Hazard Risk Analysis

Earthquakes, Tsunamis and Volcanoes

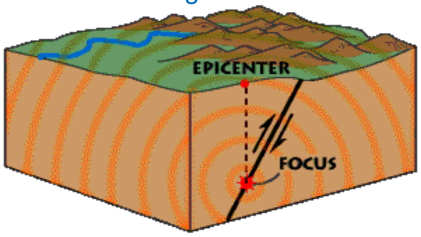
Earthquakes

Definition

Earthquakes are considered to be a special type of geological hazard. An earthquake is a series of waves that travel through the earth. Earthquakes often start where 'stress or pressure' along a fault becomes too strong for the rock, so that sudden movement occurs along the fault. The ground motion creates other hazards, namely surface faulting, changes in land elevation, ground failure, liquefaction and tsunamis.

The focus of an earthquake is the point where movement on the fault starts, and the point from where seismic waves radiate and travel through the earth. The epicentre is the point on the earth's surface directly above the focus. A fault is the surface along which a rock body has broken and been displaced.

Figure 1. Earthquake focus and epicentre. Thick black line is the fault surface, arrows show movement along the fault.



There are various ways earthquakes can cause damage, injury and death:

- **Shaking** and **ground rupture** are often the first signs of an earthquake. Violent shaking can severly damage buildings and infrastructure (especially bridges). Ground shaking can knock people off their feet. During an earthquake, the earth's crust not only vibrates, but segments of it are fractured and displaced, and cracks in the earth's surface open up. "Surface faulting" is the tearing of the Earth's surface by movement across a fault. Earthquakes are sometimes only felt very locally, but at other times earthquakes happen over larger regions.

- **Changes in land elevation** are a very common effect of earthquakes. Some parts of the Earth will be uplifted, whereas other parts may have sunk. These changes in land elevation have been known to change the course of river streams, or uplift parts of the coast line. The effects can be dramatic, as the uplift of the coast can cause marine life to die, and the sinking of land near rivers can cause serious flooding.

- **Liquefaction** (or **ground failure**) is another major effect of earthquakes. Liqefaction typically occurs in soils that have a high water content. The shaking from the earthquake increases the water pressure at shallow depths. Soil and sediment particles on top of this water will then start floating and flowing. Once the pressure in the underground water settles again, the soils and sediment will turn from a "liquid" to a solid again. Liquefaction can cause serious damage to buildings. Liquefaction is often described as "suddenly emerging quicksand." though that is a bit exaggerated. There are several signs of liquefaction to look for:

Figure 2. Lateral spreads caused by liquefaction of the soil (Photo: USGS Multimedia Gallery).

- **Lateral spreads** involve the sideways movement of large blocks of soil on the surface as a result of liquefaction in layers below (Fig.2). Lateral spreads generally develop on very gentle slopes (most commonly between 0.3 and 3 degrees) and move toward a free face, such as a stream channel. Lateral spreads often disrupt the foundations of buildings or other structures, rupture pipelines and other utilities in the failure mass.

Figure 3. Sand boil (Photo: www.showme.net).

- **Flow failures** are liquefaction-caused landslides that develop in loose sands or silts with a high water content, on natural or man-made slopes greater than 3 degrees. They often displace large masses of material for many metres at velocities ranging up to tens of miles per hour.

Figure 4. Buildings have toppled due to a loss of the bearing capacity of the ground (Photo: www.nap.edu).

- **Sand boils** or **sand blows** often form at the surface, and are small mounts of sand from which water squirts out of the ground (Fig.3).

- **Loss of bearing capacity** occurs when the soil supporting a building or other structure liquefies and loses strength. This process results in large soil deformations under load, allowing the structures to settle and tip (Fig.4). The loss of bearing capacity of a soil has been known to topple 4-story high buildings, collapse highway bridges and fail dams..

- Other hazards that are related to earthquakes are **fires**, **landslides** and the **outbreak of diseases**. The shaking during an earthquake can cause natural gas and oil (pipe)lines and electrical power lines to break, which can easily start fires. Landslides due to earthquakes can happen in any mountainous area, but especially in areas where the ground holds a lot of water (see “flow failures” above). The outbreak of diseases has happened as a result of very large earthquakes, when water and sewage lines are broken.

Some earthquakes are caused by human activity.The injection of fluids into deep wells for waste disposal, the recovery of oil and gas, and the use of reservoirs for water supplies have all been linked with the occurrence of earthquakes. Fortunately, most of these earthquakes are minor.

Discussion

Magnitude and Intensity

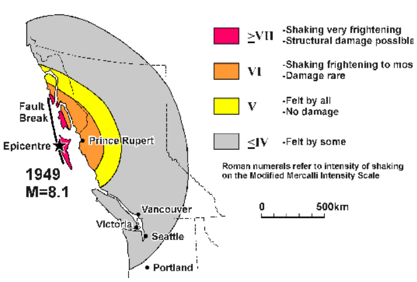
There are 2 ways to measure the effects of an earthquake: **Magnitude** or **Intensity**.

Magnitude is a measure of the amount of energy released by an earthquake. It is most commonly expressed as a relative magnitude on the Richter Scale (which measures the seismic wave amplitude on a logarithmic scale, to the base 10, as defined in 1935 by Charles R. Richter).

It is unusual for shocks smaller than magnitude 2 to be felt anywhere. Earthquakes with magnitude of 3 can be felt by humans when near the epicentre of the quake. Damage begins to occur to buildings at about a magnitude of 6. Any earthquake above magnitude 7 can be a major disaster if it occurs near a densely populated area. We don’t know much about earthquakes that happened in the past, as measuring equipment was not available to determine the magnitude of past earthquakes. Generally, most seismologists feel that historical earthquakes have not exceeded a magnitude of 9 to 9.2.

Seismic activity is also expressed in terms of felt intensities on the Modified Mercalli Scale. Each level of intensity is based on a description of how people have felt the earthquake and on the damage done to buildings and other structures. For example, buildings close to the epicenter of an earthquake often show more damage than buildings that are further away (see table with descriptions below). In Figure 5 you can see that the intensity close to the epicenter of the 1949 earthquake (area in red: shaking was very frightening and damage possible) was much higher than further away (area in grey: shaking was only felt by some).

Figure 5. The 1949 Queen Charlotte Earthquake



It is important to note the difference between the total energies given on the magnitude scale, and the felt intensities of the Modified Mercalli Scale. While an earthquake has only one magnitude, it has different intensities in different places.

Earthquake Felt Intensity - The Modified Mercalli Scale

I	Not felt except by very few people under special conditions. Detected mostly by instruments.
II	Felt by a few people, especially those on upper floors of buildings. Suspended objects may swing.
III	Felt noticeably indoors. Standing automobiles may rock slightly.

IV	Felt by many people indoors, by a few outdoors. At night, some are awakened. Dishes, windows, and doors rattle.
V	Felt by nearly everyone. Many are awakened. Some dishes and windows are broken. Unstable objects are overturned.
VI	Felt by everyone. Many people become frightened and run outdoors. Some heavy furniture is moved. Some plaster falls.
VII	Most people are in alarm and run outside. Damage is negligible in buildings of good construction, considerable in buildings of poor construction.
VIII	Damage is slight in specially designed structures, considerable in ordinary buildings, great in poorly built structures. Heavy furniture is overturned.
IX	Damage is considerable in specially designed buildings. Buildings shift from their foundations and partly collapse. Underground pipes are broken.
X	Some well-built wooden structures are destroyed. Most masonry structures destroyed. The ground is badly cracked. Considerable landslides occur on steep slopes.
XI	Few, if any, masonry structures remain standing. Rails are bent. Broad fissures appear in the ground.
XII	Virtually total destruction. Waves are seen on the ground surface. Objects are thrown in the air.

Faults

Surface faulting is an obvious hazard to structures built across active faults, such as buildings. In particular, surface faulting can be damaging for structures embedded in the ground (railway and highways) and for buried pipelines and tunnels. Sometimes however, faults are not visible at the surface and only show up after an earthquake has hit. The fault is then visible because the surface on one side of fault is higher than on the other side of the fault. Sometimes the fault offsets a structure built on it, like a fence or a road (Fig. 6).

Figure 6. A fence is offset by the San Andreas fault in California, USA. The line in red shows where the fault runs (Photo: www.smithsonianscience.org).

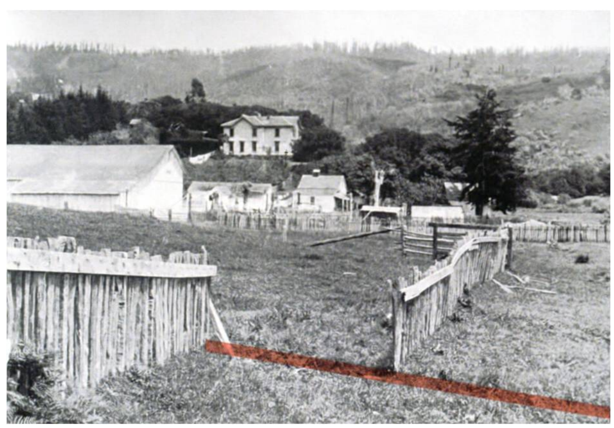
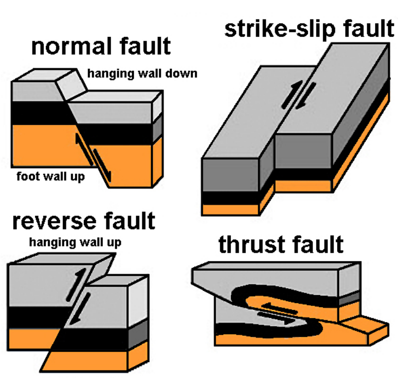


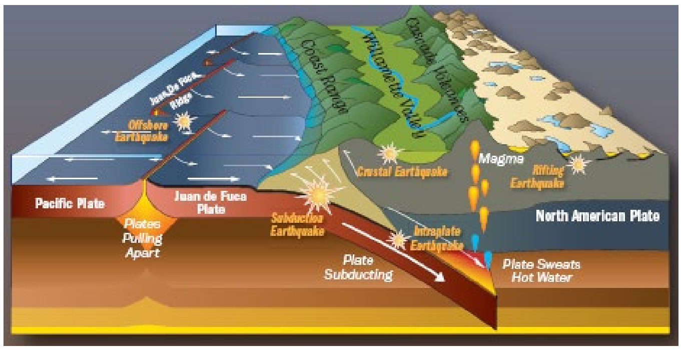
Figure 7. Normal fault, reverse fault, thrust fault and strike-slip fault (Image: www.geologycafe.com).



There are three basic types of fault ruptures (Fig. 7)

- **Normal Faults:** movement is mainly vertical and the rocks above the fault plane move downward in relation to those beneath the fault plane. Most normal faults are often steep, usually between 65 and 90 degrees. Movement along the fault is mostly vertical. Normal faults are commonly visible in the landscape as a cliff or scarp. In a “**Reverse Fault**” the movement is also mainly vertical, but in the opposite direction as in a Normal Fault. Reverse faults are also steep, which sets them apart from Thrust Faults (see below).

Figure 8 Cascadia Subduction Zone (photo credit Cape Meares Community Association)



- **Thrust Faults:** low angle faults in which the hanging wall has moved up and over the footwall. Movement on a thrust is mostly horizontal (but also vertical), and displacement can be more than 50 kilometers. They are prominent in all of the world's major folded mountain regions. In Canada, the province of British Columbia is at risk of experiencing a “mega-thrust” or subduction earthquake sometime in the (near) future. (See Figure 8). This earthquake could be a very big one, with a magnitude of M8 or M9. However, earthquakes are very hard to predict, and so we do not know when this earthquake could strike, or how big it will really be.

- **Strike Slip Faults:** high angle faults in which movement is horizontal, parallel to the strike of the fault plane. There is little or no vertical movement. Strike-slip faults are expressed in the landscape by a straight, low ridge extending across the surface. Sometimes these faults are not visible at all, and only show up because of displaced fences, roads, etc. (Fig. 6).

Seismic waves

The most important, and most noticed, effect of earthquakes is the violent ground shaking that occurs when there is movement along a fault. “Seismic energy” is released from a fault as “seismic waves.” These waves may cause damage to buildings, bridges and other structures near or on the earth's surface. There are 3 types of waves, so-calles “primary,” “secondary” and “surface” waves.Each type of wave travels through the earth at a different speed depending on the properties of the wave, and the material (rock, sediment or water) through which it travels.

Figure 9. A primary wave travels through the earth similar to a spring being pulled (Image: http://regentsprep.org).

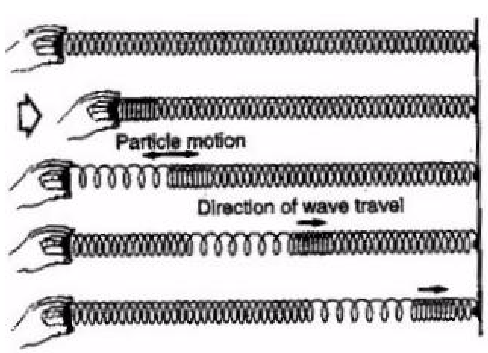
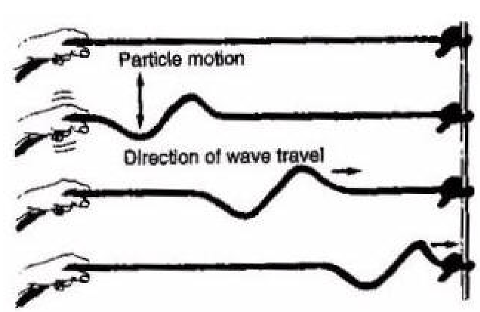
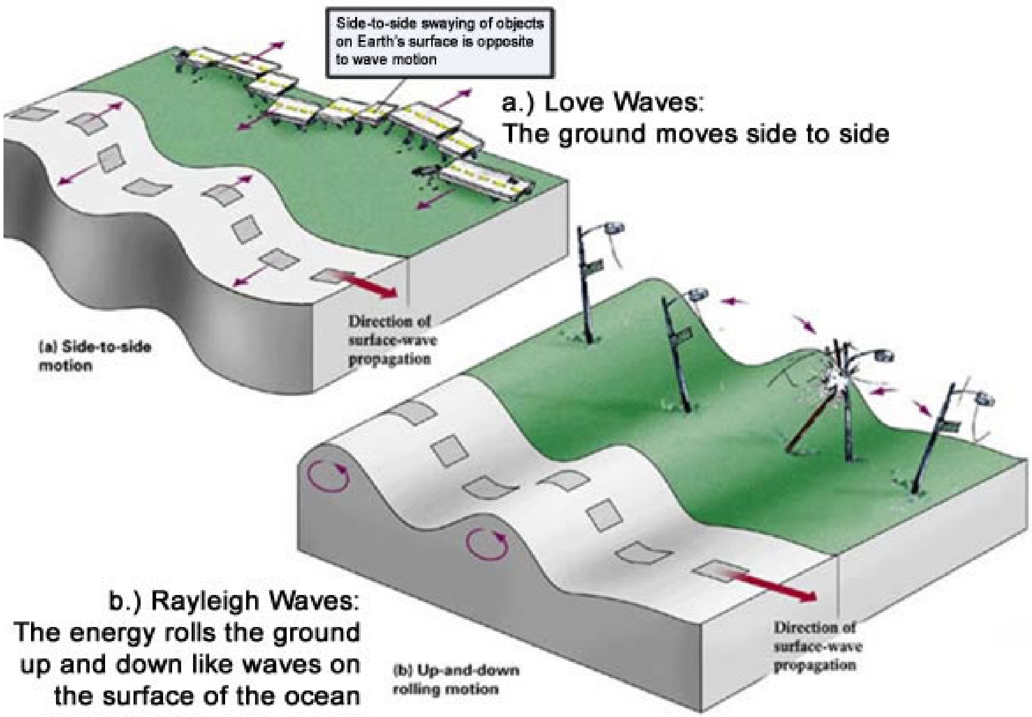


Figure 10. A secondary wave travels through the earth similar to the whipping of a rope (Image: http://regentsprep.org).



The fastest waves are the Primary (P waves) or "compression" waves. Primary waves are the first to arrive at the earth's surface. A primary wave compresses and stretches the rock through which it travels, similar to the way a spring responds to being stretched (see Fig. 9). Primary waves travel in crustal rocks at about five kilometres per second. Next in speed, are Secondary waves (S waves A secondary wave travels mostly in an up and down motion (at a straight angle to the direction the seismic wave travels), similar to the way a rope would respond to the whipping of a rope when held between 2 people (Fig. 10). Secondary waves travel through the earth's crust at about three kilometres per second. Surface waves (also called Rayleigh and Love waves) are the slowest moving, and travel near the surface of the earth with a speed of less than three kilometres per second. Surface waves cause the most damage near the epicenter of the earthquake, because of their complex motion. A surface waves moves similar to an object floating on the ocean, or by a complex horizontal and vertical motion (Fig. 11).

Figure 11. Surface wave motion. Love waves (upper) move mostly in a complex side-ways motion. Rayleigh waves move in a rolling up-and-down motion (Image: www.seismolab.caltech.edu).



It Happened Here…

Naturally Caused Earthquakes

On July 3, 2019 a Mw 63 earthquake occurred 211 km from Bella Bella, B.C. It was lightly felt on northern Vancouver Island and adjacent mainland coast and no tsunami occurred.

On October 21, 2018 a strong magnitude 6.8 earthquake occurred on off the coast of Vancouver Island, 174 km from Port Alice, B.C. There were no reports of damage.

On October 28, 2012, a major magnitude 7.7 earthquake occurred early in the morning below Haida Gwaii island (formerly known as Queen Charlotte Islands) off the west coast of Canada. It was felt across much of north-central BC, including Haida Gwaii, Prince Rupert, Quesnel, and

Houston. There were no reports of damage. Numerous aftershocks of M3 to ~5 in the hours following. A tsunami warning was issued for the coastal areas

On September 9, 2011, a Mw 6.3 earthquake occurred 91 km WSW of Gold River, B.C. This earthquake occurred about 50 km off the west coast of Vancouver Island. It was felt across southwest British Columbia, including Vancouver Island, Greater Vancouver, and as far away as Kelowna. There were no reports of damage. The last large earthquake in this area was a M 6.6 event on November 2, 2004. 13:00 PDT September 11 – It was followed by more than 100 aftershocks. The largest aftershock occurred 3 minutes after the earthquake and had magnitude 4.9. The remaining aftershocks were in the magnitude 1-3 range and approximately 50 km offshore, thus too small and too far offshore to be felt or cause any damage.

On March 16, 2011, the ground started shaking and stopped after about 10 seconds in the small community of Grenville, Quebec. The 4.3 quake's epicenter was in Hawkesbury, Ont.

On April 14, 2010, in Langenburg, Saskatchewan (population 1,048) around 12:53 am. a magnitude 4.0 earthquake shook the community. No injuries or damages were reported.

On November 17, 2009, in Haida Gwaii, British Columbia (population 948) at 7:30 am., a magnitude 6.5 earthquake was felt in the community. The lack of damage was believed to be because most buildings were built low-slung resulting in stability during the quake. Another earthquake, with a magnitude of M7.8, hit the Haida Gwaii in on October 27, 2012. Residents experienced strong ground shaking and people moved to higher ground in fear of a minor tsunami the earthquake had generated. The earthquake was also felt on the mainland of British Columbia and led to a loss of electricity in Bella Coola. No major damage or injuries were reported after the quake. However, the hot springs in the Gwaii Haanas National Park dried up after the quake.

On January 26, 1700 a "mega-thrust" earthquake hit somewhere off the coast of North America. While no modern-day scientific instruments were available to record the earthquake, the event was witnessed and recorded by First Nation communities. The earthquake collapsed houses of the Cowichan people, and caused several landslides.

Liquefaction and Ground Failure Examples

In Larouche, Quebec (population: 1,004) on November 25, 1988 at 11:46pm a magnitude 5.9 earthquake hit the Saguenay region. Liquefaction occurred within near the epicenter of the quake, in which Larouche was located. The earthquake caused tens of millions of dollars of damage to unreinforced masonry structures.

Surface Faulting and Tectonic Deformation Example

In the Inuit community of Kangiqsujuaq, Quebec (population 552) on December 25, 1989, a magnitude 6.3 earthquake caused a 10 km surface rupture in the Ungava Peninsula. It was the first confirmed case of surface faulting in eastern North America and caused changes in land elevation.

Human-caused

On March 2, 2019, an earthquake with a magnitude of 4.18 occurred near Red Deer, Alberta. It was almost a year after an earthquake on March 19, 2018, with a magnitude of 3.13 also occurred near Red Deer. The 2019 earthquake rattled homes in Red Deer and temporarily knocked out the power in parts of Sylvan Lake. A report by researchers with the Alberta Geological Society and the Alberta Energy Regulator examined the two earthquakes and determined that nearby fracking operations triggered both earthquakes and also induced other "small clusters" of seismic events in the area with tremors up to a magnitude of 2.0.

In November 2018, three earthquakes occurred in northeastern B.C. The B.C. Oil and Gas Commission blamed fracking for the earthquakes and stated that the events 20 kilometres south of Fort St. John on Nov. 29 occurred because of fluid injections during hydraulic fracturing at a Canadian Natural Resources Ltd. wellsite. The earthquakes, which were felt but caused no surface damage, measured 3.4, 4.0 and 4.5 magnitude. Fracking operations were suspended after the earthquakes pending the results of a detailed technical review. BC Hydro officials were so alarmed by an earthquake that shook the ground at its sprawling Site C dam construction project in late November, they ordered a halt to all work

Earthquakes Human-caused

Hazard Rating	High Risk ☐	Low Risk ☐	Need More Info ☐	Not Applicable ☐

Yes	No	Need More Info	Not Applicable	FACTORS
☐	☐	☐	☐	Seismic activity can cause water level changes in large dams. Is your community located near a large dam?
☐	☐	☐	☐	Deep fluid injection (or fracking), a common practice in oil and gas fields has been associated with seismic activity. Is there an oil and/or gas field located near your community?
☐	☐	☐	☐	Quarrying/ large scale excavations (i.e., mines & tar sands) cause seismic activity due to the removal of large amounts of weight (soil, rock) from the earth's surface ("crustal unloading"). Is your community located near a quarry mine and/or tar sands field?
☐	☐	☐	☐	Underground nuclear explosions have been associated with seismic activity. Is your community located near sites where underground seismic explosions are carried out?

Earthquake Natural

Hazard Rating	High Risk ☐	Low Risk ☐	Need More Info ☐	Not Applicable ☐

Yes	No	Need More Info	Not Applicable	FACTORS
☐	☐	☐	☐	The best indicator of an earthquake risk is record of them occurring in the past. Does your community have a history of earthquakes? (Check Risk Analysis Resources – Seismic Risk in Canada and Areas of Past Significant Earthquakes in Canada)
☐	☐	☐	☐	Earthquakes are often located around fault lines. Is your community located near a known fault line? (Check Risk Analysis Resources – Known Major Fault Lines in Canada)

IF YOU HAVE INDICATED THAT YOUR COMMUNITY COULD BE HIT BY AN EARTHQUAKE THEN COMPLETE THE FOLLOWING.

Ground Failure Natural

Hazard Rating	High Risk ☐	Low Risk ☐	Need More Info ☐	Not Applicable ☐

Yes	No	Need More Info	Not Applicable	FACTORS
☐	☐	☐	☐	Reclaimed soils in coastal areas, poorly compacted man-made fill, loose silts & silty sands, and/or deposits such as old or existing water bodies are prone to liquefaction. Is your community located on any of these soils?
☐	☐	☐	☐	Areas with high groundwater tables are at risk due to the increased chance of water-filled soils which are highly susceptible to liquefaction. Is your community located in an area with a high ground water table? (Check Risk Analysis Resources – Groundwater Location Map) Note that additional research may be required to determine if there is a high ground table in your community.
☐	☐	☐	☐	Lateral spreads occur in areas with little to no slope where liquefaction occurs below the surface layer. Areas that are fairly flat with loose soils below the surface are at risk. Is your community located on a flat area with loose soils below the surface?
☐	☐	☐	☐	Flow failures are liquefaction induced landslides that occur in sloped areas of loose saturated sand or silts. Is your community located on a slope of loose saturated sands or silts?
☐	☐	☐	☐	Sand boils occur when shaking causes subsurface water to rise up through the surface sand. Areas with high ground water tables and sandy surfaces are at risk. Is your community located on a sandy surface with high ground water tables?

Surface Faulting Natural

Hazard Rating	High Risk ☐	Low Risk ☐	Need More Info ☐	Not Applicable ☐

Yes	No	Need More Info	Not Applicable	FACTORS
☐	☐	☐	☐	Areas located on fault lines are at risk of this "tearing" of the Earth's surface across a fault. Is your community located <u>on</u> a fault line? (Check Risk Analysis Resources – Known Major Fault Lines in Canada)
☐	☐	☐	☐	Thrust faulting is prominent around folded mountain regions. Areas located in and/or around these regions are at risk to thrust faulting (horizontal). Is your community located in a folded mountain region?

Changes in Land Elevation (Tectonic Deformation) - Natural

Hazard Rating	High Risk ☐	Low Risk ☐	Need More Info ☐	Not Applicable ☐

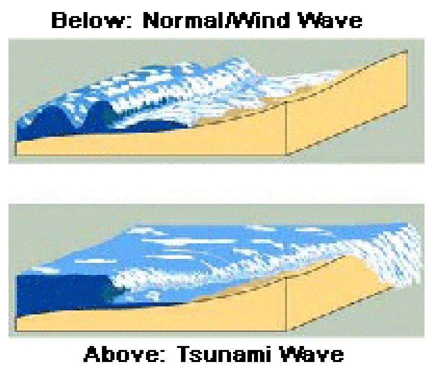
Yes	No	Need More Info	Not Applicable	FACTORS
☐	☐	☐	☐	Change in land elevation can occur as a result of an earthquake, which can result in a change in slope in the topography. River systems adjust to this by changing course. Areas that have had a change in the course of rivers and/or streams are at risk. Have the river and/or streams in your community changed course recently?

Tsunami

Definition

”Tsunami” is a Japanese word and means “harbour wave.” Tsunami waves are waves that travel in open water invisible for the naked eye. As soon as the tsunami waves approach the shore line, they grow in height and flood the shoreline fast and expectantly. Tsunami waves are normally linked to offshore earthquakes. Non-seismic related tsunamis (also called displacement waves) can be caused by a large landslide under water, the collapse of a mountain or volcano into the ocean, by a volcanic eruption or a meteorite impact into the ocean.

Figure 12 Tsunami Wave



If your community is further than 3.5 kilometers inland or more than 40 meters above sea level then you can safely state that “This couldn’t happen here.”

Discussion

Movement of the ocean floor (sudden sinking (“subsidence”) or uplift) may generate tsunamis, or seismic sea waves. Tsunami waves are extremely wide from wave crest to wave crest. They can travel across the open ocean at high speeds for many thousands of kilometres. As a tsunami approaches the shore, it breaks with tremendous force and can be extremely destructive, especially when it hits an estuary or bay. The advancing wave may crash inland, beaching boats and ships, destroying shoreline facilities and damaging property.

It Happened Here...

On October 19, 2020, a 7.5 magnitude earthquake near Sand Point, Alaska triggered a tsunami warning for that area. Nearly two hours later, Emergency Management BC confirmed an all-clear.

On January 23, 2018 a tsunami warning was triggered in B.C. following an early morning earthquake, but some residents on Vancouver Island said not enough was done to warn them. The lack of a uniform response across B.C. has officials discussing how to respond more effectively in the future.

In Tofino, British Columbia, the 1960 9.5 magnitude earthquake in Chile caused a 1.2 metre tsunami in Tofino. Damage to log booms was reported.

Terrenceville, Newfoundland (population 521) is one community affected by the 1929 tsunami that was caused by a submarine landslide, triggered by the Grand Banks 7.2 magnitude earthquake. Twenty-seven people lost their lives as a result of the tsunami and houses, boats, and fish stages were swept away. Damages were estimated around $1M.

The mega-thrust, or subduction, earthquake that hit off the coast of North America on January 26, 1700 caused a tsunami that reached as far as the coast of Japan. The tsunami was recorded in Japanese harbor logs, and that is how we know the accurate date of the tsunami. The tsunami also hit the coast of Vancouver Island, it completely wiped out the winter village of the Pachena Bay people.

Tsunamis - Natural

Hazard Rating	High Risk ☐	Low Risk ☐	Need More Info ☐	Not Applicable ☐

Yes	No	Need More Info	Not Applicable	FACTORS
☐	☐	☐	☐	Tsunamis are often caused by offshore earthquakes. Areas located near an offshore fault area are at risk. Is your community located on a coast with an offshore fault?
☐	☐	☐	☐	80% of tsunamis occur in the Pacific Ocean. Coastal areas located along the Pacific Ocean are at risk. Is your community located along the Pacific Ocean?
☐	☐	☐	☐	Areas located in a low lying coastal region, by a bay entrance or near/on tidal flats are at risk. Is your community located in one of these areas?
☐	☐	☐	☐	Areas located near or on the shores of a coastal river or inlet are at risk. Is your community located in one of these areas?
☐	☐	☐	☐	Shoreline tree cover can act as a natural barrier against tsunamis. Areas lacking shoreline tree cover are at risk. Is your community lacking shoreline tree cover?
☐	☐	☐	☐	Reefs can act as a natural barrier against tsunamis. Coastal areas without reefs are at risk. Is your community lacking a reef off the coast?

Volcano - Ash Falls, Projectiles and Lateral Blasts, Pyroclastic Flows and Lava Flows

Definition

A volcano is a vent in the crust of the earth through which molten rock (magma) is reaches the surface of the earth as lava and volcanic debris flows.During a volcanic eruption, volcanic gases and rock fragments are blown into the earth's atmosphere.

There are several volcanic processes that we can distinguish, and each has its own hazards:

- **Ashfall deposits** (also known as pyroclastic air fall or tephra) are tiny, very fine rock fragments which have been ejected, more or less vertically, from a volcano and have then fallen back to earth.
- **Pyroclastic flows** are mixtures of hot gases, ash, fine pumice and rock which are travel down the slopes of volcanoes with great speed (up to 700 km/hour).
- When magma reaches the surface it is called **"lava."** The lava is a fluid rock melt , which can contain suspended crystals, dissolved gasses and liquids.Lava reaches the surface of the earth via a volcanic eruption.
- A **volcanic blast** is one of the most explosive volcanic eruptions, during which part of the volcano is blown away. It is most destructive when accompanied by a pyroclastic flow.
- **Projectiles** are lethal rock fragments of varying sizes that are violently ejected from a volcano.
- **Mudflows** or "**lahars**" are slurries of jumbled, solid volcanic rock fragments mixed with water, and while some mudflows may be hot, most occur as colds flows. These mudflows or lahars occur mostly on volcanoes with a snow and/ or ice cap. The heat from the volcanic eruption melts the snow or ice, and then forms these dangerous mudflow mixtures.

Discussion

There are two main types of volcanoes, the "shield volcano" and the "strato or composite volcano." There are other volcano types, such as volcanic domes, cinder cones which can be found in Canda and those located in rift zones which are only found offshore from Canada.

Shield volcanoes are the largest volcanoes on earth. The slopes of these volcanoes are often very gentle, and the volcano resembles an up-side-down warrior shield (Fig. 13 and 14). Eruptions from shield volcanoes are not very violent. Lava usually flows gently down the slopes of the volcano. Mauna Loa on the big island of Hawaii is the largest (shield) volcano on earth. From

Figure 13. The profiles of Mauna Loa (a shield volcano) versus Mount Rainier (a strato or composite volcano: Image: http://usgs.com)

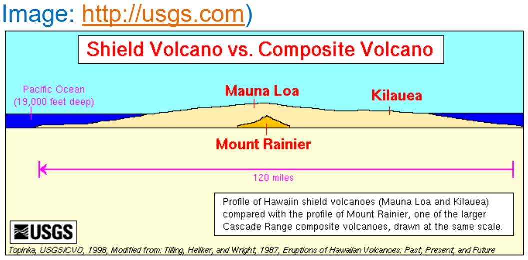
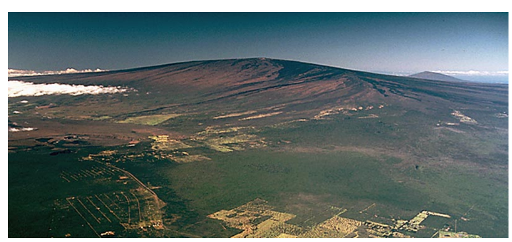


Figure 14. Mauna Loa as seen from the air (Photo: www.wikipedia.com)



the base of the volcano at the bottom of the ocean, to the top of the volcano Mauna Loa measures over 9 kilometers high (higher than Mount Everest).

Figure 15. A view of Mount Rainier (strato volcano; Photo: www.dnr.wa.gov).

A strato volcano (or composite volcano) is what many people consider as a “text book” volcano (Fig. 15). It has steep slopes, and it very often displays a white snow cap. Strato volcanoes erupt more violently then shield volcanoes, some eruptions are true explosions. These volcanoes emit lavas as well as pyroclastic flows. Lahars can occur when the volcano has an snow or ice cap. Many of the Cascade volcanoes in the Pacific Northwest are strato volcanoes, such as Mount St. Helens and Mount Rainier in the USA, and Mount Meager and Mount Garibaldi in British Columbia.

Six volcanic belts categorize the Canadian volcanoes less than 5 million years old: Anahim Volcanic Belt, Chilcotin Plateau Basalts, Garibaldi Volcanic Belt, Stikine Volcanic Belt, Wells Gray Clearwater Volcanic Field and the Wrangell Volcanic Belt.The potential destructiveness of a volcano depends to a great degree on the kind of lava it emits and by the manner of its eruption. Violent strato volcanoes produce the stiffest lava and send up great clouds of fine ash in a “cauliflower” cloud which disperses across large areas by wind. The most destructive volcanos, send out dense clouds of gases and material, the so-called pyroclastic flows, which tumble over the edge of the crater and roll rapidly down the slope.

During an explosive eruption, a volcano may produce a large plume composed of ash, gases and other volatile materials. These ashes can travel for hundreds of kilometres and cover areas at great distances from the volcanic source. The ashes pose serious public health hazards especially in settlements located downwind from the volcano. Fine ash particles may be inhaled deep into the lungs creating or making worse a variety of respiratory problems, such as asthma and bronchitis.Courser particles can lodge in the nose, causing extreme irritation, or in the eyes, resulting in scratches on the outer layer of the eye (the “cornea”). Heavy ash deposits may destroy agriculture, pollute water supplies, disrupt transportation and communication facilities, and collapse buildings and other structures. These effects can have a big influence on the local or regional economy, as farmers may not be able to harvest crops, or fish may die as the waters are polluted by ashfall.

Pyroclastic flows travel at speeds –up to 700 kilometres per hour.Since pyroclastic flows consist of hot air, ashes, rocks, and gasses they are very powerful and destroy everything in their way. Humans are typically unable to outrun a pyroclastic flow, and they are known to cause suffocation, inhalational injuries and burns.

Two types of lava flows are generally recognized and they are linked to the 2 main types of volcanoes. “Non-sticky” or “fluid” lavas are linked to shield volcanoes, also known as “low viscosity” lavas. “Sticky” or less fluid lavas are linked to strato (or composite) volcanoes, and are also known as “high viscosity” lavas. Low viscosity lavas are typical of the less violent eruptions and have higher rates of movement and can travel great distances. High viscosity lavas are typical of the more explosive volcanoes such as the composite cones of the Cascade Range. Lava flows from these volcanoes tend to move at lower velocities and travel shorter distances. Although lava flows may be very destructive of property, water supply reservoirs and agricultural lands in their paths, they rarely travel fast enough to endanger human life directly.

Volcanic blasts can produce noise which may be heard over long distances. It may also shatter windows and other glass-like structures, leading to glass cuts to the skin. Volcanic projectiles may damage houses, bridges and other human- made structures as well as start fires if hot enough.

Mudflows or "lahars" move downhill and tend to follow topography, such as ridges or river stream. Mudflows may fill rivers and lakes and cause flooding, as well as change the levels and courses of existing rivers. Mudflows may bury and destroy facilities such as highways and forest roads, and destroy reservoirs. Mudflows are most likely to occur on the more explosive strato volcanoes; almost all of the Cascade composite volcanoes have had numerous mudflows during the past 10,000 years.

Even though there have not been any lahars recorded in Canada in recent times they are not outside the realm of possibility because many of the volcanoes located throughout Western Canada are active though dormant (or "sleeping"). Past eruptions by Mount Meager, British Columbia, have resulted in lahars that reached far into the Lillooet River valley to areas that are currently inhabited or used for agriculture and recreation. If this were to occur today there would be lives lost and large damage costs to buildings and infrastructure in the region. The last eruption of Mount Meager occurred 2350 years ago, and this was a very violent eruption. Pyroclastic flow deposits have been found in the valley. These pyroclastic flows are thought to have blocked the valley and led to flooding of the Lillooet River. Pyroclastic flow deposits have also been found at Hoodoo Mountain and Mount Edziza in British Columbia.

Canada has five potentially active volcanic areas, all of which are located in British Columbia and the Yukon Territory:

1. the Garibaldi Volcanic Belt of southwest British Columbia (the northern extension of the American Cascade Arc)
2. the Wells Gray-Clearwater volcanic field of east central British Columbia
3. the Northern Cordilleran volcanic province of northwest British Columbia (sometimes referred to as the Stikine Volcanic Belt)
4. the Anahim Volcanic Belt of central British Columbia, and
5. the Wrangell Volcanic Belt of Alaska and adjacent Yukon Territory.

It Happened Here…

Lava flow

Around1750 approximately 2,000 members of the Wil Lax L'abitan Lax Ksiluux First Nation communities perished during the eruption of the Nisga'a Tseax Cone volcano. It is believed to be the last volcanic eruption and lava flow in the province of British Columbia. The Nsiga'a Memorial Laval Beds Provincial Park now lies there.

Ash Falls

On June 27, 1992, Mount Spurr erupted in Alaska, affecting Hanes Junction, Yukon (population 589). Enough ash was deposited in the Yukon area around Hanes Junction to close the Alaska Hwy for a few hours because of reduced visibility.

Volcano Natural

Hazard Rating	High Risk ☐	Low Risk ☐	Need More Info ☐	Not Applicable ☐

Yes	No	Need More Info	Not Applicable	FACTORS
☐	☐	☐	☐	Your community is at risk if it is located near a volcano. Is your community located near a volcano? (Check Risk Analysis Resources – Major Volcanoes)
☐	☐	☐	☐	Volcanoes can lie dormant ("sleeping") for hundreds or even thousands of years. Seismic activity around dormant volcanoes can signal their awakening. Areas experiencing earthquakes near dormant volcanoes are at risk. Is your community near a dormant volcano AND experiencing seismic activity?

IF YOU HAVE INDICATED THAT YOUR COMMUNITY COULD POTENTIALLY BE AFFECTED BY A VOLCANIC ERUPTION THEN COMPLETE THE FOLLOWING.

Ash Falls - Natural

Hazard Rating	High Risk ☐	Low Risk ☐	Need More Info ☐	Not Applicable ☐

Yes	No	Need More Info	Not Applicable	FACTORS
☐	☐	☐	☐	Ash falls are typical characteristics of volcanoes with violent eruptions. Areas near volcanoes known to have explosive eruptions, such as the Cascade Range, are at risk. Is your community located near known explosive volcanoes? (Check Risk Analysis Resources - Major volcanoes in Canada)
☐	☐	☐	☐	Fertile grounds near volcanoes are often evidence of previous ash falls. Fertile areas near volcanoes are at risk. Is your community situated on or near fertile grounds?
☐	☐	☐	☐	Areas downwind of volcanoes are at greater risk of ash falls because the ejected ashes can be carried by the wind. Is your community located downwind of a volcano (the dominant high atmosphere wind direction in Canada is west to east)?
☐	☐	☐	☐	Ash fall is heaviest closer to the eruption site (volcano crater) because denser and heavier ash begins to fall first. Areas close to a potential eruption site are at risk. Is your community located in close proximity to a volcano (less than a kilometer)?

Lava Flows Natural

Hazard Rating	High Risk ☐	Low Risk ☐	Need More Info ☐	Not Applicable ☐

Yes	No	Need More Info	Not Applicable	FACTORS
☐	☐	☐	☐	Very thick, sticky (high viscosity) lava produced by violent eruptions of strato volcanoes travel slower and less distance than fluid, less sticky lava from shield volcanoes. Areas **close** to these strato volcanoes are at risk. Is your community located at the foot of a **strato** volcano? (Check Risk Analysis Resources Major volcanoes in Canada)
☐	☐	☐	☐	Fluid, less sticky lavas (low viscosity) produced by less violent eruptions from shield volcanoes travel faster and farther than lavas from strato volcanoes. Areas in a **wide area** around these **shield** volcanoes are at risk. Is your community located in visual distance from a volcano?

Mudflows Natural

Hazard Rating	High Risk ☐	Low Risk ☐	Need More Info ☐	Not Applicable ☐

Yes	No	Need More Info	Not Applicable	FACTORS
☐	☐	☐	☐	Mudflows are most commonly associated with explosive strato volcanoes, such as those in the Cascade Range. Areas near known explosive volcanoes are at risk. Is your community located near a composite cone volcano? (Check Risk Analysis Resources - Composite Cone Volcano)
☐	☐	☐	☐	Mudflows are a combination of volcanic rock and water. Areas near volcanoes with glaciers, snow caps and/or crater lakes are at risk. Does the volcano near your community have glaciers, snow caps and/or crater lakes?
☐	☐	☐	☐	Mudflows often follow the topography. Areas downhill from volcanoes, along ridges or stream drainages or in river valleys are at risk. Is your community located downhill from a volcano, along a ridge, stream drainage or in a river valley?
☐	☐	☐	☐	Slopes and hillsides near active volcanoes can build up volcanic materials after an eruption. Rainfall can trigger these materials to flow downstream. Areas located on or below slopes that can potentially buildup with volcanic material are at risk. Is your community located below slopes near a volcano?
☐	☐	☐	☐	Curving inward (concave) slopes are more likely to collect volcanic material and water. This results in saturated volcanic deposits which can trigger a slide. Areas with concave slopes are at risk. Are the slopes around your community concave?

Projectiles and Lateral Blasts - Natural

Hazard Rating	High Risk ☐	Low Risk ☐	Need More Info ☐	Not Applicable ☐

Yes	No	Need More Info	Not Applicable	FACTORS
☐	☐	☐	☐	Volcanic projectiles and lateral blasts are characteristics of explosive-type volcanoes. Areas located near these volcanoes are at risk. Is your community located near an explosive-type (strato) volcano? (Check Risk Analysis Resources - Major volcanoes in Canada)
☐	☐	☐	☐	Lateral blasts can trigger a tsunami if the volcanic material hits water. Areas located on bodies of water which are also bordered by volcanoes are at risk. Is your community located near a body of water that has a volcano next to it?

Pyroclastic Flows - Natural

Hazard Rating	High Risk ☐	Low Risk ☐	Need More Info ☐	Not Applicable ☐

Yes	No	Need More Info	Not Applicable	FACTORS
☐	☐	☐	☐	Pyroclastic flows are “clouds” of hot ash, gases and rocks that flow down the sides of a volcano. Areas located on or below the slopes of a dormant (“sleeping”) or active volcano are at risk. Is your community located on or below the slopes of a volcano?
☐	☐	☐	☐	Pyroclastic flows are a characteristic of destructive volcanoes. Areas with violent volcanoes are at risk. Is your community located near a violent volcano (i.e., strato volcano)?
☐	☐	☐	☐	Pyroclastic flows are common during violent volcanic eruptions. These typically occur in strato volcanoes along the West Coast of Canada (Cascadia Volcanic Range). Is your community located in Western Canada AND near a strato volcano?
☐	☐	☐	☐	Pyroclastic flows have been known to travel over water. Areas located across bodies of water from volcanoes are at risk. Is your community located near a body of water that has a volcano next to it?
☐	☐	☐	☐	Pyroclastic flows often follow the topography. Areas downhill from volcanoes, along ridges, stream drainages, or in river valleys are at risk. Is your community located downhill from a volcano, along a ridge, stream drainage or in a river valley?

Risk Analysis Resources

Seismic Risk in Canada

The following map indicates areas of high to low seismic risk in Canada.

Figure 16 Seismic Risk in Canada

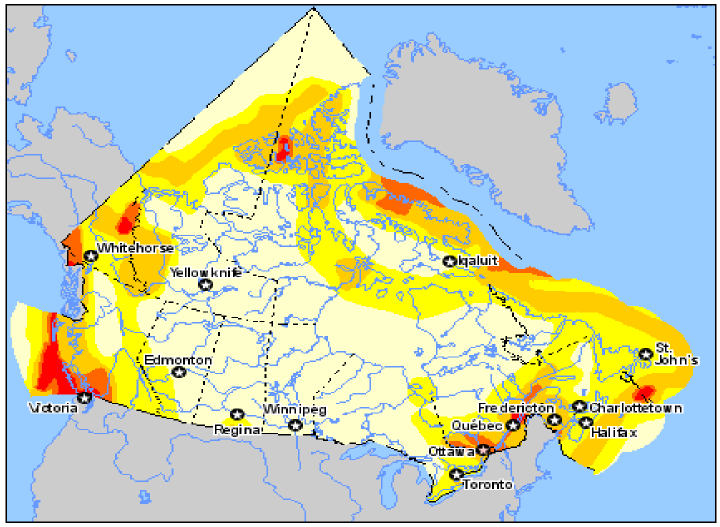
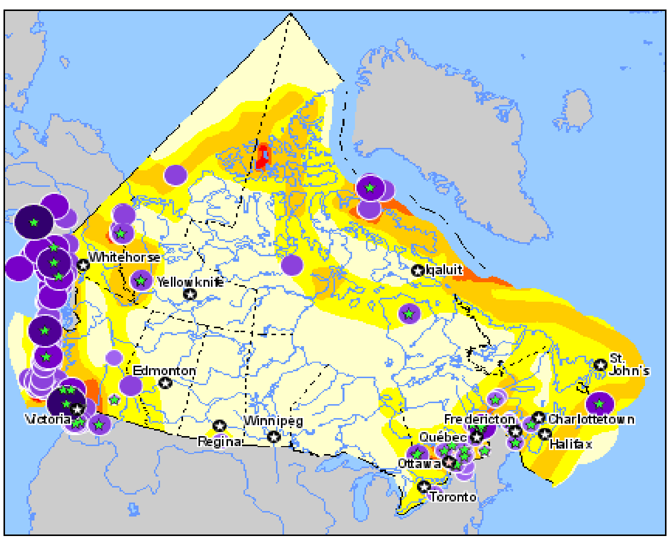
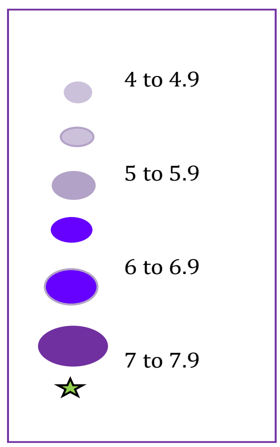


Figure 17 Areas of Past Significant Earthquakes in Canada

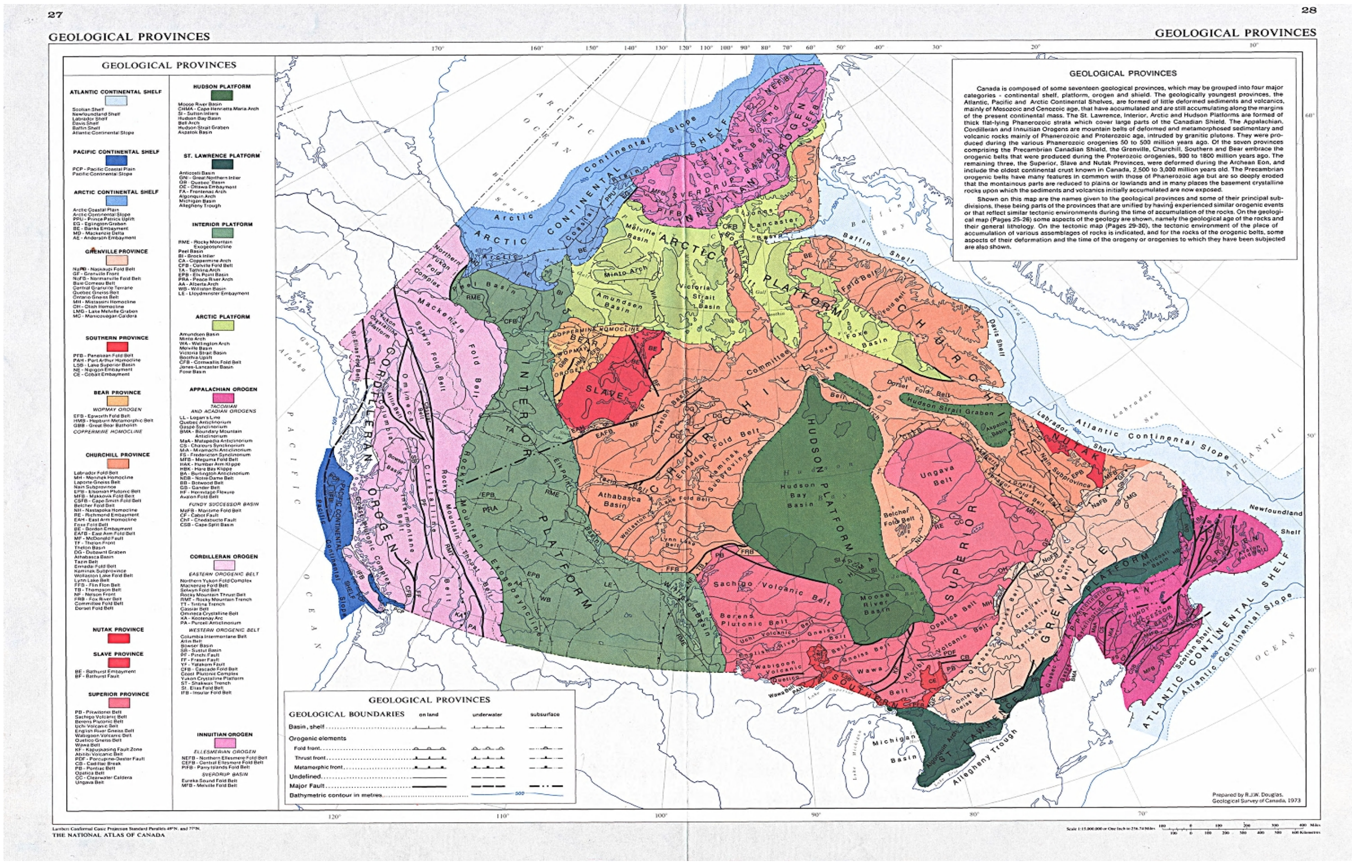


Areas of Past Significant Earthquakes in Canada



Known Major Fault Lines in Canada

Figure 18 Major Fault Lines in Canada



More information on Seismic zones in Canada can be found on the website of Natural Resources Canada:

- Western Canada
- Eastern Canada

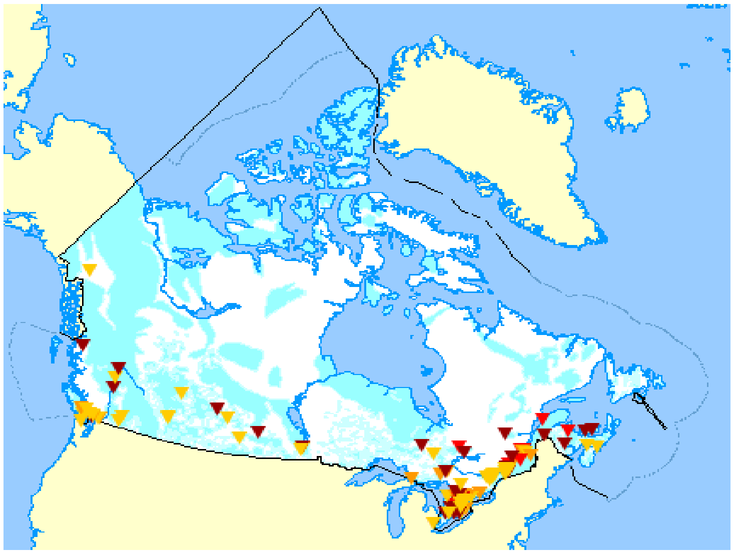
Keywords: Natural Resources Canada, earthquake, seismic zones, seismic fault lines, earthquake hazard.

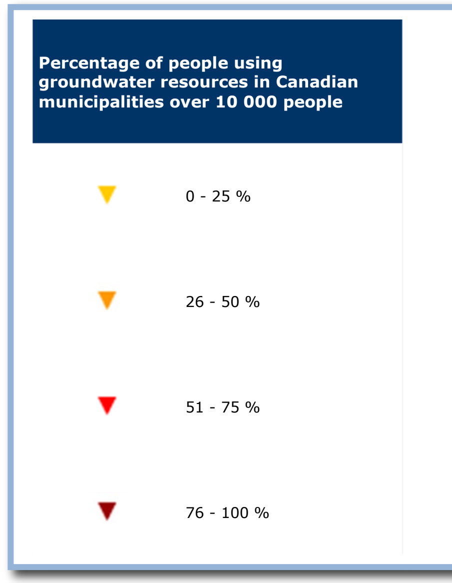
Natural Resources Canada's "The Atlas of Canada" provides a lot of information about geology and geosciences, natural hazards, and earthquakes. Additonal information is available about tectonics; and earthquakes, magnetism and tides;

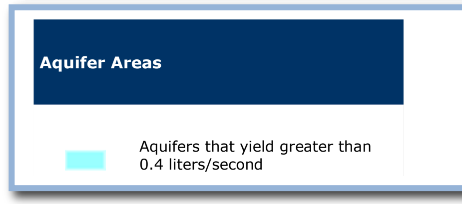
Keywords: Natural Resources of Canada, Atlas of Canada, earthquake, natural hazards

Groundwater Location Map

Figure 19 Groundwater Location Map

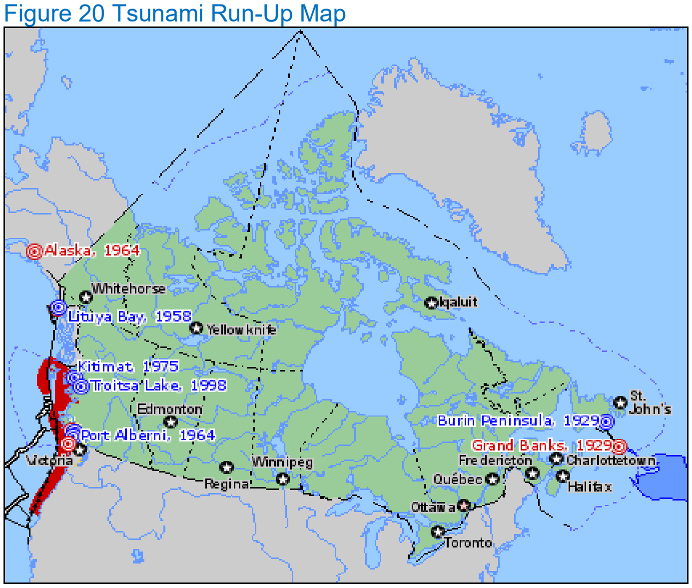


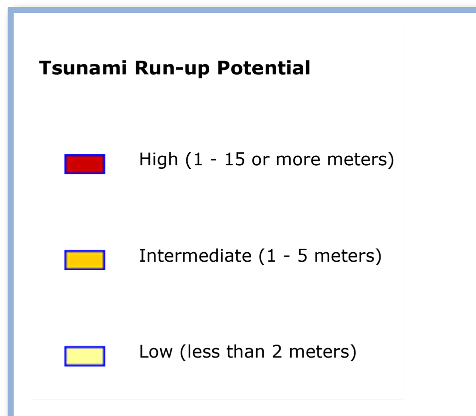




Tsunamis

Figure 20 Tsunami Run-Up Map





Natural Resources Canada's "The Atlas of Canada" provides a lot of information about tsunamis including historical data, tsunami run-up potential maps and information about the Cascadia Subduction zone.

Keywords: Natural Resources of Canada, Atlas of Canada,tsunami, natural hazards

A Native American story, *Run to High Ground*, about tsunamis and earthquakes can be found on YouTube.

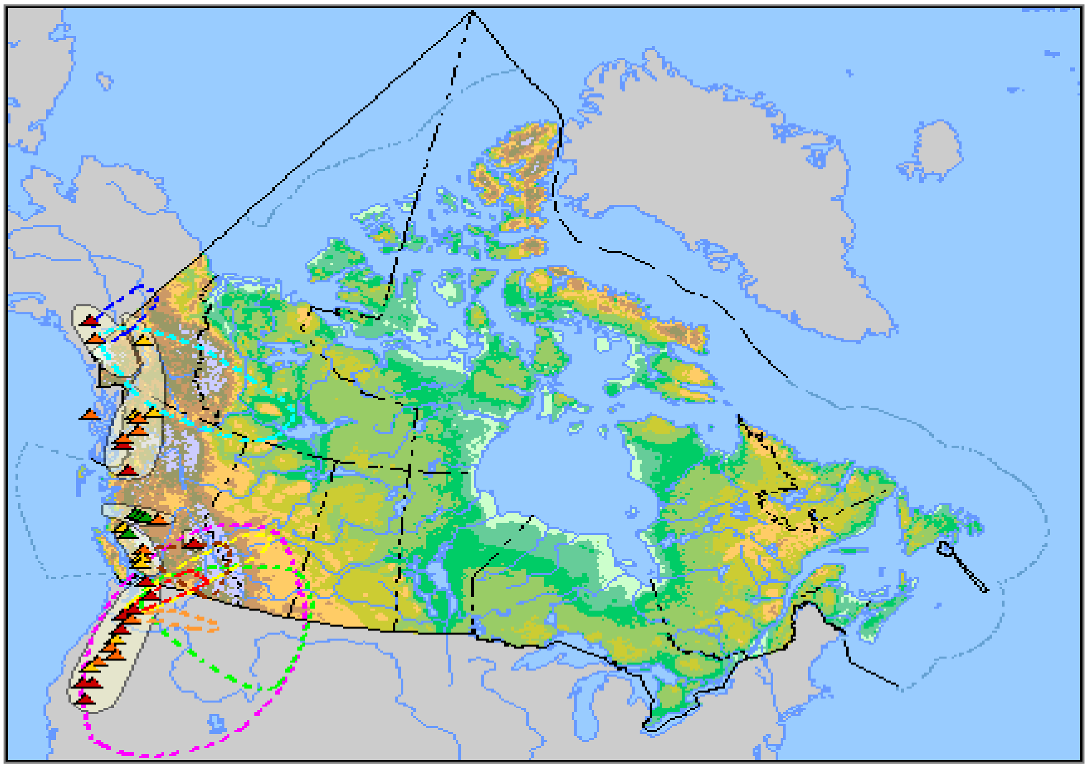
Keywords: YouTube, run to high ground', native american, tsunami, earthquake

A detailed Tsunami Inundation Map for British Columbia can be found on the EMBC web site.

Keywords: Tsunami Inundation Map British Columbia

Major Volcanoes in Canada

Figure 21 Major Volcanoes in Canada



Natural Resources Canada's "The Atlas of Canada" provides a lot of information about volcanoes, including how long it has been since a major eruption, accumulations of volcanic ash, and volcanic belts in comparison to population.

Keywords: Natural Resources of Canada, Atlas of Canada, volcano, natural hazards

Seismic Related Resources

The Institute for Catastrophic Loss Reduction (ICLR) has a lot of information about a number of natural hazards including earthquakes

Keywords: Institute for Catastrophic Loss Reduction, natural hazards, earthquake

References

Aceves Quesada, J. F., Lillian Martin Del Pozzo, A., & Lopez Blanco, J. (2007). Volcanic hazards zonation of the Nevado de Toluca volcano, Central Mexico. *Natural Hazards, 41*, 159-180. https://doi.org/10.1016/j.jvolgeores.2008.04.016

Alongi, D. M. (2008). Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change. *Estuarine Coastal and Shelf Science, 76*, 1-13. https://doi.org/10.1016/j.ecss.2007.08.024

B.C. Coast shaken by powerful earthquake. (2008). CBC News.

Baisch, S., & Harjes, H. P. (2003). A model for fluid-injection-induced seismicity at the KTB, Germany. *Geophysical Journal International, 152*, 160-170.

Baranova, V., Mustaqeem, A., & Bell, S. (1999). A model for induced seismicity caused by hydrocarbon production in the western Canada sedimentary basin. *Canadian Journal of Earth Sciences, 36*, 47-64. https://doi.org/10.1139/e98-080

Barberi, F., Ghigliotti, M., Macedonio, G., Orellana, H., Pareschi, M. T., & Rosi, M. (1992). Volcanic hazard assessment of Guagua Pichincha (Ecuador) based on past behavior and numerical-models. *Journal of Volcanology and Geothermal Research, 49*, 53-68. https://doi.org/10.1016/0377-0273(92)90004-W

Baxter, P.J. (1989). Volcanoes. In M. Gregg (Ed.), *The public health consequences of disasters 1989*. U.S. Dept. of Health and Human Services.

Bent, A. L. (1994). *The 1989 (MS 6.3) Ungava Quebec, earthquake*: A complex intraplate event. *Bulletin of the Seismological Society of America, 84*(4), 1075-1088.

Blake, S., & Bruno, B. C. (2000). Modelling the emplacement of compound lava flows. *Earth and Planetary Science Letters, 184*, 181-197. https://doi.org/10.1016/S0012-821X(00)00278-8

Bohnhoff, M. (n.d.). Man-made earthquakes. The enormous load exerted by dam reservoirs resulted in the strongest ever induced earthquake. An interview with Prof. Dr. Marco Bohnhoff. ESKP.

Calderoni, G., Rovelli, A., & Di Giovambattista, R. (2010). Large amplitude variations recorded by an on-fault seismological station during the L'Aquila earthquakes: Evidence for a complex fault-induced site effect. *Geophysical Research Letters, 37*, L24305. https://doi.org/10.1029/2010GL045697

Carey, S., Sigurdsson, H., Mandeville, C., & Bronto, S. (1996). Pyroclastic flows and surges over water: An example from the 1883 Krakatau eruption. *Bulletin of Volcanology, 57*, 493-511. https://doi.org/10.1007/BF00304435

Cassidy, J.F, Rogers, G.C., Brillon, C., Kao, H., Mulder, T., Dragert, H., … & Bentkowski, W. (2010). The 17 November, 2009 Haida Gwaii (Queen Charlotte Islands), British Columbia, earthquake sequence [Abstract]. *Seismological Research Letters, 81*, 336.

CBC News: The National. (2018, January 23). *Tsunami warning: Was enough done to warn B.C?* [Video]. YouTube.

Cesca, S., Dost, B. & Oth, A. (2013). Preface to the special issue "Triggered and induced seismicity: Probabilities and discrimination." *Journal of Seismology, 17*, 1-4.

Cook, N. G. W. (1976). Seismicity associated with mining. *Engineering Geology, 10*, 99-122. https://doi.org/10.1016/0013-7952(76)90015-6

Dellino, P., Buettner, R., Dioguardi, F., Doronzo, D. M., La Volpe, L., Mele, D., Sondor, I., Sulpizio, R. & Zimanowski, B. (2010). Experimental evidence links volcanic particle characteristics to pyroclastic flow hazard. *Earth and Planetary Science Letters, 295*, 314-320. https://doi.org/10.1016/j.epsl.2010.04.022

Doser, D. I., & Rodriguez, H. (2011). A seismotectonic study of the southeastern Alaska region. *Tectonophysics, 497*, 105-113. https://doi.org/10.1016/j.tecto.2010.10.019

Earthquake shakes Quebec, Ontario. (2011). CBC News.

Engqvist, K. (2020, October 21). *Be prepared: Know what to do in the event of a tsunami warning*. Vancouver Island Free Daily.

Ferlito, C., Viccaro, M., & Cristofolini, R. (2009). Volatile-rich magma injection into the feeding system during the 2001 eruption of Mt. Etna (Italy): Its role on explosive activity and change in rheology of lavas. *Bulletin of Volcanology, 71*, 1149-1158. https://doi.org/10.1007/s00445-009-0290-x

Goh, S. H., & O'Rourke, T. D. (2008). Soil-pile interaction during liquefaction-induced lateral spread. *Journal of Earthquake and Tsunami, 2*, 53-85. https://doi.org/10.1142/S1793431108000232

Gonzalez-Mellado, A. O., & De la Cruz-Reyna, S. (2010). A simple semi-empirical approach to model thickness of ash-deposits for different eruption scenarios. *Natural Hazards and Earth System Sciences, 10*, 2241-2257. https://doi.org/10.5194/nhess-10-2241-2010

Graettinger, A. H., Manville, V., & Briggs, R. M. (2010). Depositional record of historic lahars in the upper Whangaehu valley, Mt. Ruapehu, New Zealand: Implications for trigger mechanisms, flow dynamics and lahar hazards. *Bulletin of Volcanology, 72*, 279-296. https://doi.org/10.1007/s00445-009-0318-2

Guilbaud, M., Siebe, C., & Agustin-Flores, J. (2009). Eruptive style of the young high-mg basaltic-andesite Pelagatos scoria cone, southeast of Mexico City. *Bulletin of Volcanology, 71*, 859-880. 10.1007/s00445-009-0271-0

Gurioli, L., Sulpizio, R., Cioni, R., Sbrana, A., Santacroce, R., Luperini, W. & Andronico, D. (2010). Pyroclastic flow hazard assessment at Somma-Vesuvius based on the geological record. *Bulletin of Volcanology, 72*, 1021-1038. https://doi.org/10.1007/s00445-010-0379-2

Haeussler, P. J., Best, T. C., & Waythomas, C. F. (2002). Paleoseismology at high latitudes: Seismic disturbance of upper quaternary deposits along the castle mountain fault near Houston, Alaska. *Geological Society of America Bulletin, 114*, 1296-1310. doi: 10.1130/0016-7606(2002)114<1296:PAHLSD>2.0.CO

Hamblin, K. & Christiansen, E. H. (2003). *The earth's dynamic systems* (10th ed.). Pearson.

Hanka, W., Saul, J., Weber, B., Becker, J., Harjadi, P., Fauzi, & GITEWS Seismology Group. (2010). Real-time earthquake monitoring for tsunami warning in the Indian Ocean and beyond. *Natural Hazards and Earth System Sciences, 10*, 2611-2622. https://doi.org/10.5194/nhess-10-2611-2010, 2010.

Harris, R. A. (2000). Earthquake stress triggers, stress shadows, and seismic hazard. *Current Science, 79*(9), 1215-1225. https://www.jstor.org/stable/24105274

Hindle, D., & Mackey, K. (2011). Earthquake recurrence and magnitude and seismic deformation of the northwestern Okhotsk plate, northeast Russia. *Journal of Geophysical Research-Solid Earth, 116*, (B2). https://doi.org/10.1029/2010JB007409

Hornbach, M. J., Braudy, N., Briggs, R. W., Cormier, M., Davis, M. B., Diebold, J. B., Dieudonne, M. Douilly, R., Frohlich, C., Gulick, S.P.S., Johnson III, H. E., Mann, P., McHugh, C., Ryan-Mishkin, K., Prentice, C. S., Seeber, L., Sorlien, C., Steckler, . S., Symithe, S. J…. Templeton, J. (2010). High tsunami frequency as a result of combined strike-slip faulting and coastal landslides. *Nature Geoscience, 3*, 783-788. https://doi.org/10.1038/ngeo975

Hsu, S., Chu, B., & Lin, C. (2008). Ground movements caused by lateral spread during an earthquake. In Z. Chen, J. M. Zhang, Z., Li, K., F. Q. Wu & K. Ho (Eds.), *Landslides and engineered slopes. From past to the future*. Proceedings of the 10th International Symposium on Landslides and Engineered Slope, June 30 – July 4, Xian, China. CRC Press. https://doi.org/10.1201/9780203885284

Ioualalen, M. (2008). Earthquakes, tsunamis and their cross-calibration: The 26th December 2004 case study. *La Houille Blanche-Revue Internationale De L Eau, 1*, 27-32. doi: 10.1051/lhb:2008002

Iverson, R. M., Schilling, S. P., & Vallance, J. W. (1998). Objective delineation of lahar-inundation hazard zones. *Geological Society of America Bulletin, 110*, 972-984.

Ju, M., & Yang, J. (2010). Preliminary numerical simulation of tectonic deformation-driven fluid flow: Implications for ore genesis in the Dachang district, South China. *Journal of Geochemical Exploration, 106*(1-3), 133-136. https://doi.org/10.1016/j.gexplo.2010.01.008

Karastathis, V. K., Karmis, P., Novikova, T., Roumelioti, Z., Gerolymatou, E., Papanastassiou, D., Liakopoulos, S., & Papadopoulos, G.A. (2010). The contribution of geophysical techniques to site characterisation and liquefaction risk assessment: Case study of Nafplion City, Greece. *Journal of Applied Geophysics, 72*(3), 194-211. https://doi.org/10.1016/j.jappgeo.2010.09.003

Keller, E.A. & DeVecchio, D. E. (2019). Natural Hazards: Earth's processes as hazards, disasters, and catastrophes (5th ed.). Routledge.

Kunkel, C. M., Hallberg, R. W., & Oppenheimer, M. (2006). Coral reefs reduce tsunami impact in model simulations. *Geophysical Research Letters, 33*(23). https://doi.org/10.1029/2006GL027892

Lade, P. V., & Yamamuro, J. A. (2011). Evaluation of static liquefaction potential of silty sand slopes. *Canadian Geotechnical Journal, 48*, 247-264. https://doi.org/10.1139/T10-063

Lange, D., Tilmann, F., Rietbrock, A., Collings, R., Natawidjaja, D. H., Suwargadi, B. W., … & Ryberg, T. (2010). The fine structure of the subducted investigator fracture zone in western Sumatra as seen by local seismicity. *Earth and Planetary Science Letters, 298*(1-2), 47-56. https://doi.org/10.1016/j.epsl.2010.07.020

Manville, V., Hodgson, K. A., Houghton, B. F., Keys, J. R. H., & White, J. D. L. (2000). Tephra, snow and water: Complex sedimentary responses at an active snow-capped stratovolcano, Ruapehu, New Zealand. *Bulletin of Volcanology, 62*, 278-293. https://doi.org/10.1007/s004450000096

Marris, E. (2005). Tsunami damage was enhanced by coral theft. *Nature, 436*, 1071-1071.

Melnik, O. (2000). Dynamics of two-phase conduit flow of high-viscosity gas-saturated magma: Large variations of sustained explosive eruption intensity. *Bulletin of Volcanology, 62*, 153-170. https://doi.org/10.1007/s004450000072

Mirzoev, K. M., Nikolaev, A. V., Lukk, A. A., & Yunga, S. L. (2009). Induced seismicity and the possibilities of controlled relaxation of tectonic stresses in the earth's crust. *Izvestiya-Physics of the Solid Earth, 45*, 885-904. 10.1134/S1069351309100061

Motamed, R., & Towhata, I. (2010). Mitigation measures for pile groups behind quay walls subjected to lateral flow of liquefied soil: Shake table model tests. *Soil Dynamics and Earthquake Engineering, 30*(10), 1043-1060. https://doi.org/10.1016/j.soildyn.2010.04.016

Muhunthan, B., & Worthen, D. L. (2011). Critical state framework for liquefaction of fine grained soils. *Engineering Geology, 117*(1-2), 2-11. https://doi.org/10.1016/j.enggeo.2010.09.013

National Oceanic and Atmospheric Administration. (n.d.). *How to become TsunamiReady©*.

Natural Resources Canada. (2015a). *The 1988 Magnitude 5.9. Saguenay Earthquake*.

Natural Resources Canada. (2015b). *The M9 Cascadia Megathrust earthquake of January 26, 1700*.

Natural Resources Canada. (2015c). *The M8.1 Haida Gwaii (formerly Queen Charlotte Islands) earthquake of August 22, 1949*.

Natural Resources Canada. (2020. *Where are Canada's volcanoes?*

Natural Resources Canada. (2021). *Earthquake reports*.

Natural Resources Canada. (2021). *Frequently asked questions about earthquakes (FAQ).*

Natural Resources of Canada. (2012). *Tsunamis*. The Atlas of Canada. https://doi.org/10.4095/301267

Ocean Networks Canada. (2012, October 27). *Haida Gwaii Earthquake and Tsunami*.

Okal, E. A., & Synolakis, C. E. (2008). Far-field tsunami hazard from mega-thrust earthquakes in the Indian Ocean. *Geophysical Journal International, 172*,(3), 995-1015. https://doi.org/10.1111/j.1365-246X.2007.03674.x

Ota, Y., & Matta, N. (2009). The 1999 earthquake fault and its repeated occurrence at the Earthquake Museum of Taiwan, central part of the Chelungpu fault. *Active Fault Research, 31,* 33-38.

Palmer, S. (1989). Fundamentals of Earthquake Effects on Land and Water. In W. W. Hays (Ed.) *Workshop on Earthquake Hazards in the Puget Sound, Portland Area*, (pp. 141-145). US Geological Survey.

Parfitt, B. (2019, March 21). *Shaking the Peace: Fracking-induced earthquakes rattle BC Hydro execs and farmers alike*. Policy Note.

Peters, G., & van Balen, R. T. (2007). Tectonic geomorphology of the northern upper Rhine Graben, Germany. *Global and Planetary Change, 58*(1-4), 310-334. https://doi.org/10.1016/j.gloplacha.2006.11.041

Pomeroy, P. W., Simpson, D. W., & Sbar, M. L. (1976). Earthquakes triggered by surface quarrying - Wappingers Falls, New-York sequence of June, 1974. *Bulletin of the Seismological Society of America, 66*(3), 685-700.

Prima, O. D. A., & Yoshida, T. (2010). Characterization of volcanic geomorphology and geology by slope and topographic openness. *Geomorphology, 118*(1-2), 22-32. https://doi.org/10.1016/j.geomorph.2009.12.005

Public Safety Canada. *The Canadian disaster database*.

Rocha-Campos, A. C., Basei, M. A., Nutman, A. P., Kleiman, L. E., Varela, R., Llambias, E., …de C.R.. & da Rosa, O. (2011). 30 million years of Permian volcanism recorded in the Choiyoi igneous province (W Argentina) and their source for younger ash fall deposits in the Parana basin: SHRIMP U-pb zircon geochronology evidence. *Gondwana Research, 19*(2), 509-523. https://doi.org/10.1016/j.gr.2010.07.003

Rothaus, R. M., Reinhardt, E., & Noller, J. (2004). Regional considerations of coastline change, tsunami damage and recovery along the southern coast of the Bay of Izmit (the Kocaeli (Turkey) earthquake of 17 August 1999). *Natural Hazards, 31*, 233-252. https://doi.org/10.1023/B:NHAZ.0000020265.16134.5b

Schuster, R. L. & Chleborad, A. F. (1988). Earthquake-Induced Ground Failure in Western Washington. In W. W. Hays (Ed.), *Workshop on evaluation of earthquake hazards and risk in the Puget Sound and Portland areas*, (pp. 100-109). Proceedings of Conference XLII. U.S. Geological Survey.

Simpson, K.A., Stasiuk, M.V, Clague, J.J., Evans, S.G. & Friele, P. (2003). Preliminary drilling results from the Pemberton Valley, British Columbia. *Geological Survey of Canada, Current Research 2003-A5*.

Snowdon, W. (2020, January 23). *Fracking to blame for earthquakes, seismic clusters in central Alberta.* CBC News.

Steinbrugge, K. V. (1982). *Earthquakes, volcanoes and tsunamis: An anatomy of hazards*. Scandia America Group.

The Canadian Press. (2018, December 21). *B.C. regulator says fracking caused earthquakes near Fort St. John*. CTV News.

Thouret, J. C., Ramirez, J. C., Gibert-Malengreau, B., Vargas, C. A., Naranjo, J. L., Vandemeulebrouck, J., Valla, F., & Funk, M. (2007). Volcano-glacier interactions on composite cones and lahar generation: Nevado del Ruiz, Colombia, case study. *Annals of Glaciology, 45,* 115-127.

Thuy, N. B., Tanimoto, K., Tanaka, N., Harada, K., & Iimura, K. (2009). Effect of open gap in coastal forest on tsunami run-up-investigations by experiment and numerical simulation. *Ocean Engineering, 36*, 1258-1269. https://doi.org/10.1016/j.oceaneng.2009.07.006

Trynacity, K.. (2014). *Fracking linked to Alberta earthquakes, study indicates.* CBC News.

USGS. (2011). *Principal types of volcanoes.*

USGS. (n.d.). *Earthquake glossary*.

USGS. (n.d.). *Mount St. Helens'1980 eruption changed the future of volcanology.*

Volcano Discovery. (2012, October 28). *M7.7 earthquake – 139 km S of Masset, Canada, Sunday 29 October 2012 at 03:04 (GMT)*.

Waythomas, C. F., Scott, W. E., Prejean, S. G., Schneider, D. J., Izbekov, P., & Nye, C. J. (2010). The 7-8 August 2008 eruption of Kasatochi Volcano, central Aleutian Islands, Alaska. *Journal of Geophysical Research-Solid Earth, 115*(B12). doi:10.1029/2010JB007437

Wichura, H., Bousquet, R., & Oberhaensli, R. (2010). Emplacement of the mid-Miocene Yatta lava flow, Kenya: Implications for modelling long channelled lava flows. *Journal of Volcanology and Geothermal Research, 198*(3-4), 325-338. https://doi.org/10.1016/j.jvolgeores.2010.09.017

Xu, X., Wen, X., Yu, G., Chen, G., Klinger, Y., Hubbard, J. & Shaw, J. (2009). Coseismic reverse- and oblique-slip surface faulting generated by the 2008 Mw 7.9 Wenchuan earthquake, China. *Geology, 37*(6)*,* 515-518. https://doi.org/10.1130/G25462A.1

Zobin, V. M., & Jimenez, Z. (2008). Some regularity in the process of re-awakening of andesite and dacite volcanoes: Specific features of the 1982 El Chichon volcano, Mexico reactivation. *Journal of Volcanology and Geothermal Research, 175*,(4), 482-487. https://doi.org/10.1016/j.jvolgeores.2008.02.022