, up to magnitude 9.5.

Table 1 Twentieth century tsunamis recorded at Tofino, British Columbia

Date	Source area	Height of maximum wave (cm) ^a
November 1, 1915	Japan	12
May 1, 1917	Kermadec Islands	12
July 18, 1918	Indonesia	16
September 7, 1918	Kuril Islands	16
April 30, 1919	Tonga	15
November 11, 1922	Peru	27
February 3, 1923	Kamchatka	27
April 13, 1923	Kamchatka	15
March 7, 1929	Aleutian Islands	11
March 2, 1933	Japan	23
November 30, 1934	Mexico	22
November 10, 1938	Aleutian Islands	27
December 7, 1944	Japan	12
December 27, 1944	New Hebrides (Vanuatu)	12
April 1, 1946	Aleutian Islands	58
March 4, 1952	Japan	12
November 4, 1952	Kamchatka	58
March 9, 1957	Aleutian Islands	52
March 11, 1957	Aleutian Islands	18
November 6, 1958	Kuril Islands	10
May 22, 1960	Chile	126
October 13, 1963	Kuril Islands	16
March 28, 1964	South-central Alaska	240
May 16, 1968	Japan	12
May 16, 1968	Japan	13

Source: Wigen (1983, appendix B); only tsunamis with maximum wave heights of 10 cm or more are included.

^aSum of displacements of maximum wave and successive trough from corresponding tide levels.

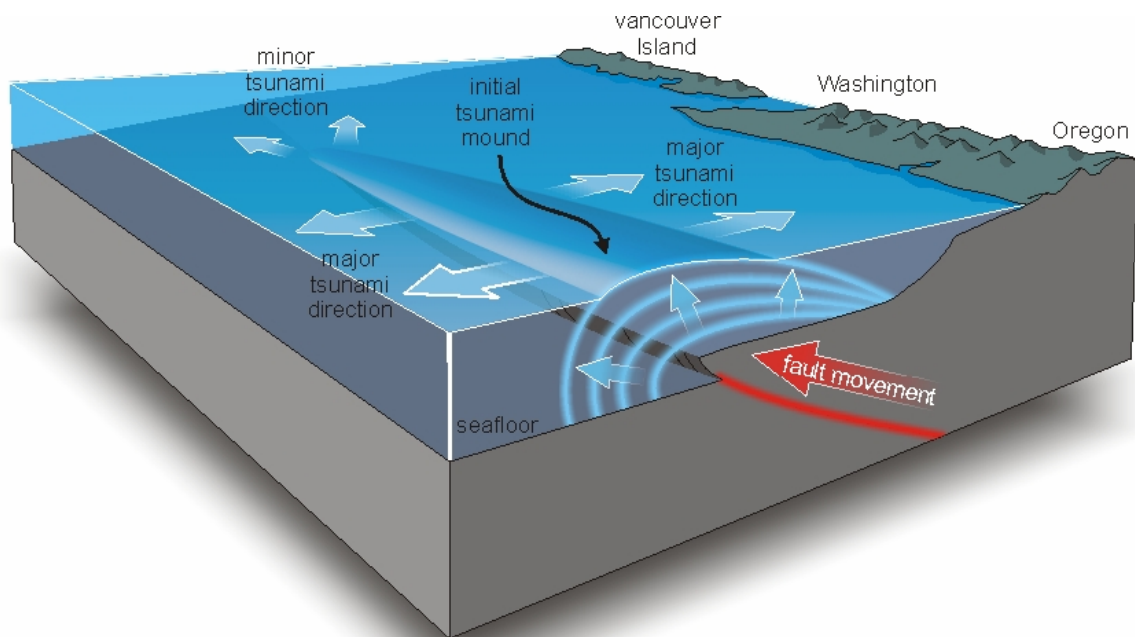


Fig. 1. The largest and most energetic waves of a tsunami travel in opposite directions away from the sea-floor rupture. Smaller waves move away from the fault in other directions.

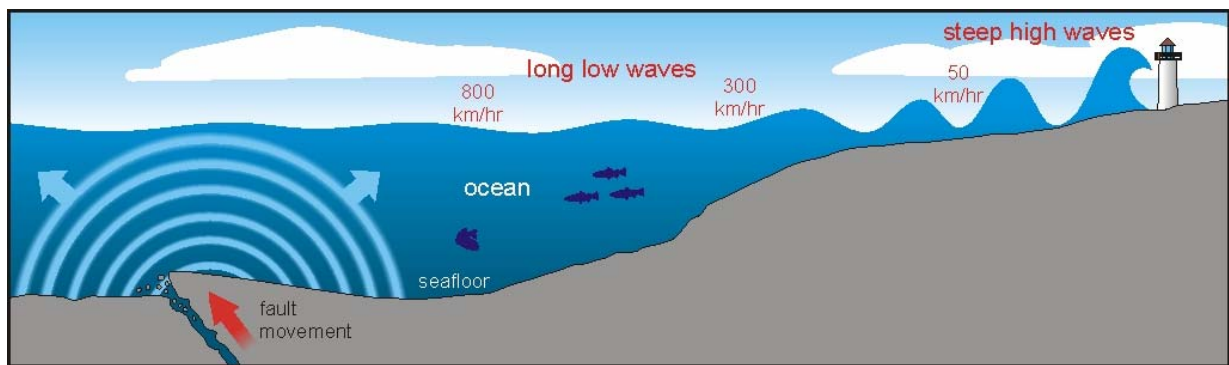


Fig. 2: Simplified diagram showing a tsunami triggered by rupture of the seafloor along a fault during an earthquake. The sudden upward displacement of the sea floor initiates waves of energy that move upward and outward from the source. As the waves shoal, they slow down, move closer together, and become higher. They then transform into turbulent, landward-surging masses of water that may run kilometres inland.

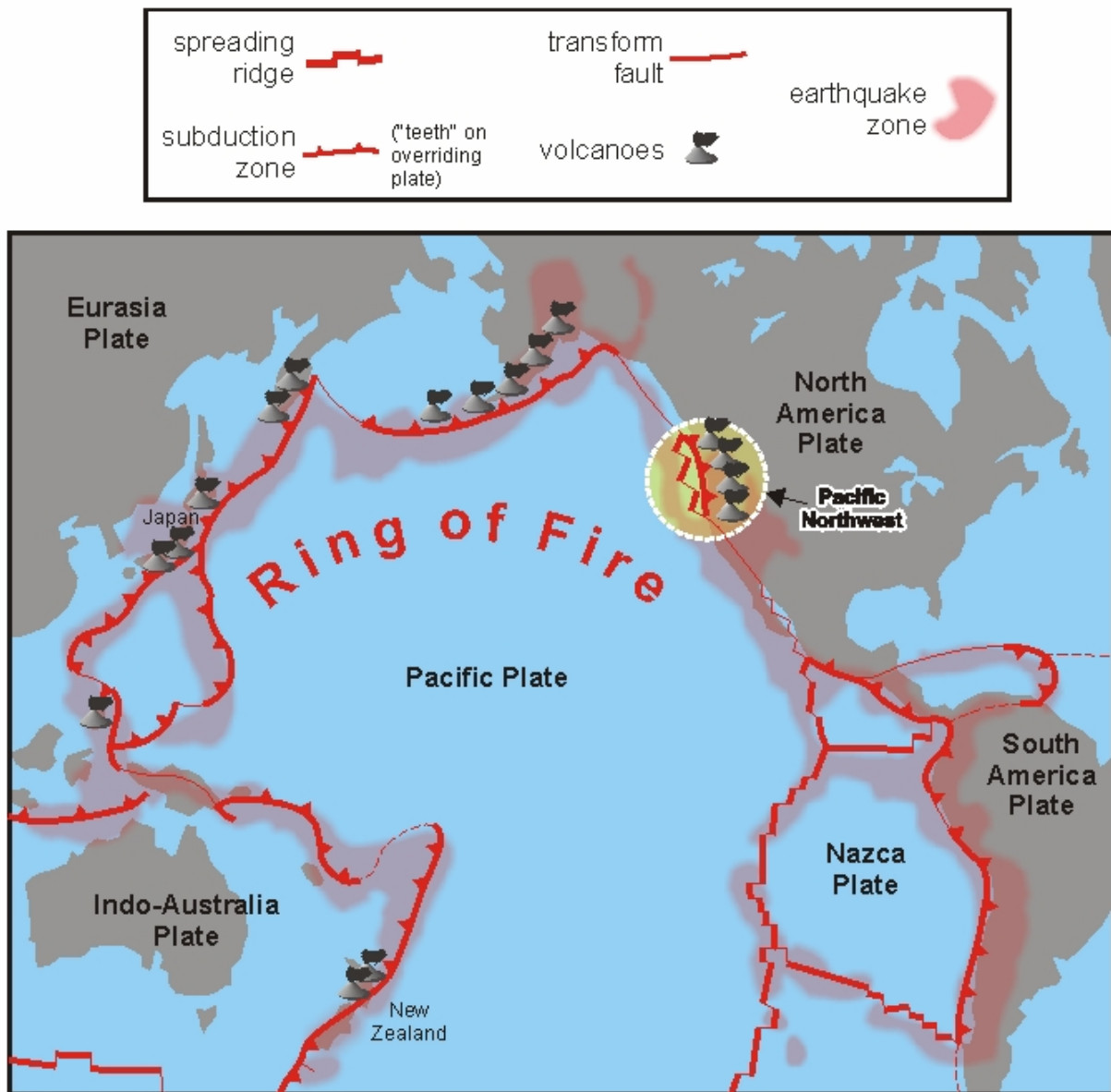


Fig. 3. Tsunami generation zones in the Pacific. The Pacific Ring of Fire is a zone of intense earthquake and volcanic activity ringing the Pacific Ocean. The coastal Pacific Northwest lies within this zone. It and others along the Pacific Ring of Fire are subduction zones, where the Pacific Plate moves beneath a series of continental plates. Most tsunamis are generated by large earthquakes at subduction zones.

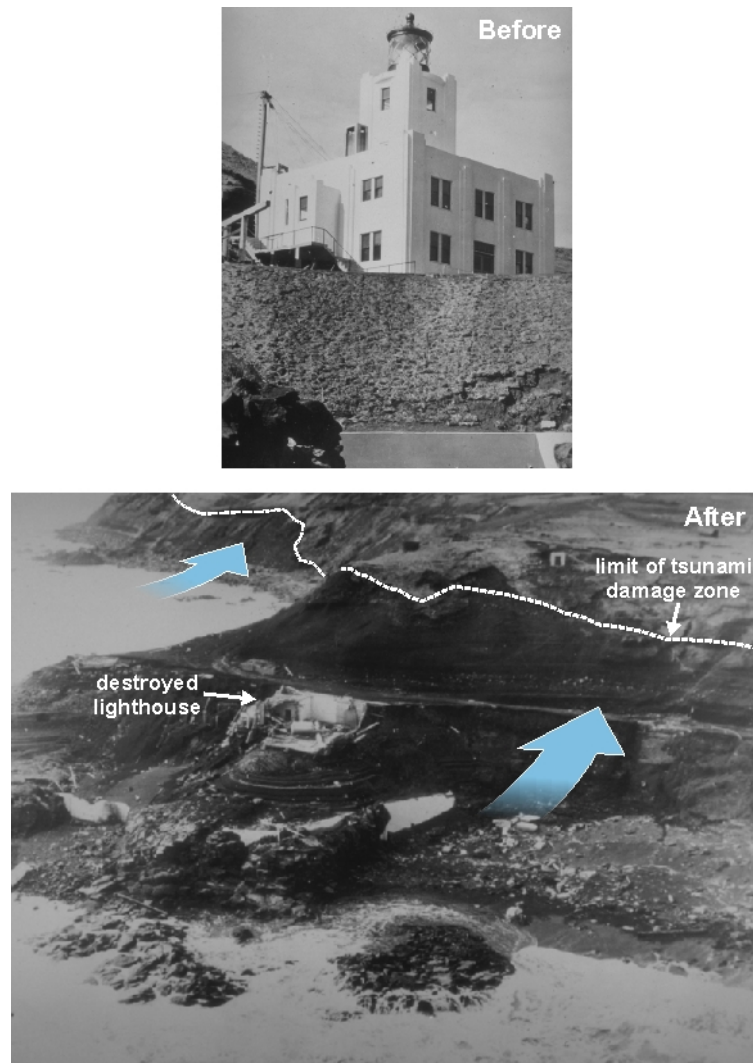


Fig. 4. The Scotch Cap lighthouse on Unimak Island, Alaska, was destroyed by a large tsunami triggered by a magnitude 8 earthquake on April 1, 1946.



Fig. 5. Car moved by the tsunami of the 1964 Alaska earthquake in Port Alberni, British Columbia, about 3000 kilometres from the epicentre.

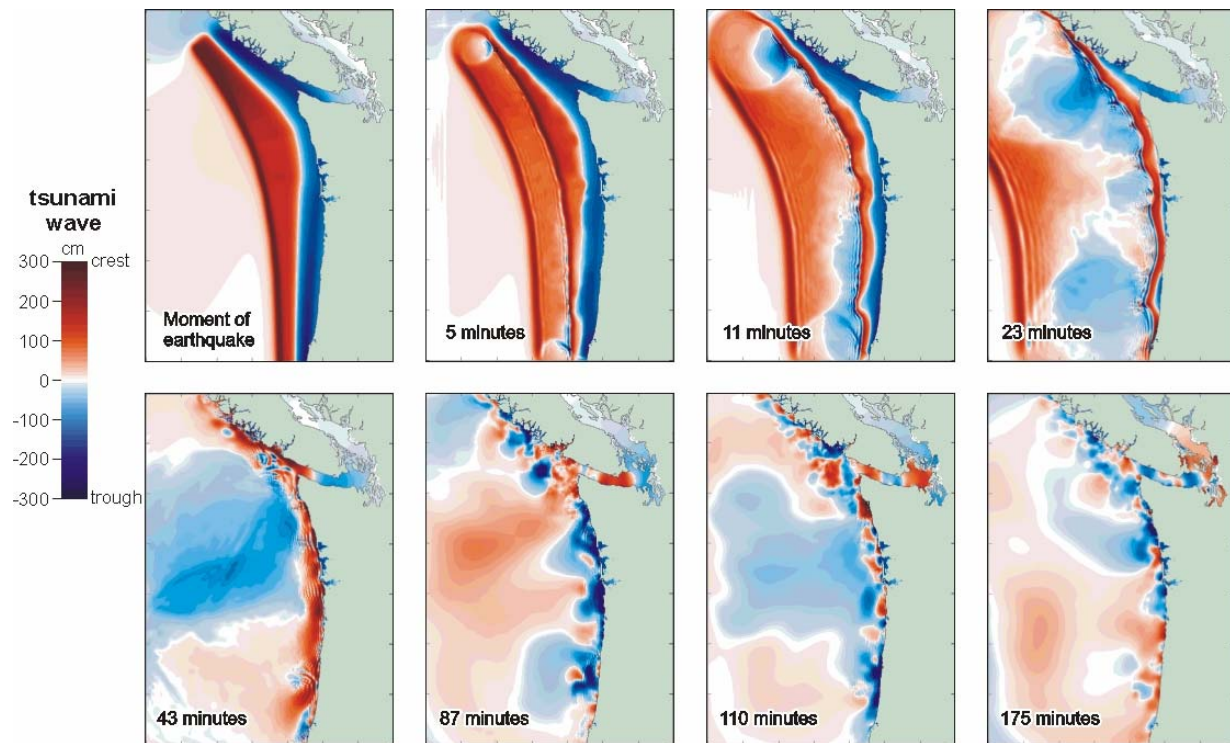


Fig. 6. Computer-simulated tsunami generated by the AD 1700 earthquake at the Cascadia subduction zone. The tsunami strikes the outer coast of North America with large waves and travels eastward along Juan de Fuca Strait. It amplifies in some west coast inlets, but attenuates as it moves through the southern Gulf Islands into the Strait of Georgia and Puget Sound.

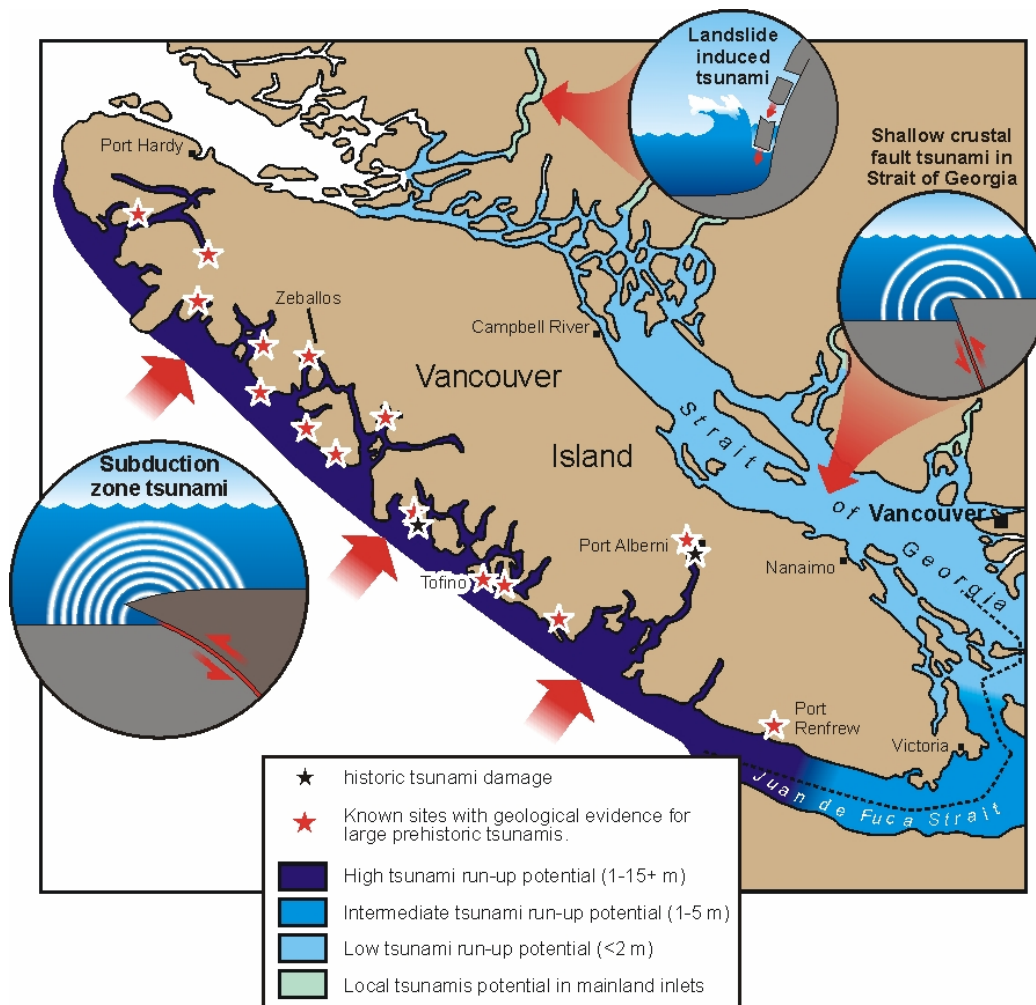


Fig. 7. Tsunami hazard zones in coastal areas of southwestern British Columbia. Western Vancouver Island is at risk from large tsunamis triggered by great subduction earthquakes beneath the Pacific Ocean. The tsunami risk in the Strait of Georgia is much smaller and is related to crustal earthquakes and undersea landslides. Local landslide-triggered tsunamis pose a hazard to some coastal communities, especially those at the heads of fiords.