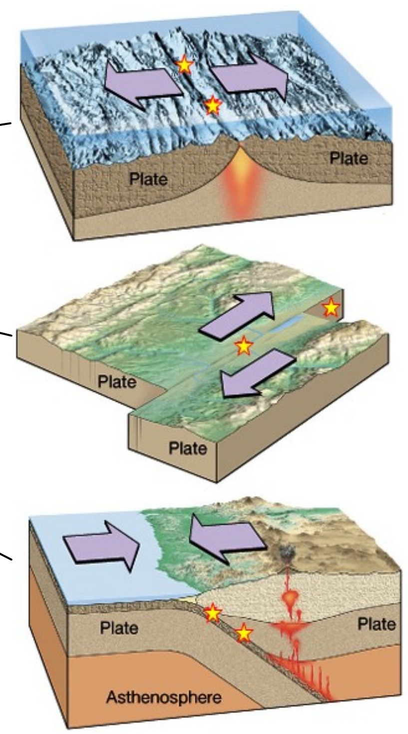
H1) Earthquakes

The plates that make up the earth's lithosphere are constantly in motion. The rate of motion is a few centimetres per year, or approximately 0.1 mm per day (about as fast as your fingernails grow). This does not mean, however, that the rocks present at the places where plates meet (e.g., convergent boundaries and transform faults) are constantly sliding past each other. Under some circumstances they do, but in most cases, particularly in the upper part of the crust, the friction between rocks at a boundary is great enough so that the two plates are locked together. As the plates themselves continue to move, deformation takes place in the rocks close to the locked boundary and strain builds up in the deformed rocks. This strain, or **elastic deformation**, represents potential energy stored within the rocks in the vicinity of the boundary between two plates. Eventually the strain will become so great that the friction and rock-strength that is preventing movement between the plates will be overcome, the rocks will break and the plates will suddenly slide past each other - producing an earthquake [see Fig. 10.4].

A huge amount of energy will suddenly be released, and will radiate away from the location of the earthquake in the form of deformation waves within the surrounding rock. **S-waves** (shear waves), and **P-waves** (compression waves) are known as body waves as they travel through the rock. As soon as this happens, <u>much</u> of the strain that had built up along the fault zone will be released[1].

Earthquakes occur in three main situations:

Divergent boundaries	**Earthquakes at spreading ridges tend to be frequent but small because the rock is too warm to allow significant locking.**
Transform faults	**Earthquakes along transform faults are less frequent, but they can be quite large. Most transform faults are beneath the oceans, but some are on land.**
Subduction zones	**The deeper parts of subduction zones can have many small earthquakes, but in the shallower parts, where the rocks are cool, earthquakes are less frequent and can be very large.**



The severity of earthquakes generated in any area will depend primarily on the degree to which the two plates are locked together along the boundary zone. The degree of locking will depend on several factors, including the rock types, the level of water saturation along the boundary, and the temperature.

[1] Not all of the strain is necessarily released with the first movement on the rock - especially for large earthquakes. Additional movement - which produces aftershocks - can take place for several days and weeks, and in some cases for months and years.

The presence of weak or poorly consolidated rocks will prevent a fault zone from becoming locked. The presence of certain minerals, such as clays or graphite will lubricate a fault zone and also reduce the locking tendency.

Water will lubricate a fault zone, and thus will reduce the tendency for locking to take place. This is particularly significant if the rocks have clay minerals.

Temperature, which increases systematically with depth, will affect the tendency for locking. The higher the temperature the greater will be the tendency for the rocks to behave plastically, and hence the degree of locking will be reduced.

The actual location of an earthquake within the earth, is called its "**focus**" [Fig. 10.2]. The point on the surface directly above the focus is known as the "**epicentre**". The location of an earthquake is determined from seismic records, specifically by measuring the time interval between the first P wave and the first S wave [Fig. 10.8]. The distance from the seismic station to the focus of the earthquake can be determined from the time interval between the P and S events [Figure 10.9] (As a rule of thumb, the distance in km is roughly equal to 10 times the interval in seconds.) By comparing distances from several seismic stations it is possible to determine the location of the epicentre [Fig. 10.10]. If enough accurate data are available from seismic stations relatively close to the epicentre, it is also possible to determine the depth of the earthquake, that is the location of the focus. A detailed examination of seismic data can also provide information on the **focal mechanism**, which is the orientation of the plane of movement. It is important to determine the focal mechanism because this can tell us something about the stress regime in the area, and the geological reason why the earthquake occurred, and hence will allow us to speculate on the likelihood of further earthquakes in the area.

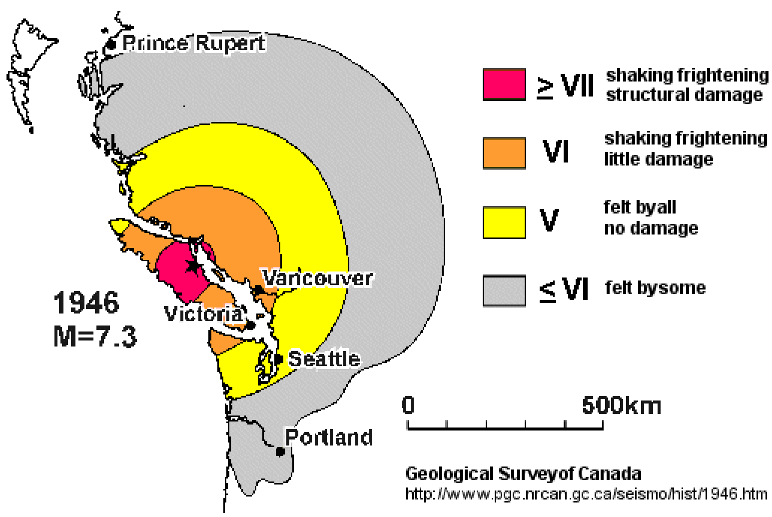
Most earthquakes occur within the range of 5 to 100 km depth, and all very strong earthquakes originate within this range. The maximum depth for earthquakes is 700 km because at greater depths the rocks are too hot and plastic to behave in a brittle manner.

In an area of subduction— like our area—we talk about the relatively shallow earthquakes (< 40 km) as being **crustal earthquakes**, because they take place within the continental crust (of the North America Plate in our case). Most of the deeper earthquakes take place along the subduction zone, or within the subducting oceanic plate.

The **Richter Scale**—more appropriately called the **magnitude scale**—is one means of expressing the <u>magnitude</u> of an earthquake (i.e., the amount of energy released). The largest earthquakes occur along subduction zones in areas of converging plates in places like Chile, Ecuador, Alaska, Japan and southeast Asia. Earthquakes over magnitude 8.5 have been measured in all of these areas. The magnitude scale is logarithmic. A difference of 1 magnitude unit is equivalent a 10-fold difference in the amplitude of the waves on a seismograph, but to a 32-fold difference in the amount of energy released. Each year there are about 20 earthquakes over magnitude 7, and more than 100 over magnitude 6. An earthquake over magnitude 3 can only be felt in the area immediately around the epicentre, and there are tens of thousands of these each year.

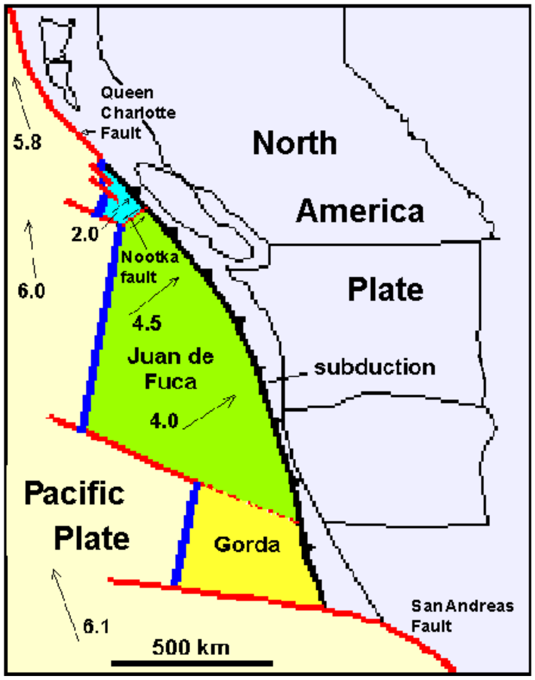
The amount of damage likely to be caused by an earthquake - or earthquake intensity - is measured on the **Mercalli Scale**, which ranges from I to XII [pages 268-269 and Table 10.1]. The intensity assigned to any earthquake is based on observations of witnesses and assessment of damages in the area around the epicentre, and for tens to hundreds of kilometres away. Intensities close to the epicentre will be different from those farther away. Where the intensity is around VI there will be minor damage to buildings. If the intensity is X or more many buildings will be destroyed, and there will be serious damage to dams and bridges and triggering of landslides. Variations in intensity with respect to distance from the epicentre will be affected by regional geology. In Eastern North America, where the underlying rocks are generally old and hard and strong, the effects of an earthquake are felt over a much wider area than is the case for the younger, softer and more variable rocks of western North America.

Mercalli intensities for the 1946 Vancouver Island earthquake (Courtenay area) are shown on the diagram to the right.



The amount of damage caused by an earthquake will also be related to the type of foundations on which buildings are built. Buildings on solid rock tend to be damaged less severely than those on unconsolidated sediments. The explanation behind this is that different geological materials and structures have different harmonic frequencies. Masses of solid rock normally have frequencies of significantly less than one second, while unconsolidated sediments have frequencies in the 1 to 3 second range. Many buildings also have harmonic frequencies of around 2 seconds. The high-energy vibrations from an earthquake are at the slower frequencies (longer than 1 second) and when these waves are transmitted into unconsolidated sediments they can set up vibrations in the sediments with much higher amplitudes than those of the waves themselves - in some cases the amplitudes are several tens of centimetres. These vibrations are then transmitted to the buildings, many of which vibrate at similar frequencies - causing them to collapse. Particularly severe damage can also occur in areas where sediments are saturated with water, since the shaking can cause the sediments behave like a fluid so that they can no longer support buildings.

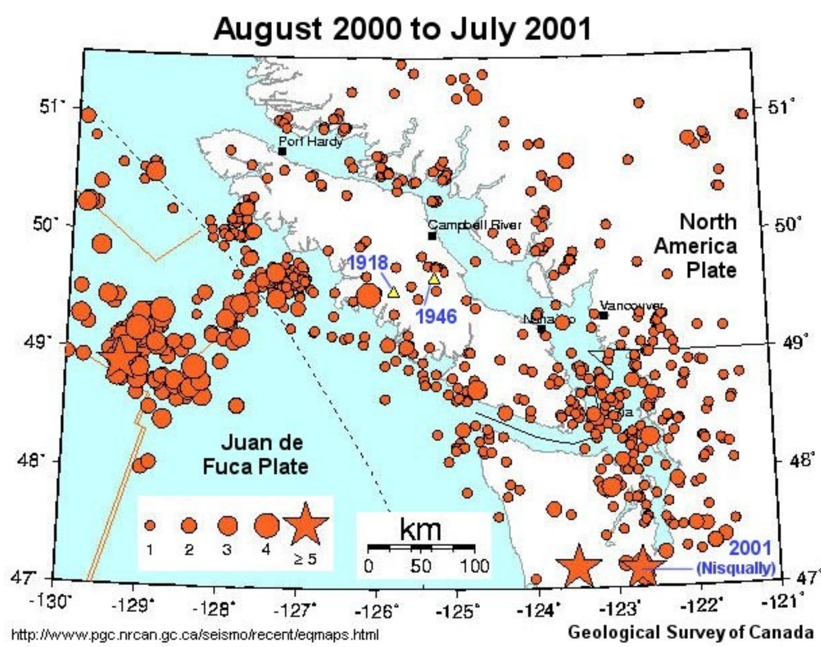
H2) Earthquakes in southwestern British Columbia



The Pacific Plate is moving north relative to the North America Plate, at a rate of about 6 cm per year (see figure to the left). In the area north of Vancouver Island this motion takes place along the **Queen Charlotte Fault** (a transform fault), while to the south of Oregon, the motion is along the **San Andreas Fault** (also a transform fault). In between these two areas there is spreading along the northeasterly trending **Explorer**, **Juan de Fuca** and **Gorda** ridges. The Juan de Fuca plate and Gorda plates are moving easterly at around 4 cm per year relative to North America, and are being subducted beneath southern British Columbia, Washington and Oregon. The Explorer Plate is moving easterly at around 2 cm per year.

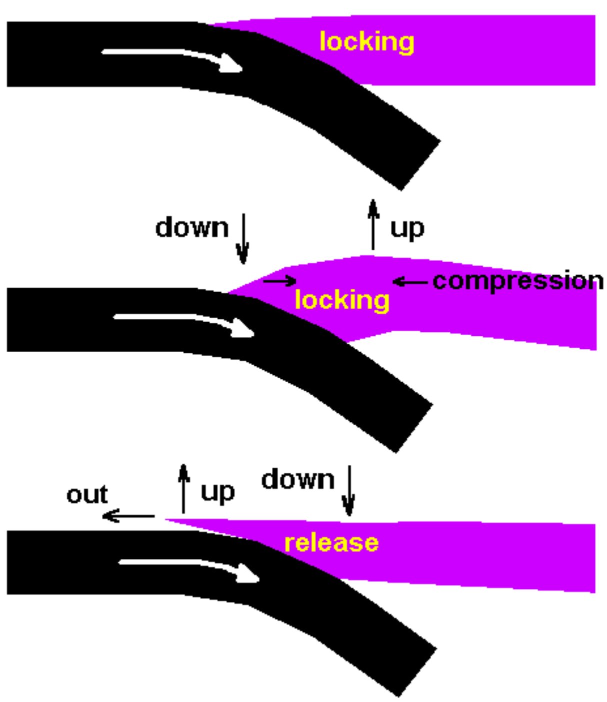
The 2 cm/y difference in rates of movement of the Juan de Fuca Plate and the adjacent Explorer Plate is expressed in motion along the **Nootka Fault** (another transform fault), which extends easterly towards central Vancouver Island.

The earthquake activity of southwestern British Columbia over a one-year period is shown on the map to the right.



The area of greatest activity is associated with the Nootka Fault between the JDF and Explorer plates. There are numerous small earthquakes off the western coast of Vancouver Island that may be related to deformation of sediments in that area. There is persistent earthquake activity in the Puget Sound area. Although it does not show up on this map, many of these earthquakes are quite deep and are interpreted to be related to bending of the Juan de Fuca Plate as it descends beneath the North America Plate. The significant M6.8 Nisqually quake of February 2001 is also shown on this map. This earthquake occurred at a depth of 58 km, which places it at the boundary between the subducting Juan de Fuca Plate and the North America Plate.

There have been two large earthquakes on Vancouver Island in this century, one of magnitude 7.0 in 1918, and one of magnitude 7.3 in 1946. The 1946 quake was significantly larger than the devastating 2010 earthquake in Haiti. Although this earthquake caused damage to buildings along the coast from Campbell River to Nanaimo, most structures survived - largely because almost all buildings then were of wood-frame construction. Only one person died. The exact geological origin of the 1946 earthquake is not known, partly because there wasn't as much seismic data gathered at that time as there would be now, and also because no surface evidence of ground displacement has ever been found. The suggested scenario is that the motion took place along a fault which runs parallel to the length of Vancouver Island to the west of Courtenay - the Beaufort Range Fault. Because we don't really understand the nature and origin of the 1946 earthquake, it is difficult to know when we might expect another similar one.



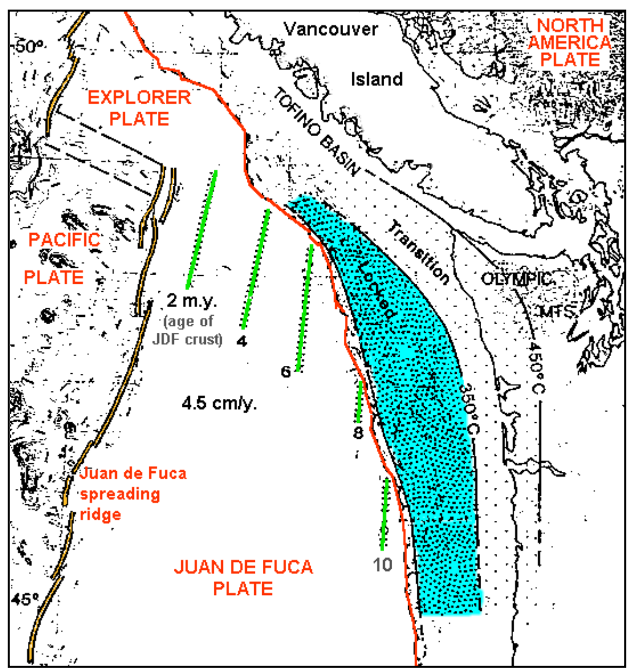
The greatest risk for a very large earthquake in our region is along the subduction zone, where the Juan de Fuca Plate descends beneath the North America Plate. When the plates along a subduction are locked the continental plate tends to get warped upward as shown on the figure to the left. When the strain becomes great enough to overcome the locking, the oceanic plate slips downward, and the warping of the continental plate is released. This commonly results in a dramatic down-dropping of land near to the shore - by as much as several metres in some cases. Major earthquakes, of magnitude 8 or more, have occurred along virtually all of the world's subduction zones within the last century - but there has not been a subduction-zone earthquake in this area for 300 years.

The last major earthquake on the Juan de Fuca subduction zone was on January 26th of the year 1700. The story behind our understanding of the timing of this event is a fascinating one that spans two continents and three cultures. The evidence can be summarized as follows:

As related in First-nations oral histories, a number of First-Nations villages on Vancouver Island were damaged or destroyed. On a winter's night around 300 years ago. All of the inhabitants of one village died as they were washed into the sea.
At many locations along the west coast, from Vancouver Island to California, there is evidence of a sudden drop in the land level (of up to 1 m). The buried soils found in these areas are consistently dated to around 300 years ago. The death of many trees in these coastal areas has been dated using tree-ring methods to somewhere between the end of the growing season of 1699 and the beginning of the growing season in 1700.
There was a major tsunami in Japan on January 27th 1700. The timing of the waves at different locations indicated that they came from the west. As there was no earthquake recorded in Japan at the time, nor in anywhere else where earthquakes were being recorded (which includes most of the Pacific rim), it has been concluded that the earthquake must have occurred along the western coast of North America at around 9 PM on January 26th.

For more information on the 1700 earthquake see: http://records.viu.ca/~earles/1700quake

We now have convincing evidence to suggest that there will be another large earthquake in our area sometime in the future - although we don't know when. The evidence from studies of coastal soil profiles suggests an earthquake frequency of around 500 years (although the pattern is not regular and gaps can be as little as 200 years and as long as 700 years).



All of the available data show that there is convergence on this boundary in the order of 4 cm per year, and geodetic studies of Vancouver Island and the Olympic Peninsula have shown that the plates are locked. For example, there is consistent evidence that Vancouver Island is being compressed and squeezed upward with respect to the adjacent parts of the North America Plate. This type of deformation is consistent with a locked plate boundary (see figure above).

Scientists at Geological Survey of Canada in Sidney, have used estimates of temperature gradients along the subducting Juan de Fuca Plate to determine the extent of the locked zone (see figure to the right). Based on the temperature estimates it has been estimated that there is a locked zone extending over a width of 50 to 100 km and lying just off the coast. This width is less than that observed in most other similar situations. For example in South America the locked zone extends well underneath the continent. One reason for the restricted width is that subduction is taking place relatively near to the spreading centre (the Juan de Fuca Ridge). The subducting oceanic crustal material is only between 4 and 8 m.y. old (green lines on figure above), and thus has not cooled down as much as the 50 m.y. old crustal material subducting beneath South America, or the 100 m.y. old crustal material subducting beneath Japan.

The restricted width of the Juan de Fuca locked zone, and its location off-shore, may limit the potential magnitude and damaging effects of a subduction zone earthquake in this area, however it is still believed that an earthquake of between magnitude 8 and 9 will occur in this area at some time in the future. It could be next month, but it might not be for another 300 years.

The potential for earthquakes in our area is discussed on the website of the Geological Survey of Canada's earthquake research centre in Sidney: http://earthquakescanada.nrcan.gc.ca/index-eng.php and of the British Columbia Geological Survey: http://www.em.gov.bc.ca/Mining/Geolsurv/Surficial/quake/default.htm

Review questions

1. Why would there be no significant earthquakes at a plate boundary where the plates are not locked?
2. Name the three main factors that control the extent to which plates can be locked.
3. If the S-P time interval is 35 seconds, what is the approximate distance from the seismic station to the focus of the earthquake?
4. How much more energy is released by a magnitude 8.3 earthquake, as compared to a magnitude 7.3 earthquake, and to a 6.3 earthquake?
5. Explain the difference between and **magnitude** and **intensity** (i.e., Mercalli intensity) as expression of the size of an earthquake.
6. Why is earthquake damage likely to be more severe for buildings built on unconsolidated sediments as opposed to solid rock?
7. The northward motion of the Pacific Plate relative to the North America Plate takes place along two major transform faults. What are they called?
8. The Nootka Fault is a transform fault, but it is not situated between the crests of any ridge segments. How can we account for its existence?
9. How does the evidence of uplift of parts of Vancouver Island support the idea of a locked segment along the Juan de Fuca subduction zone?
10. Summarize the evidence that a major earthquake occurred in our region in January of 1700.
11. In what way might the relatively young age of the Juan de Fuca Plate have implications for the width of the locked segment on the subduction zone?