The Catastrophic Earth - Natural Disasters

The Shaking Earth - Earthquakes

INTRODUCTION

The two extreme natural catastrophes of 2004-2008 originated as earthquakes: the Sumatra earthquake of December 26, 2004 and the Sichuan earthquake of May 12, 2008. See the following web sites for more information:

Sumatra earthquake (December 26, 2004)

Sichuan, China earthquake (May 12, 2008)

In the first case the devastation was actually caused by the ensuing Tsunami. In the second case the earthquake itself was devastating, and ensuing landslides and the extreme difficulty of accessing all inhabitants in the very rural region significantly aggravated the seriousness of the catastrophe. Poorer, rural villages were hardest hit in terms of human lives and property damage primarily because houses and buildings were old and not built according to any regulations. Close to 25% of the dead were schoolchildren caught under school buildings that collapsed due to shoddy construction.

Can understanding about earthquakes themselves enhance our capacity to minimize the devastation caused by these unpredictable events? Unquestionably. Taking charge of our own fate means spending resources and energy in ways most likely to improve outcomes. There are many choices about how to act and about how to spend resources (time, money, expertise and other resources). Knowledge about how the processes work and what causes the consequences are absolutely necessary for making good decisions about minimizing the effects of natural hazards.

That means that Earth scientists are not the only ones who need to know about earthquakes. Law and policy makers, engineers, politicians, all need to understand so that their decisions will be based on information not superstition and ignorance. The historic earthquake near Lisbon in 1755 and the recent Kashmir earthquake both resulted in about 100,000 killed. These catastrophes were 250 years apart! What do we know today that wasn't known then? Are we not better informed about how and why earthquakes occur? Are we not better able to make living with earthquakes less dangerous?

Left panel: Lisbon 1755, magnitude approximately 8.7, roughly 50 times more energy released compared to the Kashmir 2005 earthquake. Right panel: Kashmir 2005, magnitude 7.6. Approximately 100,000 people were killed in each of these two earthquakes, occurring 250 years apart.

Click here PLAY VIDEO to view a video montage produced by the National Geographic of recent earthquake events.

CONTRIBUTIONS FROM SCIENTISTS

What do scientists do? Careful ***observations*** and experimentation eventually permit them to ***explain*** some phenomenon. If explanations are not sufficient, more observations will be needed. This is often the bottleneck. Making observations can be difficult. NEVERTHELESS, explanations are necessary before scientists can ***anticipate*** or "predict" what might happen at a different time, place, or under different circumstances. Only when we are in a position to anticipate what might happen can we confidently ***recommend*** actions to take which will improve lives.

Perhaps most important to successful scientific contributions to society are appropriate questions that drive the work. What do we need to know? This too will be a theme for this course's lesson on Earthquakes. In this Lesson you will become familiar with earthquake science by practicing these types of scientific thinking.

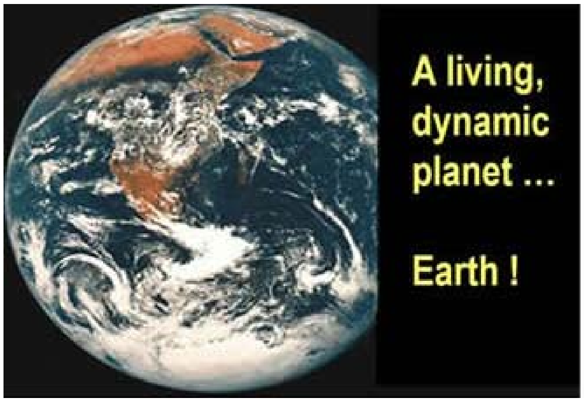
INSTRUCTIONS and QUIZ

Study and make notes based on the online course material and the textbook reading assignments, and read the commentaries that follow. The review questions will allow you to assess your understanding of the key concepts.

This Module will be covered in the Earthquakes Quiz. Consult the FAQs for information on taking the Quizzes.

Links to outside sites are included for your interest. You are NOT responsible for information obtained from web sites outside this course. Some animations and video clips are included.

To understand the causes of earthquakes requires knowledge about geology and physics at a global scale. Understanding about why earthquakes are devastating requires insight into local geologic and engineering conditions. Catastrophes occur at local scales, and energy must travel from the cause to the effect. Our home planet is a dynamic, active place and we, as its stewards, must understand it well in order to live safely and wisely.



In this Module, your goals should be to become more comfortable with the following important scientific concepts: plate tectonics, seismic wave energy propagation, behaviour of geologic faults, and motion and modes of failure of engineered structures (buildings, dams, bridges, etc). These and other areas of knowledge are needed to consider the impact of earthquakes on human society and our efforts to reduce harmful effects of ground motion caused by earthquakes.

QUESTIONS TO CONSIDER

One way to consider objectives is to think about what types of discussions you will be able to participate in once the content has been learned. At the end of this Module, you should be in a better position to participate in discussions about the following questions:

- Where do earthquakes happen and how often do they occur?
- In what ways can "solid" ground move?
- What can be learned about earthquakes by simply observing distribution, size, and timing all around the globe?
- Which earthquakes will be devastating?
- How does earthquake energy travel from the cause to the effect?
- What can we learn about our planet from earthquake seismology?
- How can we live safely in earthquake-prone regions?
- What type of earthquake forecasting is possible?

LEARNING GOALS

Use the following learning goals as a self-assessment tool to help you gauge your understanding of the course material presented in this Module.

By the end of this Module, you will be able to:

1. Understand that stress causes strain, and differences between plastic, elastic, and brittle deformation
2. Describe how a fault slips in an earthquake and why shaking and damage are not always greatest at the epicenter
3. Explain the global distribution of earthquakes (i.e. rare, large and frequent small quakes) in terms of tectonic plate interactions and the forces that drive them
4. Describe how the Earth builds, stores, and releases energy in earthquakes (elastic rebound)
5. Describe the different types of seismic waves and how they move through the Earth
6. Describe how an earthquake is recorded and how we locate the epicenter
7. Compare and contrast the meanings and uses of earthquake magnitude and intensity scales
8. Explain the different magnitude scales, which one is best for large quakes, and why
9. Explain factors that determine earthquake intensity
10. Describe how local ground conditions can affect shaking
11. Understand the principle behind early warning systems, and know how much warning time they can give
12. Explain what we can and cannot predict about large earthquakes

13. Explain the difference between forecasting and prediction
14. Predict how local ground conditions will affect the duration and amplitude of shaking
15. Identify fault zones that could produce an earthquake damaging to Vancouver
16. Make informed decisions about earthquake safety - how to act, how to prepare
17. Understand the basics of how buildings can be designed or retrofitted to better resist collapse or damage

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ORGANIZATION

The Shaking Earth contains the following five units (A - E).

UNIT	TOPIC
A	**Global Distribution:** Where and how often do earthquakes occur, especially in the Pacific Northwest?
B	**Earthquake Sources:** What observations and explanations do we have about the source of an earthquake?
C	**Seismic Energy and Waves:** What observations and understanding do we have about the energy that travels away from earthquakes?
D	**Forecasting:** What is the difference between "prediction" and "forecasting"? How can we use current understanding to forecast where and when an earthquake occurs and what effects it will cause?
E	**Engineering for Survival:** How is current knowledge used to make recommendations about how to survive with modern infrastructure in earthquake zones?

READINGS

Read all of **Chapter 2**.

UNIT	TOPIC
A	Global Earthquake Distribution

Outline

In the introduction we outlined how scientists conduct their work. Scientists:

Observe... Explain... Predict... Recommend...

Generally, science research work is driven by real needs. In our part of the world (the Pacific Northwest in general, and the SW corner of BC in particular), some of the important questions scientists ponder include:

- When was the most recent earthquake in BC?
- How often do they occur around here?
- Where do they occur?

We will follow this line of thought in this Unit, following this Outline:

1. Observations about local (Pacific Northwest) earthquakes
2. How are such observations made?
    - Detecting ground motion
    - Locating ground motion
3. Global distribution of earthquakes
4. Connecting earthquakes to Plate Tectonics
5. Back to SW British Columbia

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1. Observations about Local (Pacific Northwest) earthquakes

When was the last earthquake to hit British Columbia? Yesterday? Last week? Last month? Last year? February 28, 2001? How would you find out? Many resources exist to track daily or even hourly global seismicity, or seismic (earthquake) activity around the world. For example, information about global activity can be found at:

http://www.iris.edu/seismon/

In British Columbia, the Canadian Geological Survey (Pacific Division, Sydney BC), publishes maps and tables summarizing earthquake activity over the previous 30-day or 12-month periods on their web site:

http://earthquakescanada.nrcan.gc.ca/index_e.php

For most recent 30-day period (August-September 2011), earthquakes occurred as shown on the map in Figure EQ.1.

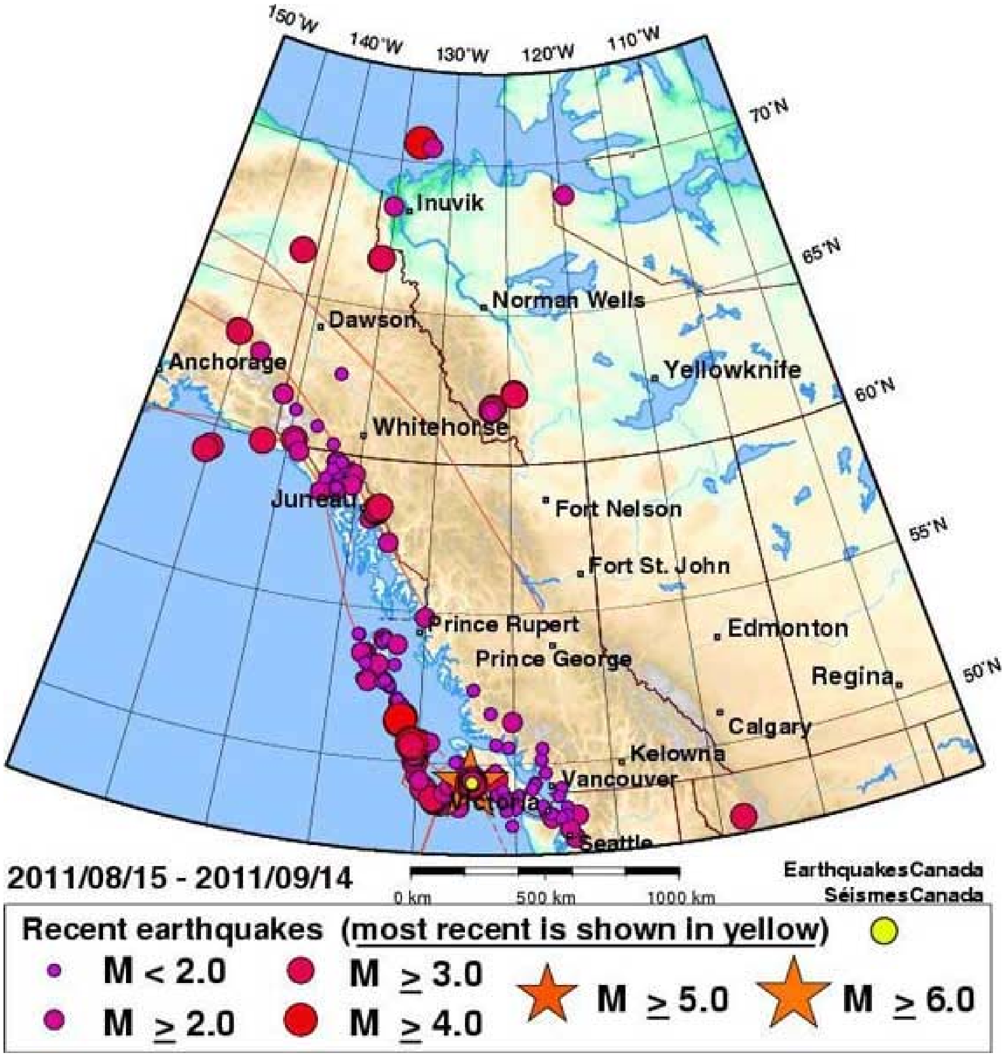


Figure EQ.1 Earthquakes in Western Canada between August 15 and September 14, 2011. As indicated by the legend, dots show earthquake locations, their size indicates the size of the earthquake. Stars are "big" earthquakes. The yellow dot was the earthquake recorded most recently before the map was saved. From NRC-GSC, Pacific Geo-science Centre, Sydney B.C.

What can you observe by looking at this map of earthquakes? Most earthquakes seem to occur in specific areas, but there are a few single ones that don't follow the pattern. Evidently, earthquakes do not occur with equal likelihood everywhere. Later we will learn why they cluster in the southwest of B.C., especially offshore.

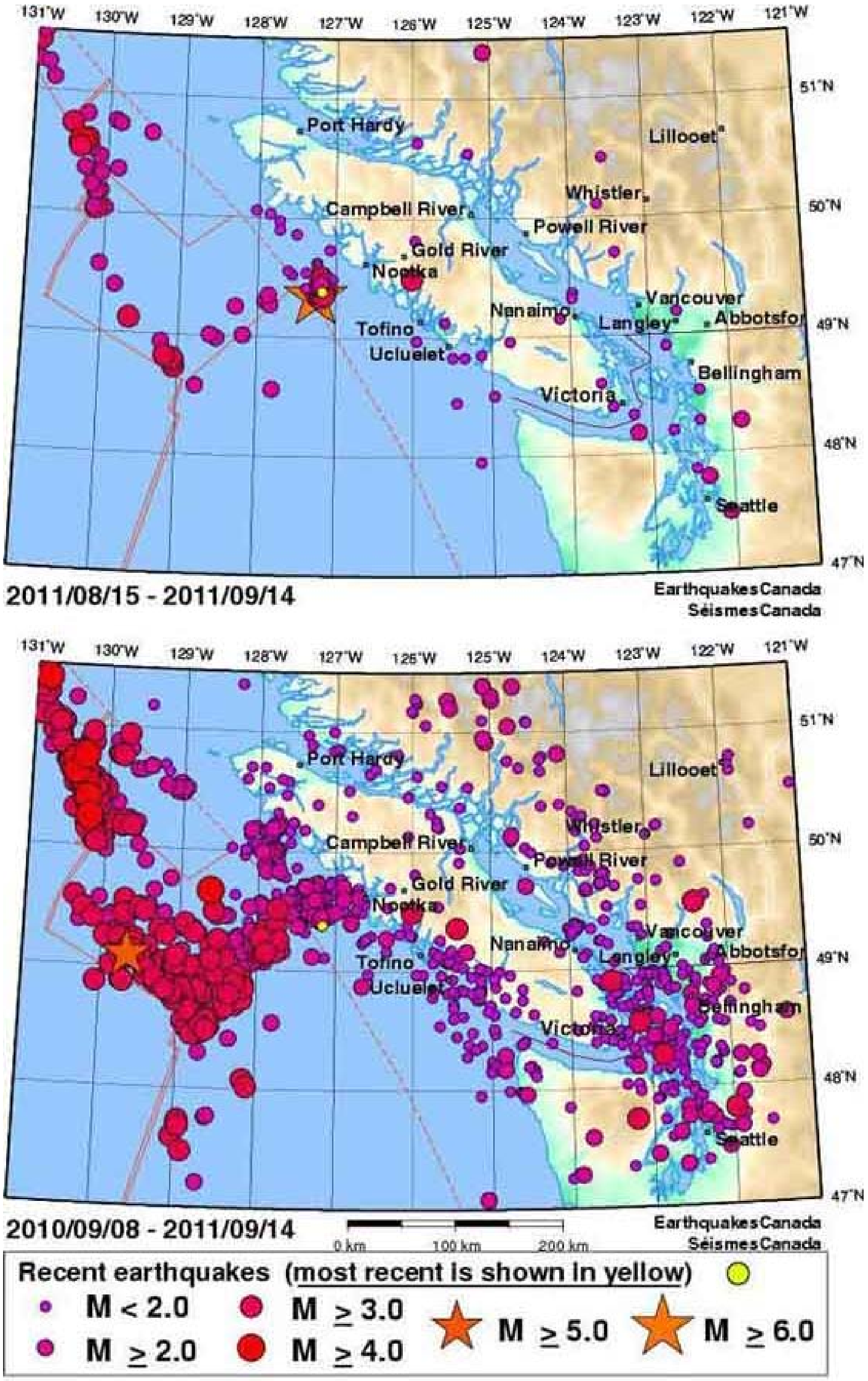


Figure EQ.2 top panel: Earthquakes in Southwest British Columbia over the most recent 30-day period, between August 15 and September 14, 2011. bottom panel: Earthquakes in the same region over a one-year period, between September 8, 2010 and September 14, 2011. Legend is as indicated for Figure EQ.1 above.

Let us look at the region close to home, Southwest BC, as shown on the top panel of Figure EQ.2. Notice how all the little earthquakes are close to, or on land, while the larger quakes are offshore and appear to cluster around specific areas.

Does this pattern persist for longer than a month? The map on the bottom panel in the figure shows all earthquakes for a year. Do you think these observations suggest that the pattern persists for a year? Yes, but with one or two exceptions. Generally larger earthquakes occur to the west of Vancouver Island, especially along a line pointing offshore starting about 2/3 up the coast. These are caused by Earth motion near the Nootka Fault. On this map, known faults are identified by lines (they are more visible on the top panel of Figure EQ.2).

This seems like a lot of earthquakes. Were they all felt by people? No. In fact all except about 4 (including the most recent one on September 9) of these quakes were too small to be felt. This is an example of how severity and frequency of phenomena are usually inversely related (as you learned in the previous Module of the course).

Have these observations contributed to society's needs? Yes, to some extent. We now have a better idea of where earthquakes occur and where bigger ones are most likely to occur. We also know more about how often earthquakes occur in our part of the world. Simply divide the total number of earthquakes in Figure EQ.2 by 365 and you have an average of how many 'quakes per day! Furthermore, these maps provide information about which areas of our province are more prone to earthquakes. This alone is significant information for individuals and for local governments. For example it helps with decisions about how much time and money to spend on earthquake preparedness. We will consider mitigation and preparedness in a later Unit.

But it would be more useful to know how many earthquakes there were of a specific magnitude. This simply involves categorizing the list of earthquakes according to size (access the list from Geological Survey of Canada). Summarizing these events in a bar graph like the one in Figure EQ.3 below is one way of analysing this question.

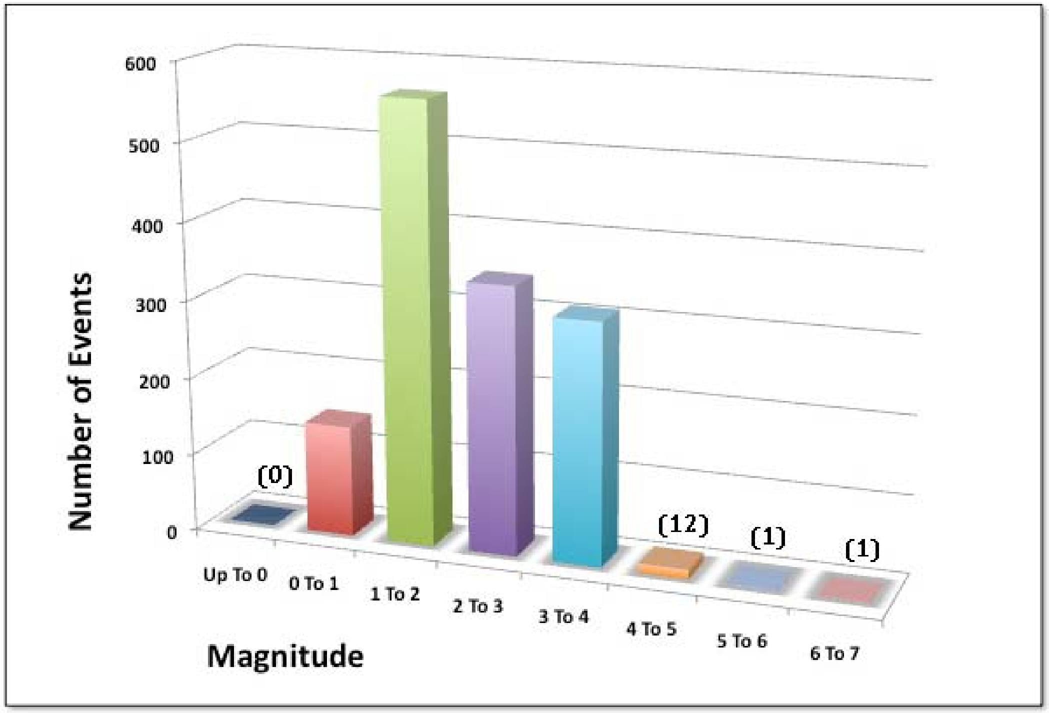


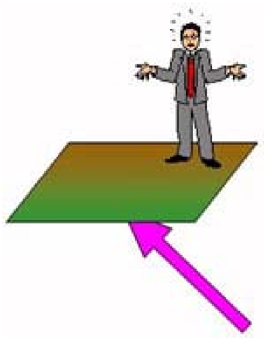
Figure EQ.3 Distribution of magnitude for earthquakes in Southwestern BC, September 2010 to September 2011. Numbers in parenthesis show the actual number of events for quakes with magnitude less than 0 and more than 4.

By organizing our observations in this new form (a graph instead of a map) it becomes quickly evident that the vast majority of earthquakes were less than magnitude 4 (magnitude is explained in detail later). This certainly is good news because small earthquakes simply are not dangerous. Unfortunately, it only takes one earthquake larger than magnitude 6 to cause major damage (see for example, Kobe 1995).

Now our observations have informed us about location and frequency, not just about earthquakes in general, but about the ones we should be worried about. The next question we should consider is "How were these observations made?"

One last note about Figure EQ.3 above. It seems to suggest there could have been earthquakes with magnitude less than 0. Does this make sense? Yes, it does because the scale for earthquake magnitude is *logarithmic*. Negative logarithm values mean that the original number (before converting to logarithms) had a value between 0 and 1. Therefore the amount of energy released by these earthquakes was very small. There will be more on magnitudes in a later section.

2. How are observations made?



In the previous section, we talked about making observations to answer "Where" and "How often" for earthquakes in the Pacific Northwest. However, we realized that there were many recorded events that were too small to "feel". Is this a contradiction? "Too small to feel", yet they were recorded? What must be done to observe such events? How do we "observe" what we can't "see"?

The answer is in the instrumentation. Scientists are continuously faced with developing tools and techniques to observe phenomena beyond the reach of our human senses. In this case, our goal is to observe ground motions that are too small for humans to feel.

Detecting Ground Motion. Let's be careful about just what we need to observe. We want to detect slight ground tremors, but we need to keep track of exactly when they occur. In fact, it would be sensible if we could draw a graph that showed ground motion related to time. Such graph is called a seismogram, and an example is shown in Figure EQ.4.

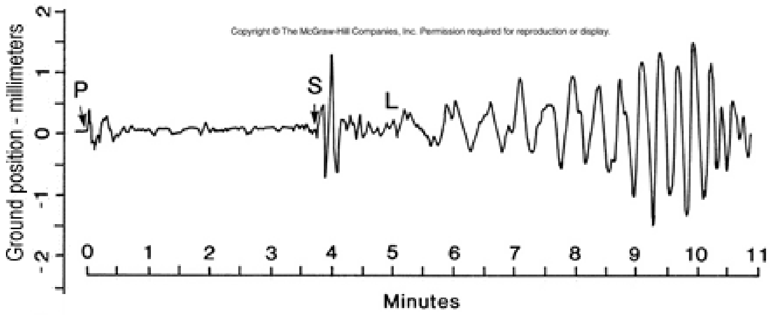


Figure EQ.4 A seismogram. The instrument records ground position. As time passes, slight ground motions are recorded and the complete pattern of ground motion is visible for 11 minutes. The labels P, S, L indicate characteristic components of the seismic wave. These will be discussed in detail in the Unit C of this Module.

How are slight ground motions detected and recorded? Here is a cartoon image of the fundamental principle underlying the action of a "seismometer" (a meter that responds to seisms - i.e. ground motions.)

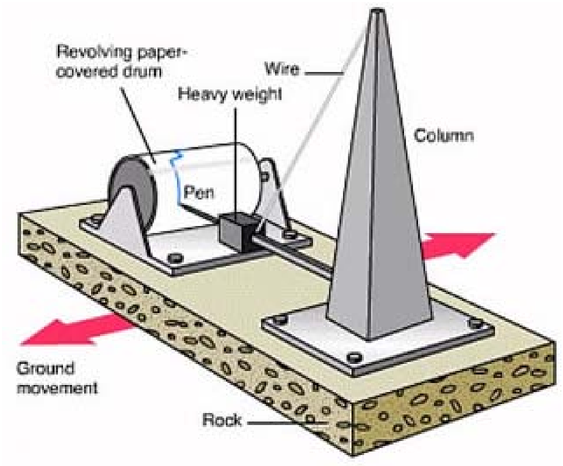


Figure EQ.5 A simple illustration of how a seismometer works. A frame and column fixed to the Earth supports a suspended mass (heavy weight) attached to a pen. When the ground (and frame) moves, the weight and pen tend to stay put. If a roll of paper is firmly attached to the same frame as the column, it too will move relative to the pen. Basically, the moving ground drags the paper across the fixed pen, which stays in place because it is supported by the suspended weight. Today we use digital versions of this scheme, but the basic idea has not changed.

Click here for an animated illustration of the suspended pen seismometer.

DID YOU KNOW?

The **Pacific Museum of the Earth** have seismograms on display that record earthquakes off our coast. Visit the Museum, located at the UBC Earth and Ocean Sciences Main Building or go on a virtual tour.

Locating Ground Motion. So now we can address our goal to detect ground motion too small to be felt. But do we have to place an instrument everywhere an earthquake might occur? Of course, this would be impractical. So there is a second question: "How can ground motions be used to determine where the actual earthquake occurred?"

We can draw an analogy between seismic questions and detection of sound. We all know sound energy travels. We also know that we are quite good at estimating the location of the sound's source because we have two ears that are both detectors. Our ear/brain system can detect *differences* between when sound reaches our ears. Seismology works the same way. All we have to do is detect motion from two sensors, then use the difference in time when seismic energy (ground motion) reaches the two instruments to estimate the location.

In fact, three seismometers are needed to get a unique estimate of the source of the seismic energy (the earthquake). We record the time ground motion is observed at 3 or more locations then use what's known about energy travel times to find source location. There are of course some challenges:

a. The Earth is spherical so travel times must be recorded accurately. We have to be sure that what was recorded at different locations actually came from the same event.

b. In addition, the Earth's composition is complex. The signals travel through many different types of materials. The challenge is to know about these materials in order to estimate travel times, but it turns out that we need to know the travel times in order to guess what the materials are!

This rather complex situation is explained later in this Lesson.

So, assuming we can record ground motions caused by distant earthquakes, we are now in a position to make recordings (observations) that allow us to ask "What is the **global** distribution of earthquakes"? Results of many decades of such observations will be presented in the next topic.

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3. Global distribution of earthquakes

Where do earthquakes occur around the world? Most textbooks show maps of the global distribution (for example, see *Keller et al. Figures 2.8 and 2.9* one of which is shown below).

▲ **FIGURE 2.8 GLOBAL EARTHQUAKE DISTRIBUTION** A map of global seismicity (1963–1988, **M** 5+), showing epicentres of plate boundary (heavy concentration of dots) and intraplate (isolated dots) earthquakes. *(U.S. Geological Survey National Earthquake Information Center)*

The same information is plotted again in the next figure (Figure EQ.6). Some questions worth considering are (1) "How many observations of earthquake signals were needed to generate this map?" and (2) "How long might it have taken to build this map?" Without going into details the answer is *nearly a century of work*. The most interesting feature of these maps is the definite pattern of earthquake locations around our planet. **The vast majority of earthquakes occur at the margins of Earth's tectonic plates.**

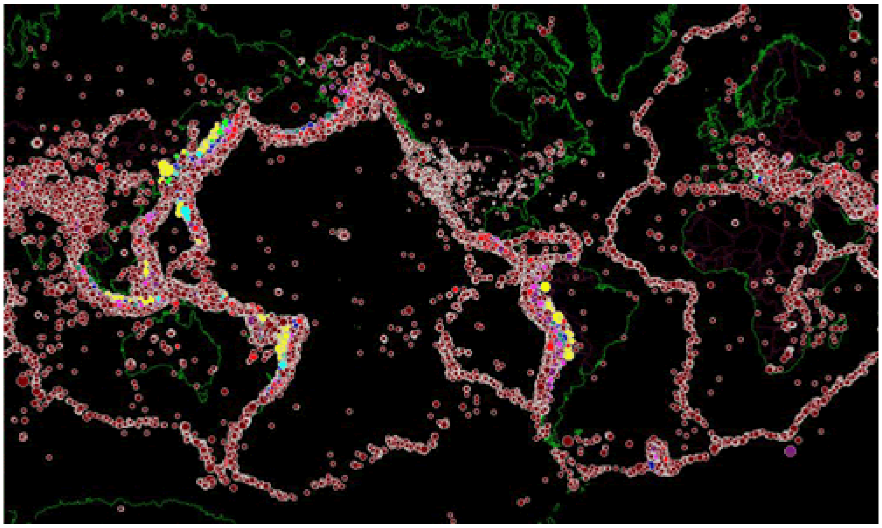

Figure EQ.6 Global earthquake locations. The legend is given below. Map generated using the free software called "Seismic/Eruption" found at http://bingweb.binghamton.edu/~ajones/.

Figure EQ.7 is the same map as Figure EQ.6 but only the largest of earthquakes shown. These earthquakes occur in rather predictable locations, and the very largest of recorded earthquakes have all occurred on the edges where continents meet oceans. Can you imagine the implications of this information for hazard assessment and for mitigation efforts?

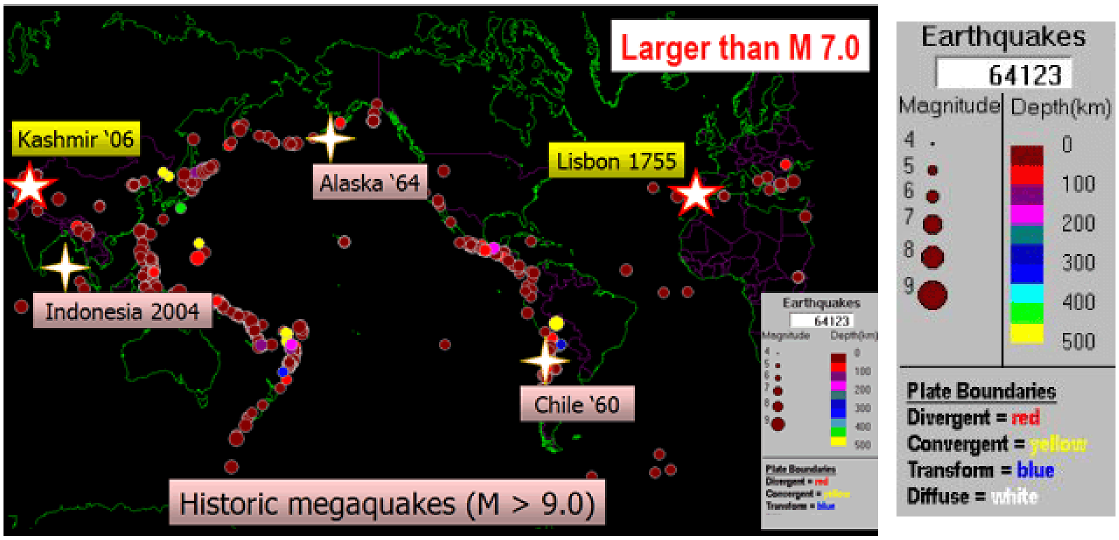

Figure EQ.7 Global locations of earthquakes with magnitude >7.0 with emphasis on historic megaquakes (magnitude >9.0). On the right is the legend used for the 2 maps in Figures EQ.6 and EQ.7. These maps were generated using the free software called "Seismic/Eruption" found at http://bingweb.binghamton.edu/~ajones/.

Having seen (observed) where earthquakes occur we should ask "Are we addressing *our* 'needs'?"

- When and where do earthquakes occur in BC? What must be observed to obtain this information?
- How are observations made?
- What is the global distribution of earthquakes?
- Do we know more now than the Lisboans did in 1755?
- Are we any better off now than a year ago? a few decades ago? a century ago?

We have indeed begun to obtain useful information for our 'needs'. However, observations do lead to the question "WHY?". *Analyses* are needed before science can continue further.

In fact, the patterns of earthquakes are very useful for identifying where on the Earth's crust is there the greatest tendency to break catastrophically. Earthquake studies not only help decide whether those living in specific locations on Earth need to pay particular attention to minimizing the effects of earthquakes. These studies also help us understand the underlying causes for earthquakes. This is our next topic to consider.

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4. Connecting Earthquakes to Plate Tectonics

Shown below is Figure EQ.6 from the previous section. We know about the existence and behaviour of Earth's tectonic plates and the resultant concentration of earthquakes at their boundaries. We will be learning more on this topic in this section. Let us begin with a simple characterization of tectonic plates and a discussion of how they relate to earthquakes.

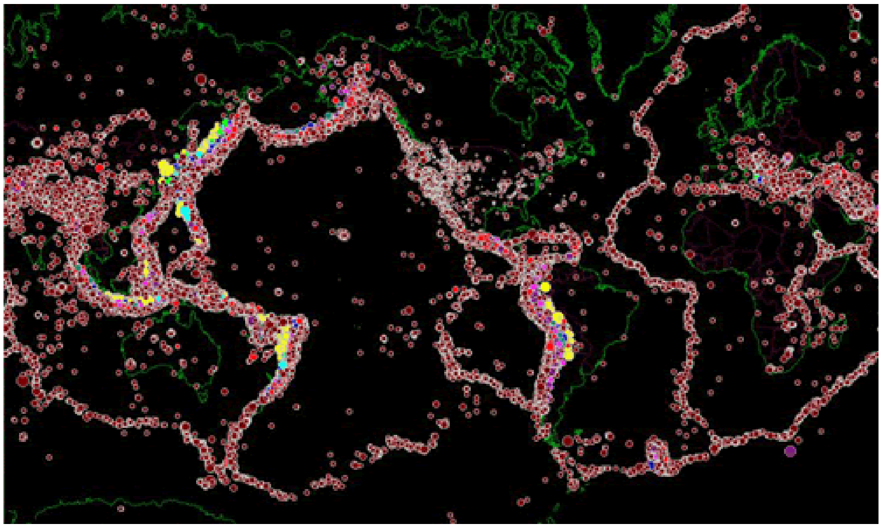


Figure EQ.6 Global earthquake locations.

The Earth's lithosphere is composed of 9 major plates (and many minor, little plates). There are 2 types of plates: oceanic and continental plates. Oceanic plates are fast moving (cms/year), young (less than 200 million years old), are formed at mid-ocean ridges, and destroyed at subduction zones. Continental plates are slow moving (mms to cms/year), much older than oceanic plates, and do not get subducted because they are more buoyant than oceanic plates. See Figure EQ.8 below.

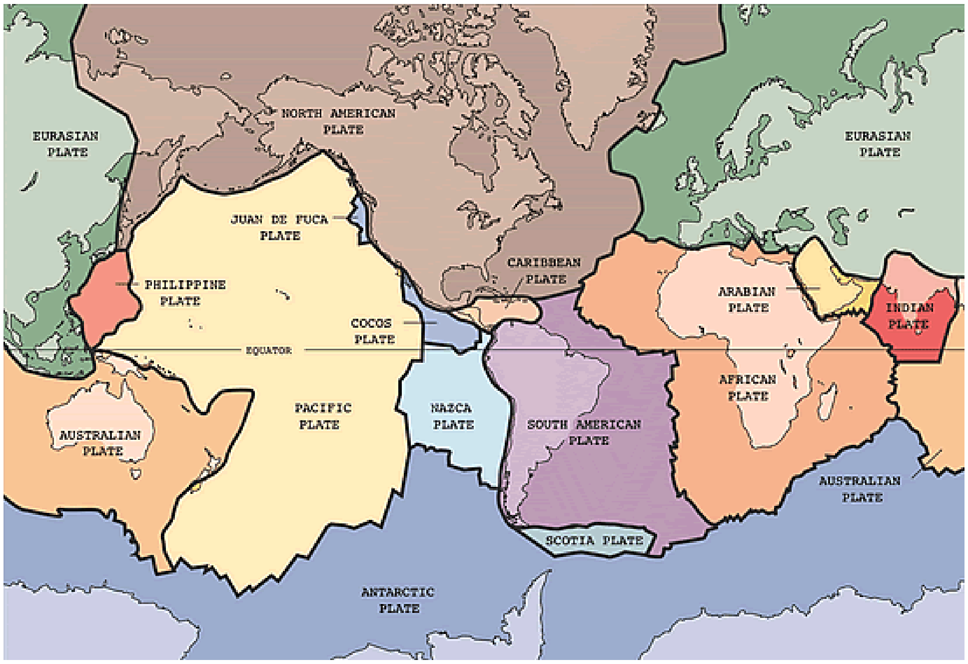


Figure EQ.8a Tectonic plates of the Earth. Retrieved from USGS.

With plate motion varying from close to 0 to a maximum of roughly 15 cm per year, imagine the consequences of shifting plates around on a sphere. Because the plates have nowhere to go, they will have to interact with each other. There will be places where they collide, places where they are moving apart, and places where they are sliding past each other.

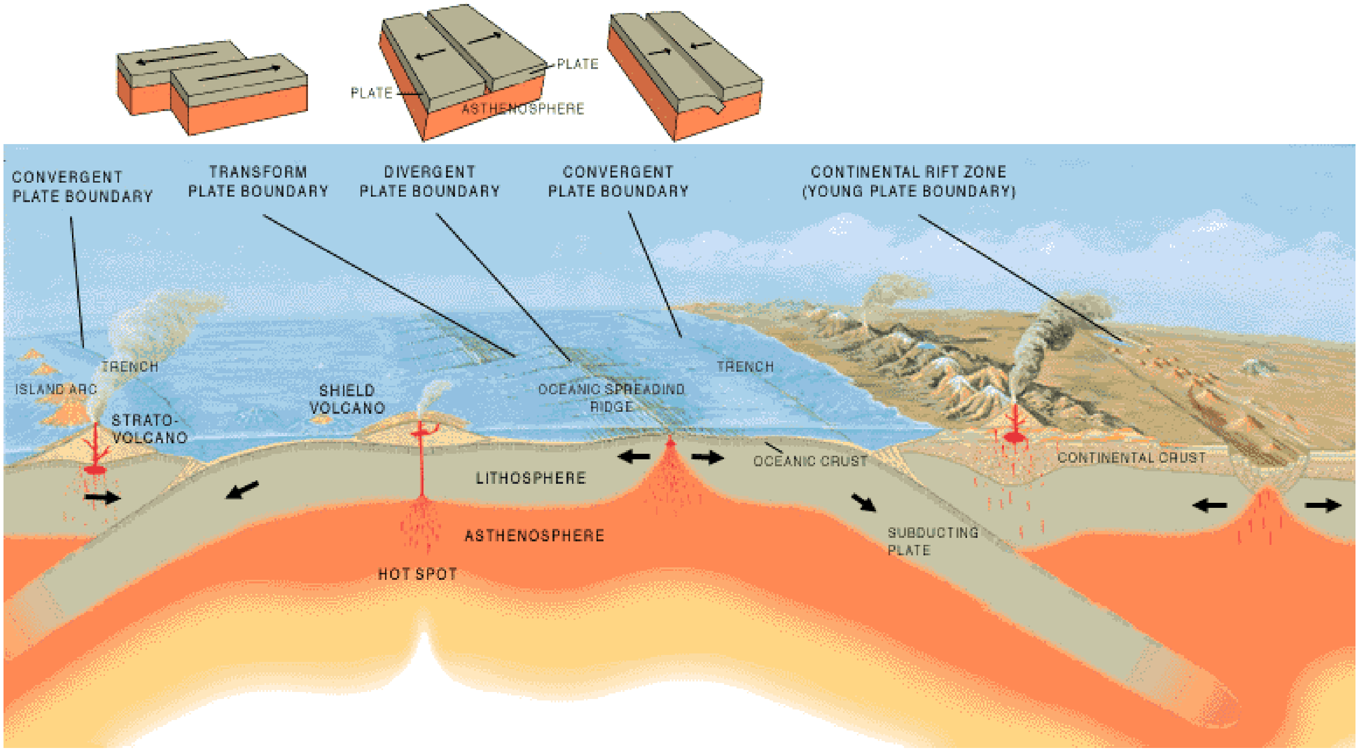


Figure EQ.8b Types of Plate Boundaries. Artist's cross-section illustrating the main types of plate boundaries: convergent, divergent, and transform. Cross section by José F. Vigil from This Dynamic Planet. It is a wall map produced jointly by the U.S. Geological Survey, the Smithsonian Institution, and the U.S. Naval Research Laboratory.

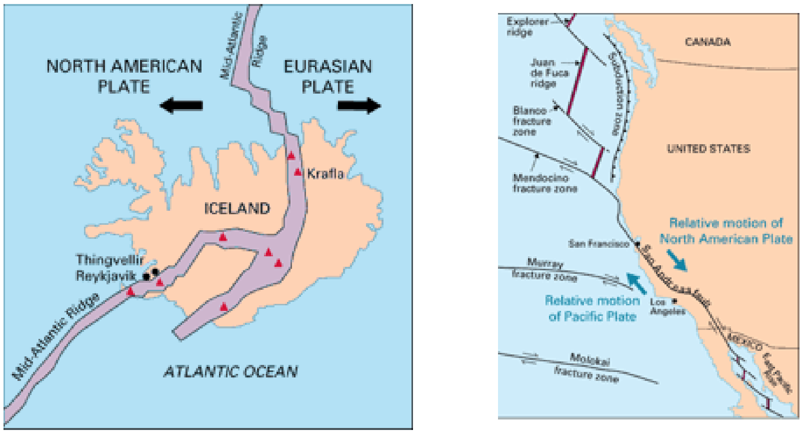
There are in fact 4 types of boundaries (refer to figures above and below):

1. **Divergent**. In this type of boundary, plates are moving apart, leading to tension or stretching. Due to the tensional forces, rocks break and many small(ish) earthquakes occur. Divergence occurs at mid-ocean ridges or spreading centres.

2. **Transform.** Here, plates move past each other, leading to shearing forces between plates. Rocks are being sheared, thus many earthquakes occur here. These are moderate to large 'quakes, but not as large as those that occur in the next 2 boundary types below.

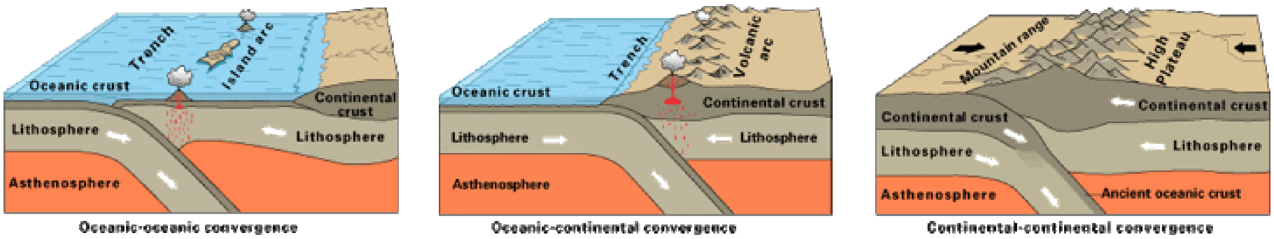
3. **Convergent type 1**. In this and the next type, plates move toward each other and collide, leading to compression. In this type, one of the plates is less dense than the other (see examples below). Thus, one plate subducts or dives under the other at subduction zones. Rocks are compressed and extensive small to very large earthquakes occur. In fact, the largest earthquakes occur at subduction zones.

4. **Convergent type 2**. Same as in Type 1, plates move toward each other and collide, leading to compression. Here, neither plate is subducting or plunging, thus the plates crumple up like a rug being pushed together. Rocks are compressed and extensive small to very large earthquakes occur.



(a) divergent boundary

(b) transform boundary



(c) convergent type 1, ocean-ocean

(d) convergent type 1, ocean-continent

(e) convergent type 2, continent-continent

Figure EQ.8c (a) The Mid-Atlantic Ridge (MAR) is mostly an underwater feature. On Iceland, portions of the MAR is above sea level. This section is known as the Reykjanes Ridge; (b) The Blanco, Mendocino, Murray, and Molokai Fracture Zones are some of the many transform faults that scar the ocean floor and offset ridges. The San Andreas Fault is one of the few transform faults exposed on land; Schematic diagrams of a (c) oceanic-oceanic convergent boundary; (d) oceanic-continental convergent boundary; and (e) continental-continental convergent boundary. Maps and figures from the U.S. Geological Survey.

CHECK YOUR UNDERSTANDING:

Which of the plate boundaries above would you expect to be associated with the LARGEST earthquakes?

a. divergent b. convergent c. transform d. intraplate e. all of them

Figure EQ.9 illustrates the concepts of plate boundaries. Segments of divergent boundaries are shown all along the southeast side of the Pacific Plate. Convergence occurs all along the western and northern edges, mostly at a "subduction zone". In fact, the Pacific Plate is diving under its neighbouring plates along these edges. Along the eastern edge of the plate (at the boundary with the North American Plate) there are segments of a strike-slip or slide-past boundary. The famous San Andreas Fault in California is part of this boundary.

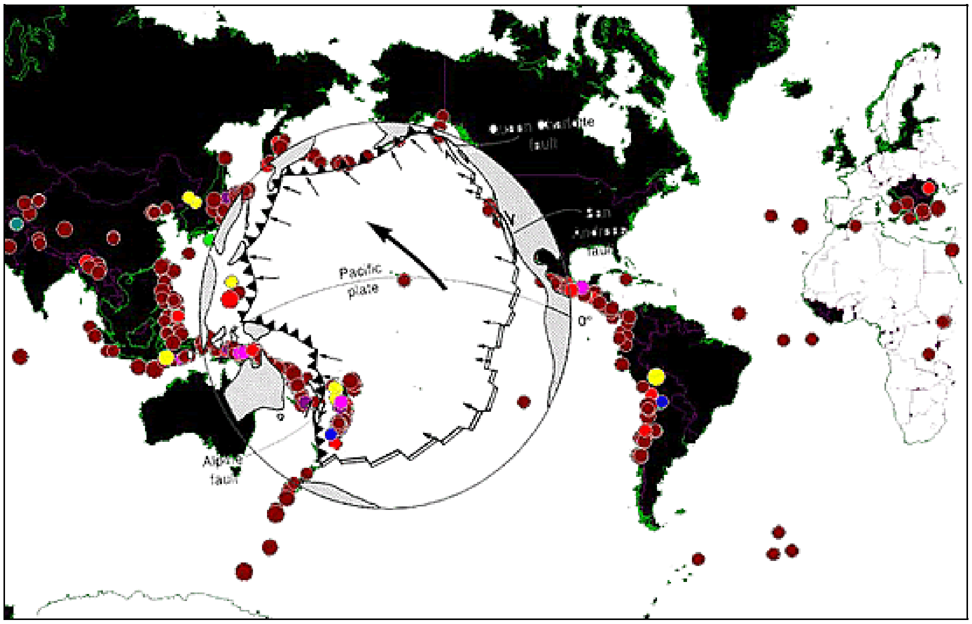
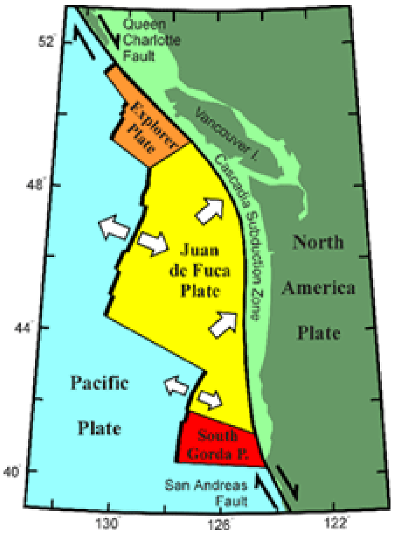


Figure EQ.9a (top) An outline of the Pacific plate on the Earth's sphere showing its major plate boundaries. Under this outline is a stretched map of the world.



(left) Cartoon of the west coast of North America showing where the three types of plate movements take place. Cartoon from Natural Resources Canada Earth Sciences Sector

A cartoon of the west coast of North America illustrates 3 out of the 4 plate boundary types closer to home (refer to cartoon above). The Queen Charlotte and San Andreas Faults on the northern and southern ends of the map are transform margins where plates are sliding past each other (note the thin black arrows indicating the direction of movement). Can you tell which plates are sliding past?

Note the Juan de Fuca plate (yellow) and how it interacts with adjacent plates. To the west, it is diverging from the Pacific Plate at the Juan de Fuca Ridge (a mid-ocean ridge). To the east, the Juan de Fuca is subducting underneath the North American Plate. This means that the Juan de Fuca is growing on its western side as it is being consumed on its eastern side (note the large white arrows indicating plate movement). As we would expect, this region experiences significant earthquake activity. Along the **transform faults** in the offshore region (e.g., the M=8.1 Queen Charlotte Island earthquake of 1949); within the **convergent** subducting ocean plate (e.g., a magnitude 6.5 earthquake beneath downtown Seattle in 1965); along the **divergent** Juan de Fuca Ridge which separates the Juan de Fuca Plate from the Pacific Plate; and within the continental crust (e.g., a magnitude 7.3 earthquake on central Vancouver Island in 1946).

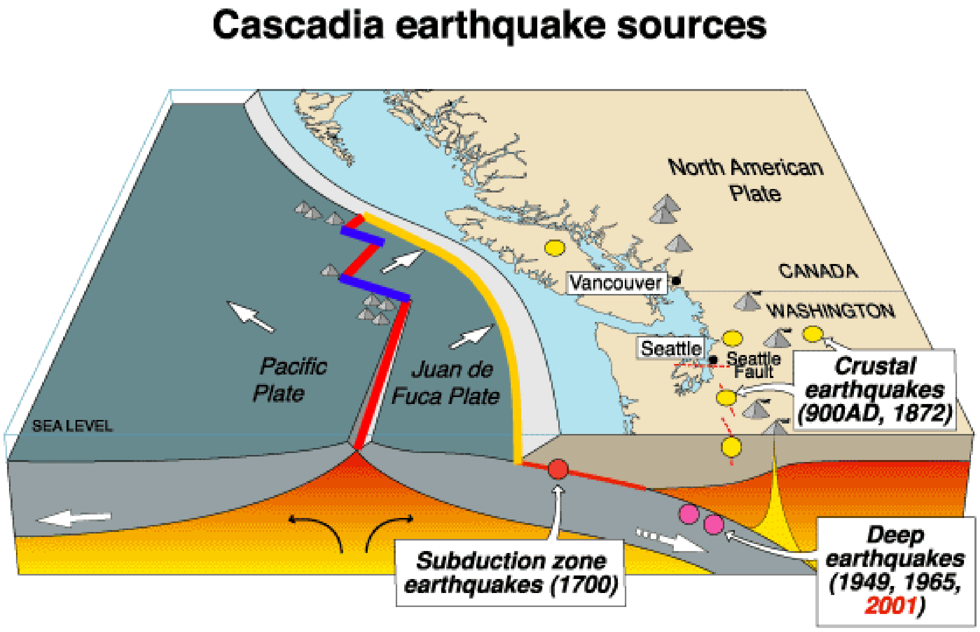


Figure EQ.9b Large earthquake events in the Cascadia region. Schematic courtesy of Natural Resources Canada.

Figure EQ.9b above shows that the Cascadia region has experienced large earthquakes not only at the subduction zone, but also at two other fault locations. Crustal and deep earthquakes have been produced at faults **within the shallow crust** and **in the subducting slab**.

What makes the plates move across the Earth's surface? Two forces drive the motion as shown to the right in Figure EQ.10. One, gravity pulls on the denser portions of plates that are diving under others. Two, heat within the Earth causes convection cells to cycle within the mantle. What does this cycling mean?

The process is similar to fluid motion in a coffee cup that is heated gently. Earth's core is very hot (the outer core is essentially molten iron). Heat rises, thus some regions of the mantle (the huge zone of soft rock between the outer core and the lithosphere) rise because of the heating from the core. As rising material reaches the surface, some material is ejected as lava, but much of it rolls over and carries on moving across the surface. As it cools, it becomes more dense and sinks.

Eventually magma becomes dense enough to no longer be buoyant, thus it sinks. Thus, there are regions of hot rising magma, regions of cooler descending magma, and connected regions with lateral motion. Hard, rigid, plates are dragged across the Earth's surface by these regions of lateral motion.

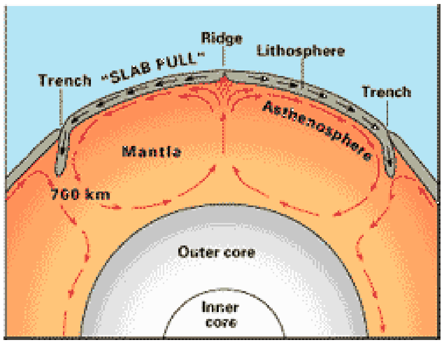


Figure EQ.10 Conceptual drawing of assumed convection cells in the mantle. Retrieved from http://pubs.usgs.gov/publications/text/unanswered.html

To summarize this process, less dense material (crust) floats on top. Convection causes circular motion within the Earth's mantle causing the crust to get dragged across the surface. At collision zones, older, cooler, denser material dives, and stiffer slabs get pulled. At spreading centres new crust is created causing plates to move apart.

This is a simplified explanation based upon a wide range of scientific observations gathered by scientists from various fields of discipline over many years. We will learn about some of the information used to develop this understanding, but many of the details are very technical. You are welcome to check out several courses offered here at UBC by the Department of Earth and Ocean Sciences that provide opportunities for learning more about these geoscientific details.

The Theory of Plate Tectonics has had a profound impact on all scientific investigations about our planet. There are many lines of evidence that support the theory - so much that there is no doubt about its usefulness. Our text book includes a discussion on some of these ideas, including:

- actual measurements of plate motion using GPS technology
- ocean floor topography, depth, thickness, and ages
- remnant magnetism on the ocean floor
- regions of active plate building (rifting)
- geology and paleontology across plate boundaries
- fault plane solutions showing directions of motion at faults

What has this to do with global earthquake distribution? Earthquakes occur primarily at plate boundaries. The largest earthquakes occur where the largest amount of energy is being accommodated, i.e. at collision zones (of both types). The world's largest earthquakes occur at collision zones.

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5. Back to SW British Columbia

We started this Unit by considering the needs of people living in the Pacific Northwest. This region, from Northern California to Central British Columbia, is often referred to as "Cascadia". It is a region of relatively high earthquake risk because of the subduction zone that starts just off the coast and extends under the Cascade range of mountains.

We asked, "Where and how often do these earthquakes occur in Cascadia?" Careful observations carried out over many years helped answer these questions. But many other questions can, and should be asked. For example, "When was the last damaging earthquake?" That one is easy: the Nisqually M6.8 'quake of February 28, 2001 and it was felt by many in Vancouver, including those on UBC campus. "Was this a significant event in terms of damage, cost, or lives lost?" Not really. The earthquake source was too deep to cause tremendous damage, but a few lives were lost in the lower Puget Sound region, and there was significant damage to older buildings and infrastructure (roads, bridges, etc.) that were not built to withstand the stresses caused by ground motion (see photos below).

Figure EQ.11 Images of damage to buildings and cars near the Washington Capitol Building in Olympia, WA (left) and to Highway 101 (right). Photos retrieved from The Nisqually Earthquake Information Clearinghouse.

Click here PLAY VIDEO ▶ to view a video composite of the Nisqually event.

Another good question to ask is, "Why are there so many small earthquakes in our region (recall the histogram of earthquakes in Figure EQ.3)?" Answering this question is by no means easy. Hypotheses abound, but obtaining observations that provide support for these hypotheses involves many experts, many studies, and careful integration of all the information.

Where plates converge, the structure of the Earth's surface becomes complicated. This can be demonstrated by bringing two slabs of putty together and watching how they crumple. Figure EQ.12 shows a 3D sketch of plates under and offshore Vancouver Island. In the detailed section (black and white portion) note the pieces comprising the wedge-like section called the "Accretionary Wedge". These pieces are separated by faults. Most of the "little" earthquakes are associated with relatively small motions along these faults which occur as the Earth moves along these faults to accommodate the convergent motion of the two plates.

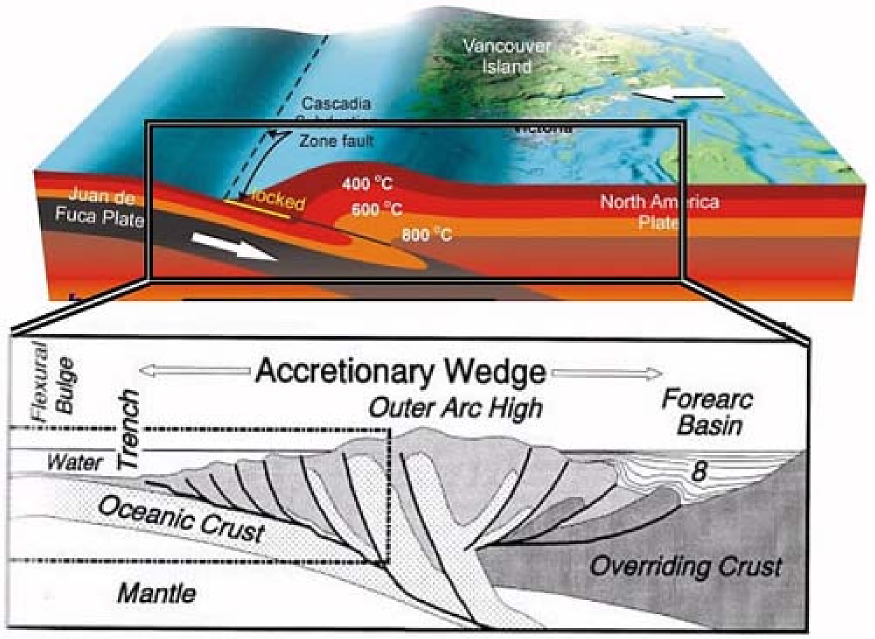

Figure EQ.12 An exaggerated 3D depiction of the convergence zone between the Juan de Fuca plate and the North American plate under Vancouver Island. The blow-up sketch in black and white illustrates how rocks of the oceanic and continental plates are deformed by the tremendous forces of converging plates.

Do observations of small earthquakes in southwest BC show that they are occurring in a similar pattern? Seismic echo sounding reveals detailed images of the Earth between the surface and 60 or so kilometers depth. Seismic echo sounding is an observation technique that involves generating strong pulses that travel through the Earth like sound waves. These bounce off variations within the Earth, and the echoes are detected by numerous seismometers that have been placed in the ground at suitable locations. The resulting pattern of echoes can be processed with sophisticated computer programs to make "echograms" or images of the subsurface. Figure EQ.13 below shows an example produced in the mid 1990's by the Lithoprobe project, a 20-year Canada-wide project directed by Dr. R. Clowes of UBC and involving many scientists as well as industry sponsors.

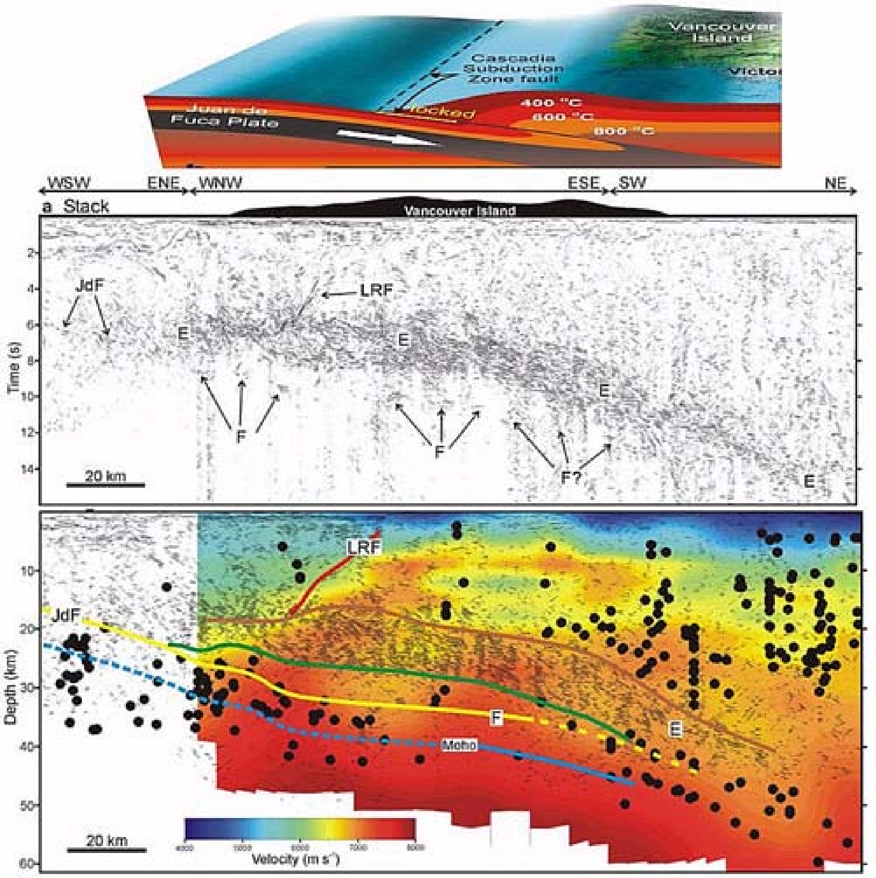

Figure EQ.13 Images of seismic reflection data under the same portion of the Earth shown in Figure EQ.12. The central panel shows the echoes obtained by seismic reflection work. The bottom panel is the same echogram but coloured according to the speed of seismic (i.e. sound) pulses. Black dots indicate locations of small earthquakes. Note that the dots follow patterns that are interpreted as faults above the major feature which is the region between the descending (subducting) plate and the over-riding North American Plate.

Translating observations into understanding is what science is all about. Is basic observation enough to minimize disaster? Perhaps, given the political will to implement policy. But observations alone are not enough to establish the desired "prediction" and "understanding". Some of the 'needs' that must be addressed to better understand earthquakes include:

- Recording all ground motions
- Investigating the mechanisms of geologic faulting
- Studying ground motion, and the stresses within the ground
- Experimenting with construction designs

We will pursue many of these and other issues in the next units of this Module.

UNIT	TOPIC
B	Earthquake Sources

Outline

We learned that observations and explanations lead to "predictions" about earthquakes, and "recommendations" about how to manage safe living in earthquake zones. We started by asking a few simple questions about when, where and why earthquakes occur, focusing on the Pacific Northwest Region, or Cascadia.

In this second unit we will ask more specific questions. For example, "How are plate motion, stresses accumulating in rocks, breaking of rocks, faults, and failure along faults, all related?" Only knowledge obtained by observation and careful analysis can provide explanations which will prevent the kinds of fear and confusion parodied in Figure EQ.14 below.

Figure EQ.14 Cartoon, source unknown.

Like all good investigations, our work will be driven by key questions. For this Unit there are seven, constituting our Outline:

1. How can "solid" ground move?
2. What are the types of faults?
3. What causes faults to jump?
4. How does stress change before, during, after an earthquake?
5. What happens at depth before, during, after an earthquake?
6. What factors affect "strength" of an earthquake?
7. What forces are causing stress on the Earth?

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1. How can "solid" ground move?

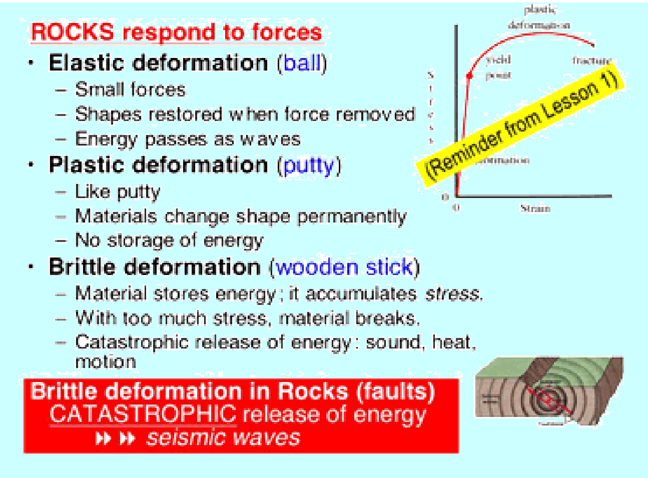
A review of concepts learned from the Fragile Systems Module of this course is shown below. These are basic definitions that we will use frequently in this Module.

How do the ideas relate to real geologic materials? Rocks have been observed to behave in all three ways, depending upon the size of forces involved and whether rocks are hard and brittle or soft and plastic. A rock's material behaviour depends upon	

its temperature and the minerals that compose it.

When an earthquake makes ground move, is it motion or deformation? Three types of ground motion can be observed:

- Permanent shifts in ground position
- Slow plastic movement, and
- Short oscillations after which ground returns to it's origin



ROCKS respond to forces

- **Elastic deformation** (ball)
  - Small forces
  - Shapes restored when force removed
  - Energy passes as waves
- **Plastic deformation** (putty)
  - Like putty
  - Materials change shape permanently
  - No storage of energy
- **Brittle deformation** (wooden stick)
  - Material stores energy; it accumulates *stress.*
  - With too much stress, material breaks.
  - Catastrophic release of energy: sound, heat, motion

Brittle deformation in Rocks (faults)
CATASTROPHIC release of energy
⏩ ⏩ *seismic waves*

The forces that make rocks move or deform are associated with tectonic motions. The types of forces will be outlined later. For now, let's summarize how the three types of motion (deformation) are observed in nature.

1. **Elastic deformation** Under elastic deformation, the forces acting on a rock are relatively small. Thus the resulting shape of the rock is not **permanently** changed. The shape is restored once the force is removed such that no evidence is left that the rocks ever experienced any force at all. This is the type of deformation experienced by rocks when energy is passed through the rocks as waves (to be discussed in the next unit). This response is very similar to the behaviour of a rubber ball as it bounces.

   Examples of elastic deformation in nature are of course not permanently visible. However, we know such deformation exists from moving pictures of wave motion. After the waves pass, if the ground returns to it's original position, we know that elastic deformation has occurred.

   Is an elastic deformation "not a problem"? Correct, so long as motion does not cause damage before it's over. However, because waves are propagated (transmitted) because of *elastic behaviour*, catastrophes even at great distances can result. The Mexico City disaster (1985) is a prime example of how elastic behaviour carrying enough energy caused major damage. Refer to *Keller et al. Figure 2.24*

2. **Plastic deformation** Plastic deformation occurs when the applied force permanently changes the shape of a rock without "breaking" it. The behaviour of putty in response to forces applied is similar.

   Examples of plastic deformation are everywhere (see Figure EQ.15). Look for bends or folds in layered rocks, either at a small scale in exposed rocks, or at very large scales in the patterns visible in mountain ranges.

Figure EQ.15 Plastic deformation is visible in rocks everywhere, both at small scales (left) and at the scale of whole mountain ranges (right).

3. **Brittle deformation** Consider a wooden stick being bent until it breaks. As forces applied to the material increase, the material stores the energy, i.e. we say that stress is accumulating. When the stress (force per unit area) exceeds the strength of the material, the material breaks. The accumulated energy is rapidly released as heat, motion, and sound. (Sound waves radiate away as pressure waves from the breaking stick).

   This is effectively a "catastrophic" release of energy. When rocks break catastrophically after accumulating stress over time, the resulting motion is called an **earthquake**. The energy is dissipated in the form of waves (i.e., the various types of seismic waves) that radiates away from the location of breakage.

   Visible evidence of broken rocks is not easy to find but there are examples of breaking when earthquakes occur on faults that are near the surface. Four examples are given in the Figure below.

Figure EQ.16 (Left panel) A displaced a railway line caused by a strike-slip fault rupture following the earthquake in Izmit, Turkey, on August 17, 1999. (Right panel) Rupture caused by movement on the Fault near the city of Bam, Iran.

Figure EQ.17 (left) Part of the 1987 magnitude 6.6 Edgecumbe (New Zealand) earthquake surface rupture passing through a road producing significant off-set on either side of the rupture zone (Photo by L. Homer).
(right) *Keller et al. Figure 2.31* This small scarp was produced by ground rupture during the 1992 Landers earthquake (M7.3) in California.

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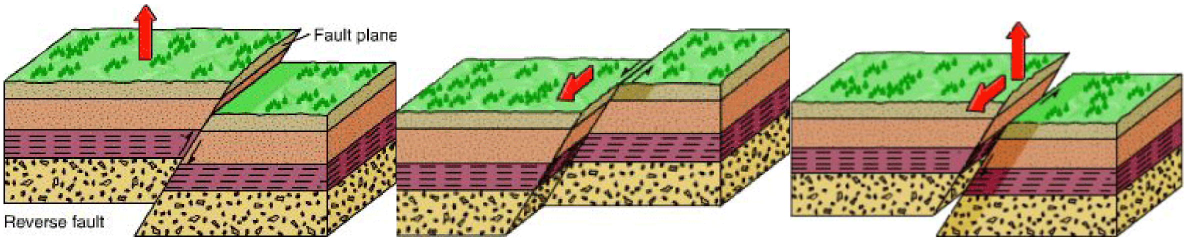
2. What possible types of faults are there?

Making predictions and recommendations related to a phenomenon (in this case earthquakes) require knowledge about how the phenomenon behaves. Faults seem to be the "source" of earthquakes so let's focus our attention on these.

Based upon observations made over centuries by many geologists and engineers, three types of faults can be described. Recall that a **fault** is a region where rocks have broken over some area. The fault is the fracture plane in the Earth where the two sides move relative to each other. The different types of faults are defined in terms of the relative motion of the two sides.



a. Dip slip **b. Strike slip** **c. Oblique**

Figure EQ.18 Three types of faults based upon relative motion.

There are several variations of the terminology, but the main types of faults can be defined as follows:

A. **Dip-slip faults** involve vertical motion along a slanting plane. There are two types of dip-slip faults defined in terms of the direction of motion of the *side which leans over it's neighbour*. As shown in Figure EQ.18a, **reverse faults** are those where the side leaning on its neighbour moves up. **Normal faults** are those where the side leaning on its neighbour drops down, as might be expected if gravity had it's way.

B. **Strike-slip faults** involve motion that is horizontal. There are two types of strike-slip faults, defined in terms of which direction the two sides move. If you stand with one foot on each side, either the left or the right side will appear to be coming towards you. In fact it does not matter which way you face; the sense of the motion is the same either way.

C. The third fault type, **oblique faults**, involves motion that is a combination of the vertical and horizontal directions of motion. We will not study this type in great detail.

Click here PLAY VIDEO to watch an animation of the types of relative motion at faults.

Click here PLAY VIDEO to watch another animation from *Keller et al.*.

CHECK YOUR UNDERSTANDING:

What type of fault is shown in the photo below? a. normal b. reverse c. strike-slip

After observing fault motion from the cartoons and videos above, are you now able to tell in which type of plate boundary would dip-slip and strike-slip faults occur? Observe how the opposite sides across normal dip-slip faults are pulled away from each other. That is, tensional forces are operating, which can only occur at divergent boundaries. In reverse faults, each side across the fault is being pushed towards the other. Here, compressional forces are operating, which occurs at convergent boundaries (types 1 and 2). Lastly, strike-slip faults, where rocks on both sides are sheared, occur at transform boundaries.

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3. What drives faults to jump?

As we have learned before, an increase in stress leads to breaking. What observations allow us to make this statement? Actual experimentation should convince you that "sticky" boundaries will behave this way.

Demonstration: Place a block of wood (such as a 6-inch piece of a 2X4) or a brick on a sheet of sandpaper that has been nailed to a base. Attach a rubber cord to the block, add extra weight onto the wood block, and pull the block smoothly across the sandpaper with the rubber cord. What happens?

Friction between the block and sandpaper causes the block to jump rather than move smoothly. If you add more weight to the wood block, you will observe that the force needed to get the block to jump will be larger. Note that the jumps will also be bigger. If you were to tie two blocks together with an additional rubber cord, a "coupled earthquake" is simulated.

Now place the block on a surface covered with baby powder. Observe how the block moves smoothly without jumping when pulled. This demonstration and its implications are all explained with images, videos, and models at the USGS Earthquake Model web site. The demonstration is shown in Figure EQ.19 below.

Now consider a fault buried deep in the ground. What would happen around the ends and edges of the zone that is "released"? This scenario would be similar to the wood block on sandpaper but now buried in jello. Let's now explore how stress (stored energy) changes around the fault's line and it's edges.

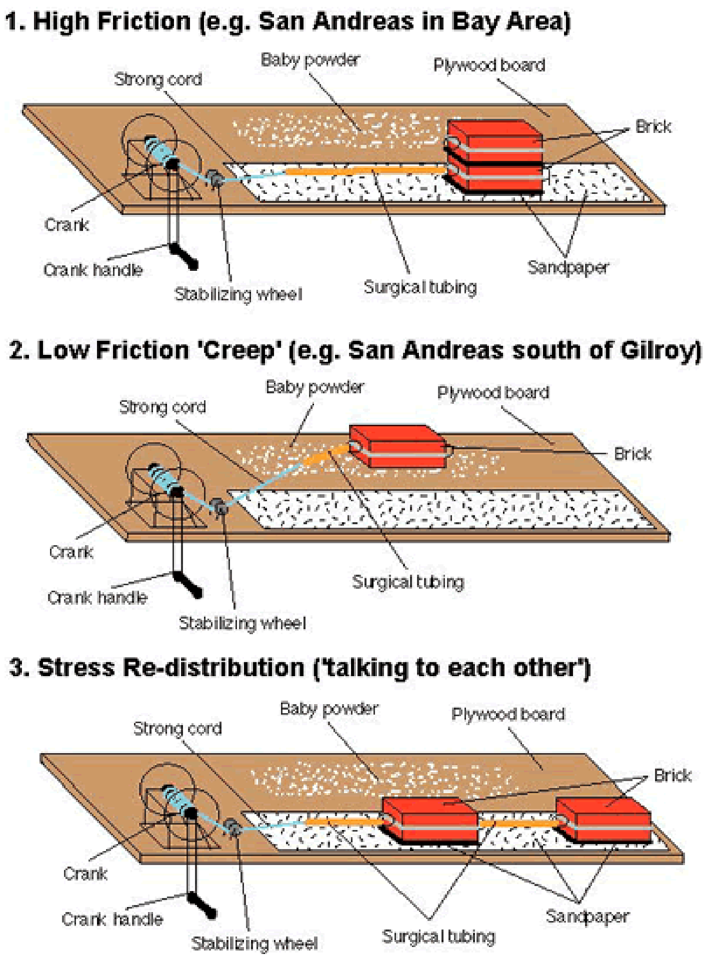

Figure EQ.19 A model to demonstrate how accumulated stress (in the rubber tubing) and the effect of friction (between bricks and sandpaper) results in unpredictable motion. From the USGS Earthquake Model web site.

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4. How does stress change before, during, after an earthquake?

The answers to the question in the title are of interest because faults never fail all at once. An earthquake might logically be expected to enhance the likelihood of further earthquakes in regions near the original one, where ground was not shifted to relieve accumulated stresses.

The observations needed to study this issue are very challenging. UBC's Professor E. Hearn is involved in just such research. An ideal fault to study is one that has experienced earthquakes fairly frequently, both major and minor. One such fault is a major fault in Turkey that regularly fails and causes many small and large earthquakes. Unfortunately for the Turkish city of Izmit, it is perched directly on top of this fault. An earthquake that hit in 1999 was a significant catastrophe for Izmit where over 17,000 people were killed, about 44,000 were injured, causing an estimated $8.5 billion in damage.

Figure EQ.20 illustrates how the fault failure process occurred. Stress is released by an earthquake, but at the ends of the zone where faults moved, stress can actually increase, raising the likelihood of earthquakes in those areas.

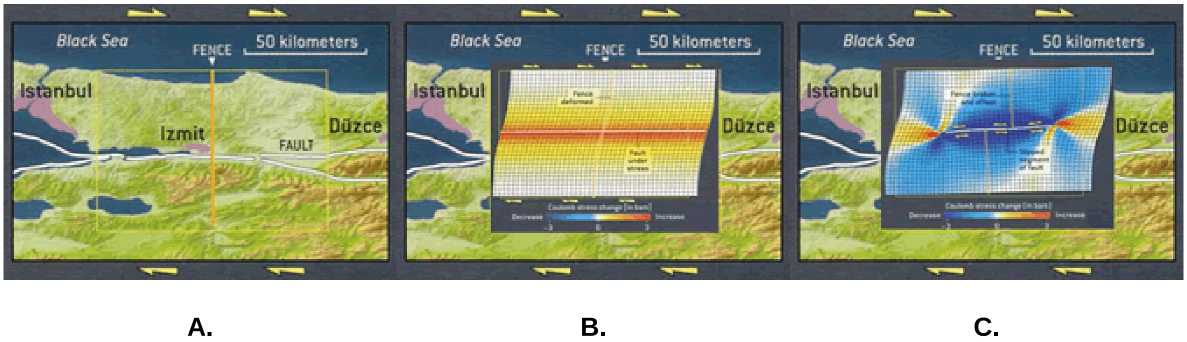

Figure EQ.20 Stress effects at a real fault: 1999 Izmit, Turkey earthquake. (A) shows a map with the fault marked in white. (B) overlays a grid that has been deformed just like the ground. The red areas in the centre denote where stresses are high because no motion occurred at the sticky fault. (C) shows how stress changed immediately after the fault 'breaks'. Blue zones are those where stress is relieved, red zones are those with newly increased stress.

Many interesting animations and other resources about this and other topics are given at Ross Stein's US Geological Survey web site: Effects at Real Faults. One of these animations can be found below.

Play the video to understand the concept of Figure EQ.20 as illustrated in animation. Watch the captions change below the figure. Also, more than one changed stress image is shown because there are several types of stress, differentiated by the directions associated with the stresses. The technical details are not important, but understanding how stresses can change as a result of earthquakes is.

We will revisit this topic again later. In the mean time, it is interesting to ponder what kind of scientific work is necessary to establish a good understanding of earthquakes and their effects. From the discussion above, we have found that this involves:

a. careful field work involving deployment of many instruments to measure stresses all over the countryside around the fault, and
b. sophisticated mathematical simulation of the physics of moving solids.

Again, "observations" and "experimentation", the hallmarks to understanding, analysis, and eventually prediction and recommendations.

5. What happens at depth before, during, after an earthquake?

When there is motion at a fault, is this motion simple? No, in fact, faults fail in complicated patterns. The motion along faults is NOT uniform and faults do not fail in a single jolt; there are foreshocks and after-shocks associated with all earthquakes, especially large ones.

Some fascinating results of research on fault motion illustrate how complicated the actual motion along a fault can be.

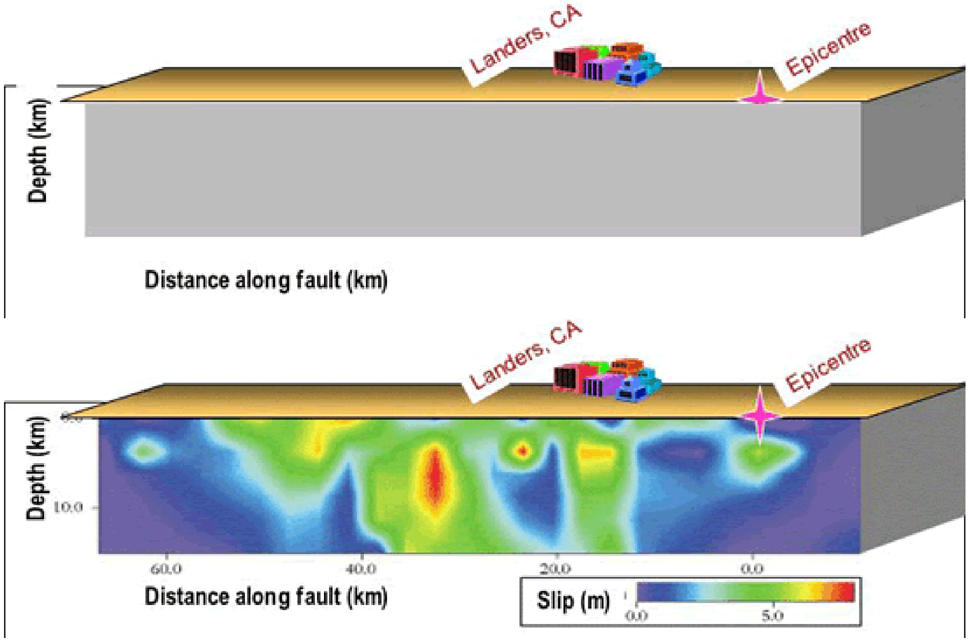

Figure EQ.21 Failure along a real fault is not simple. A cut-away view of the 1992 earthquake in Landers, California, Mw 7.3. Map of slippage shown in bottom panel is from "The Physics of Earthquakes" by H. Kanamori and E.E. Brodsky, Physics Today, June 2001.

The top panel in Figure EQ.21 above depicts a view onto the fault's face, with the western side cut away to show the motion of the fault along a 65-km long section extending from the surface to 12 km depth.

The bottom panel shows the same view of the fault in colour representing the amount of motion experienced during a real earthquake. In the area where motion started (directly underneath the epicentre), the slippage was small compared to the motion experienced 35 km to the north of the epicentre (indicated by the red zone centred at 5 - 10 km depth). This area experienced the most ground motion with slippage along the fault of 7 metres. Elsewhere there was much less motion, as indicated by the colours in the image.

These results might leave you wondering how scientists manage to make such observations. This is a good question, which is unfortunately beyond the scope of our course. For those with the inclination to learn more about this work, the reference in the caption is the place to look. These types of scientific investigation involves careful recording of ground motion at many locations in the vicinity of the event, followed by a complete analysis of what the measurements reveal about ground motion along the fault.

In addition to the complex motion on the fault, there are usually many different earthquakes associated with the main (largest) event. The map below (Figure EQ.22) shows the epicentres of over 100 events in and around Northridge, LA, California. Some 'quakes were moderate and many were rather small. All occurred within a few months of the main earthquake on January 17, 1994.

The take-home message is that **no earthquake is a single isolated event**. Large earthquakes are usually part of a sequence of many earthquakes. The foreshocks occur first, although they do not always occur. Then comes the main earthquake. Lastly, the aftershocks occur, decreasing in frequency with time. The largest of the aftershocks is usually 1 magnitude smaller than the mainshock. The designation of whether a quake is a fore, main, or aftershock is usually not firmly established until the entire event is over.

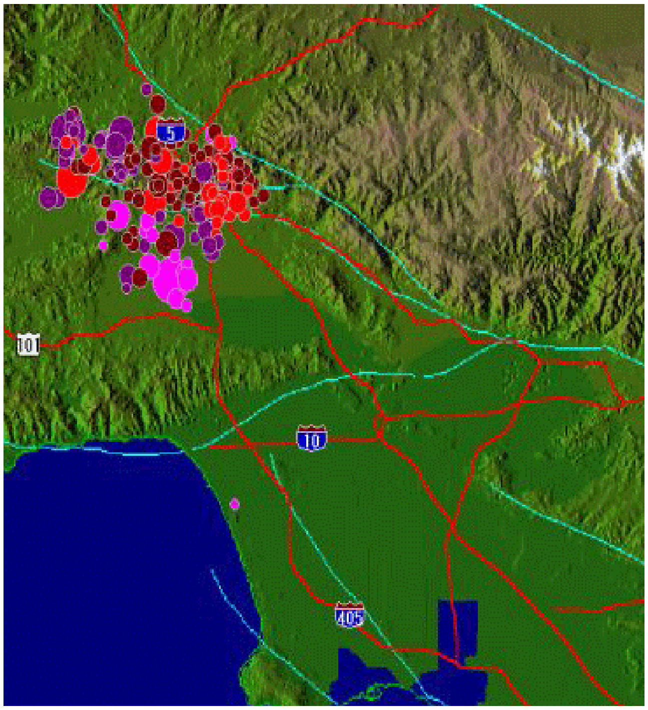

Figure EQ.22 Map showing epicentres of earthquakes in and around Northridge, LA, California. Note that large earthquakes are usually part of a swarm of earthquakes, with many foreshocks and after-shocks. Most after-shocks occur within two days but may continue for four months. Map generated using the free software called "Seismic/Eruption" found at http://bingweb.binghamton.edu/~ajones/.

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6. What factors affect "strength" of an earthquake?

Another important "need" that drives earthquake science concerns the size of earthquakes. What does **size** or **strength** mean anyway?

Answer: The **size** of an earthquake (called it's ***magnitude***) is related to the energy released when it occurs.

There are three conditions that affect the amount of energy released during an earthquake:

1. Area of zone broken
2. Strength of rocks being broken
3. Amount of motion

Given these conditions, what kinds of observations could be made so that the energy released can be determined? We could make our size estimates based upon the wave energy that emanates from the source location. Measuring the actual energy itself would of course be rather difficult.

The oldest method of estimating earthquake magnitude was developed by Charles Richter, and his procedure gives us the **Richter Magnitude**, M_L. It is not used very often any more because the procedure is accurate only if a particular type of seismometer is used and if the earthquake occurred in Southern California. Elsewhere, the differences in ground types would result in a magnitude that is poorly estimated.

There are other ways of estimating magnitude (for example, based upon P-wave and S-wave amplitudes), but the most reliable method involves careful records of ground motion at many locations. These records are then analysed to determine how much the ground moved at the earthquake's source location, and over what area this motion occurred. Obviously this was a challenging task, but not anymore. Research organizations worldwide committed to installing the necessary large number of instruments and analytical facilities to make these types of observations routine.

In addition to estimating the amount of motion and the area involved, the types of rocks involved must be known because tougher rocks require more energy to break than weaker ones. With these three parameters the so-called **Seismic Moment** M_0 can be determined from the following simple equation:

$$M_0 = [\text{strength of the rocks}] \times [\text{area involved in the breakage}] \times [\text{distance the fault moved}]$$

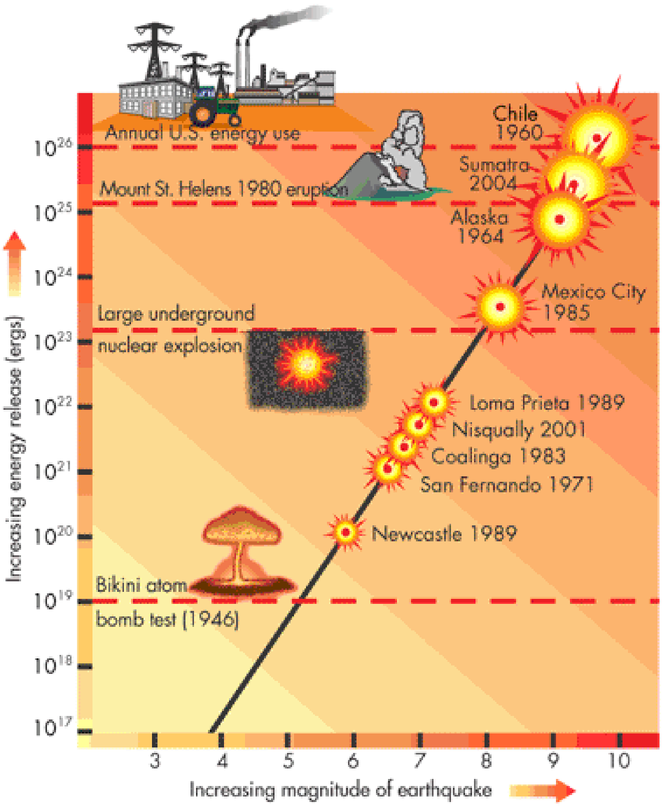
The product of three parameters produces an estimate of the energy released by the earthquake event. The earthquake magnitude or **Moment Magnitude** M_W is calculated as:

$$M_W = \frac{2}{3} \times \log_{10} M_0 - 6$$

This estimate is not based on any assumptions about how energy traveled through the ground, and hence is a more reliable estimate for earthquake magnitude. However it requires sophisticated observations in order to determine the parameters. The formula for M_W involves logarithms. It is an "empirical" formula, i.e. it was determined by considering a great many situations and finding the best mathematical relationship that explains them all.

The amount of energy released by an earthquake can range from close to zero to an amount similar to all the energy involved in an average 10 day hurricane, all released at once in an earthquake. This range is so large that scientists use a logarithmic scale for characterizing earthquake energy. Thus an earthquake of magnitude 7 involves **approximately 32 times as much energy** as a magnitude 6 earthquake. The graph below from *Keller et al. Figure 2.4* illustrates this logarithmic scale. Selected milestone events are highlighted. Note that earthquakes of magnitude 4 or less are rarely felt and never cause much harm.

▶ **FIGURE 2.4 EARTHQUAKE ENERGY** The relation between earthquake magnitude and released energy allows comparisons with other energy sources. The energy released by the 1960 earthquake in Chile, the most powerful historic seismic event, was greater than the entire annual consumption of commercial energy in the United States. *(Modified from the U.S. Geological Survey)*



CHECK YOUR UNDERSTANDING:

1. How much ENERGY does a magnitude 7 quake release than a magnitude 4 ?

a. 3 times

b. 32 times
c. 100 times
d. 1,000 times
e. 33,000 times

2. How much SHAKING does a magnitude 7 quake release than a magnitude 4 ?

a. 3 times
b. 32 times
c. 100 times
d. 1,000 times
e. 33,000 times

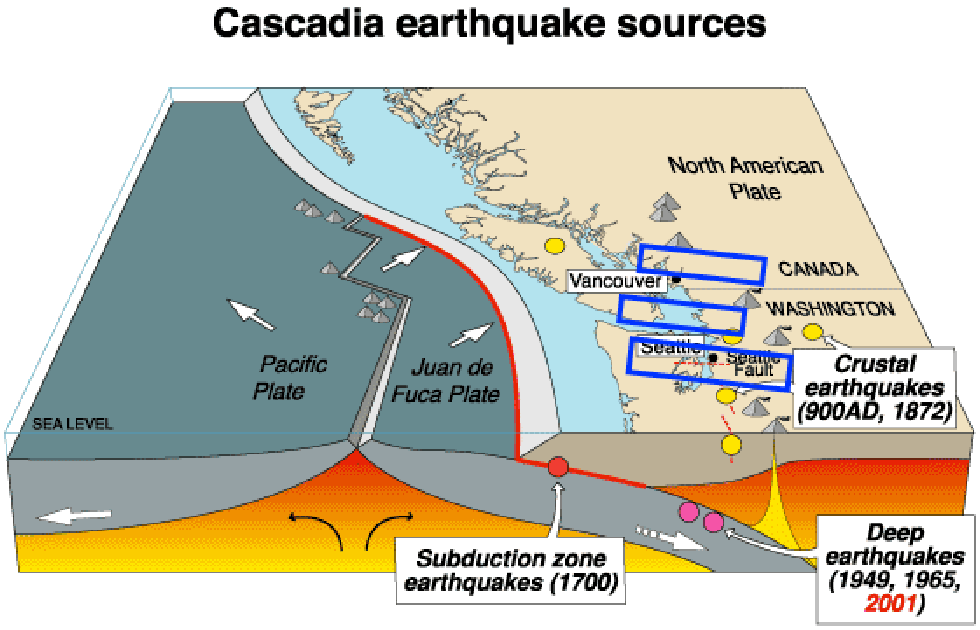


Figure for the two questions below.

CHECK YOUR UNDERSTANDING: Use the Figure above to answer the following questions:

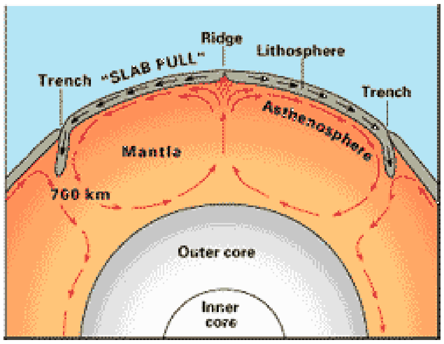
1. Which of the two types of faults (outlined in red or blue) in the following figure are likely to release roughly 10^{25} ergs of energy when an earthquake occurs there? What will M_w for this event be?

2. Which of the two types of faults will likely experience an earthquake of magnitude 4.0? How much energy will likely be involved?

These questions are important for residents of THIS part of the world (this means YOU, if you are at or near UBC!). We are only able to make educated guesses (i.e. "predicting") to answer these questions because we have observations and analyses from past scientific work. Furthermore, if we knew something about how often these 'quakes occur, we could recommend action to help make living here safer. More on that aspect later.

7. What forces are causing stress on the Earth?

Recall that earlier we learned that Earth's internal heat is the primary source of energy. We also learned that gravity contributes to plate motion by pulling denser plates as they plunge at subduction zones. Because the lithospheric plates on Earth's surface are generally rigid, it should be evident that forces are acting at the plate boundaries resulting in specific responses. In fact, three types of forces can affect plates. These are referred to as:



- **compressional forces** - those that cause squeezing
- **tensional forces** - those that cause a pulling apart of material
- **shear forces**- those that cause twisting or shearing

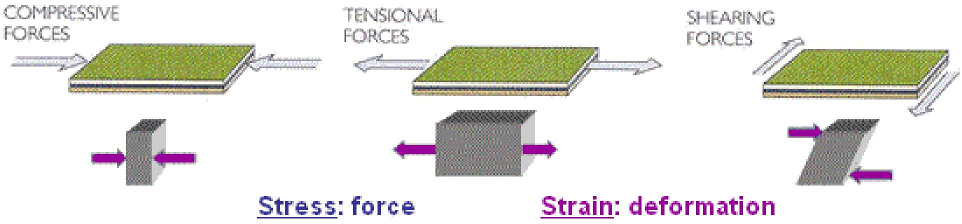
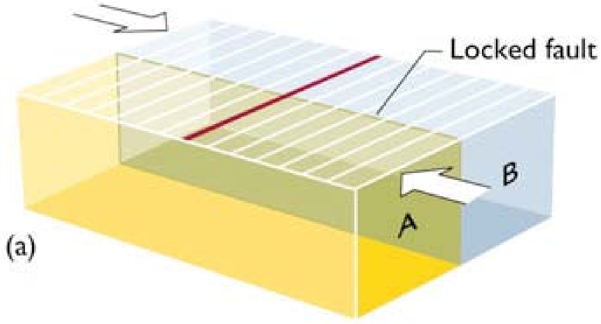


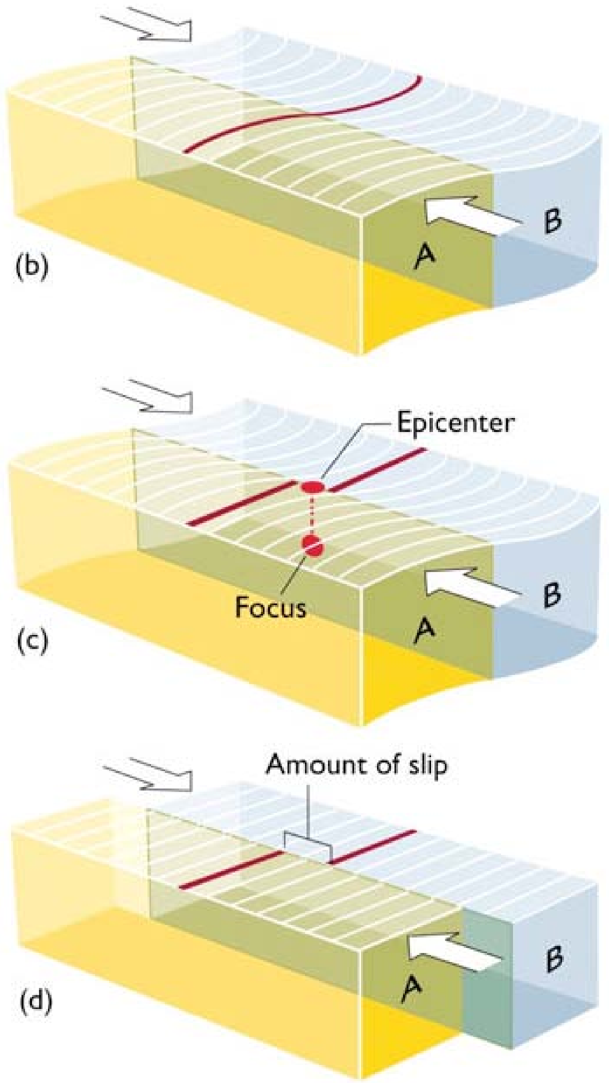
Figure EQ.23 Three tectonic forces operating at plate boundaries: compression or squeezing (diagram on the left), tension or pulling apart (middle diagram), and shear or sideways forcing (diagram on right). The animation illustrates the distinction between stress and strain, explained again in the text.

This is a good time to review the relation between **stress** and **strain**. Stress refers to the *force per unit area* while strain describes *how materials change shape* as a result of the stresses involved. These terms must be considered carefully whenever they appear in discussions.

CHECK YOUR UNDERSTANDING:

1. Describe the sequence of events shown in the series of images below:





2. What type of stress is shown in (d) above?
a. compression
b. tension
c. shear
d. elastic

Now we can use our understanding to predict which tectonic boundaries will experience greater accumulation of stress. Recall that stress accumulates so long as the forces are not allowed to dissipate. Therefore, settings in which more force makes it harder to dissipate energy will accumulate more stress. Then, when the setting does finally break, the resulting release of energy will be larger.

CHECK YOUR UNDERSTANDING: Use the Figure below to answer the following questions:

1. Which tectonic boundaries will accumulate more stress before breaking: convergent, divergent, or strike-slip boundaries?

2. Consider Cascadia... Which boundaries in the figure below are convergent, divergent, strike-slip?

3. Consequently, which boundaries are likely to have the biggest earthquakes?

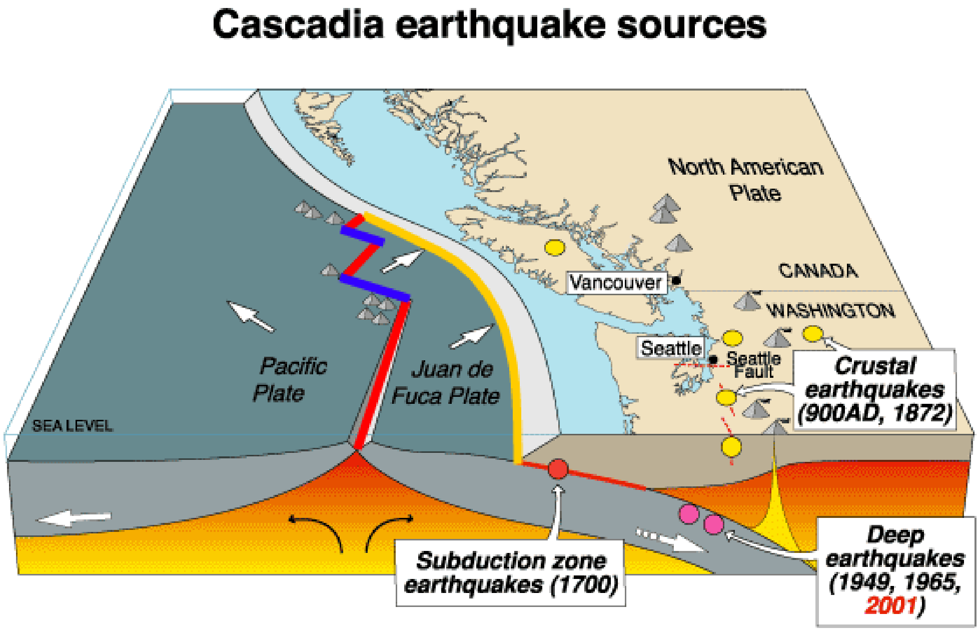


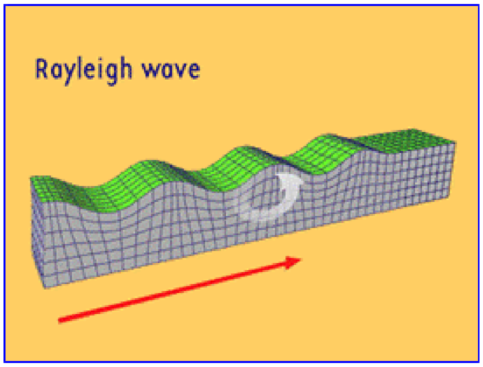
Figure for the three questions above.

UNIT	TOPIC
C	Seismic Energy and Waves

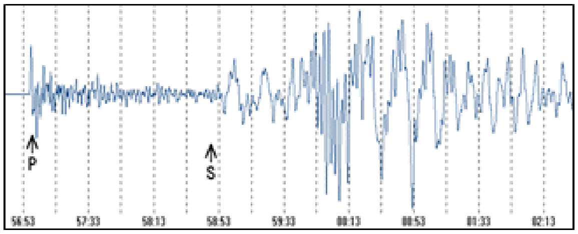
Outline

Shaking ground, traveling earthquake energy, seismology... these are all topics for today. The questions driving our lesson for today are:

1. **What are the characteristics of the shaking we feel?** We will consider eye witness accounts and actual measurements of ground motion.
2. **How close to earthquakes does violent shaking occur?** The "felt zone" is discussed.
3. **What form does traveling seismic energy take?** This involves characterizing the various types of seismic waves.
4. **What happens to energy traveling away from its source?** Seismic wave behaviour needs to be considered.
5. **Can we *use* seismic waves to learn about the earthquake what caused it, or about the intervening ground?** Yes! We will learn how seismic signals can be used to estimate source location and magnitude. We will also learn how seismic signals are used to learn more about Earth's structure.



All these topics involve learning about what scientists have observed about traveling seismic energy, and about how that understanding can be used to ensure the safety of all those living on this Planet - especially those folks living in earthquake prone regions.



1. Ground Motion: Short Oscillations

Earlier we outlined 3 types of ground motion: permanent, slow plastic, and short oscillations that return to its origin. Our focus in this section is the last type. It is very useful to characterize the shaking we feel because this is what causes all the grief.

How do we learn about ground shaking? Eyewitness accounts are a good start. There are of course many descriptions of people's experiences during an earthquake. An evocative description was written by Dr. Francis L. Parker about a very large earthquake in South Carolina, in 1886 (see box, right).

Measurements of ground motion provide a quantitative description. The instrument used is called an "accelograph" because it records the acceleration (change in speed) of the ground. This is similar to a seismometer, but it responds to much larger variations in ground motion. In SE British Columbia accelographs are permanently deployed at locations shown in the map below.

The Charleston, S. Carolina earthquake of 1886 was approximately M7.3, but no recording instruments existed then. Dr. Francis L. Parker wrote of his experience: "*I then began to feel the vibrations of the earth very distinctly, and realized that they were produced by an earthquake. From that instant, the vibrations increased rapidly, and the ground began to undulate like a sea. I could see perfectly and made careful observations, and I estimate that the waves were at least two feet in height."*
From B. A. Bolt, **Earthquakes**, 5th ed, Freeman Press, 2004.

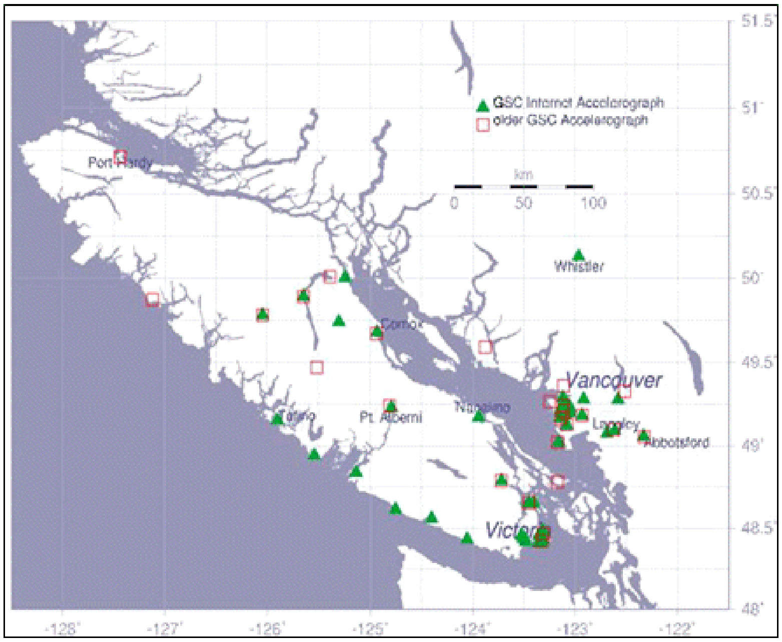


Figure EQ.24 Map of strong motion seismometers (accelographs) deployed in SW British Columbia.

Data on ground motion look just like seismograms except that they show larger ground motions. They are very useful to the construction industry because they show just what kind of ground motion a building or structure is expected to withstand. Examples are shown in the following figure.

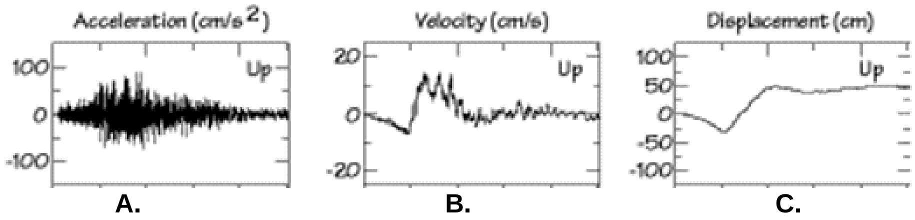


Figure EQ.25 Ground motion in the up/down direction shown in three different ways.

A. The parameter measured is "Acceleration" in cm per sec^2 which quantifies how rapidly the speed/velocity is changing. The ground starts out still (zero velocity), then starts accelerating as its velocity changes from 0 to something.
B. "Velocity" in cm per sec measures how fast the ground is moving. A negative velocity simply means the ground is moving "backwards" - for example, downwards in this case.
C. "Displacement" in cm measures the position of the ground relative to its origin (zero displacement). Here the ground drops, rises, then levels off.

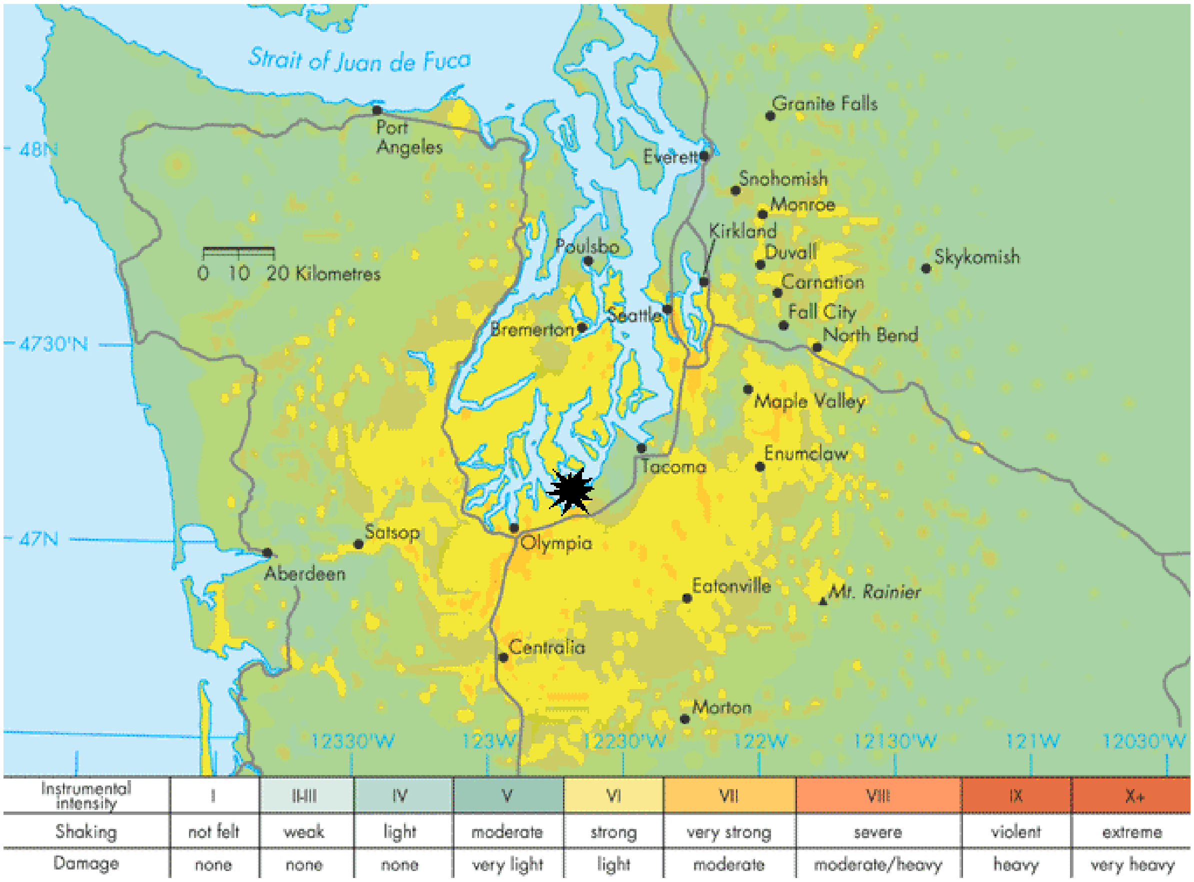
---

2. How close to earthquakes does violent shaking occur?

How far away from the source will ground motion be significant? This is a very sensible question to ask, and the answer is based on experience.

Here is a map of observations about ground motion caused by the Nisqually earthquake of February 28, 2001. The earthquake was M6.8, and the **hypocentre** (point where energy was released; also called the **focus**) was roughly 50 kilometers deep. (Refer to *Keller et al. Figure 2.3* for a diagram of basic earthquake features.) The map below shows the "Felt Zone", the region where ground motion was felt. Such maps are built simply by collecting eye-witness accounts from people around the region.

In the map below, the red/orange to yellow regions are where motion was experienced. Evidently the area where motion was felt was widespread and irregular. Why is the area described irregular? This has to do with the type/characteristics of the ground. This topic and its implications will be considered in a later section.



Instrumental intensity	I	II-III	IV	V	VI	VII	VIII	IX	X+
Shaking	not felt	weak	light	moderate	strong	very strong	severe	violent	extreme
Damage	none	none	none	very light	light	moderate	moderate/heavy	heavy	very heavy

Figure EQ.26 The felt zone map for the Nisqually earthquake, February 28, 2001. Epicentre (point on the ground above the hypocentre or focus) is indicated by the black exploding star. Red/orange to yellow regions are those where motion was experienced. Figure modified from *Keller et al. Figure 2.7b*.

---

3. Types of seismic waves

When faults slip, where does all the released energy go? The released energy is converted to wave energy. This can travel great distances, in a manner similar to the propagation of ripples after a pebble is tossed into water.

MORE QUESTIONS...

1. After waves pass, the ground returns to its original position. Does this mean that the ground is exhibiting ***elastic***, ***plastic***, or ***brittle*** *behaviour?*

2. If the ground does return to it's original position, how can seismic waves be so dangerous?

Now it should be clear that it will be useful to learn about seismic waves and the transport of earthquake energy great distances away from the epicentre.

Let's begin by characterizing the types of waves that arise when an earthquake happens. First we must distinguish between two main classes of seismic waves (refer to Figure EQ.27 on right):

A. **body waves** are those that travel through the interior of materials; and

B. **surface waves** are those that travel only along surfaces

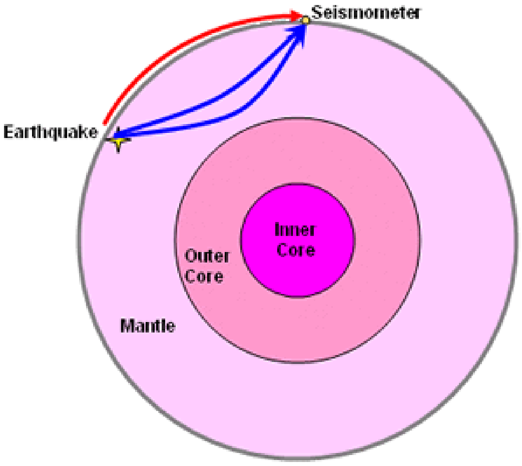


Figure EQ.27 Body wave (blue lines) travel inside materials while surface waves (red line) travel along surface boundaries.

A. **Body waves**. There are two forms of body waves. The distinction is based on the type of particle motion associated with the wave.

   1. When particles move back and forth in line with the direction the waves are traveling, the wave is called a **pressure or primary wave**. These are more commonly referred to as **P-waves**. View the P-wave animation below.
   2. When particles move from side to side, perpendicular to the direction that waves are traveling, the wave is called a shear or **secondary wave**. These are referred to as **S-waves**. S-waves travel slower than P-waves, hence the terms "primary" and "secondary" to characterize rate of energy transfer. View the S-wave animation below.

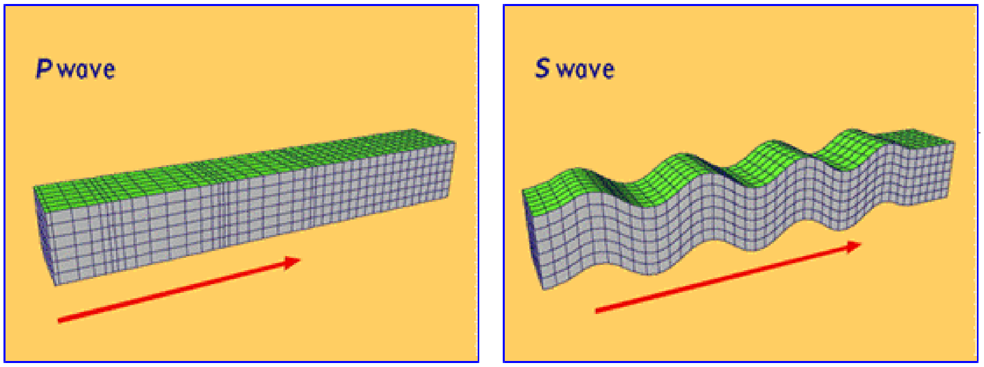


Figure EQ.28 (Left panel) Particles move back and forth in line with a P-wave direction of travel. (Right panel) Particles move side to side to the direction of a passing S-wave. Click on each image to view the animation.

B. **Surface waves**. Wave energy that travels along boundaries (rather than through materials) is called **surface wave energy**. There are several types, again distinguished by particle motion. The two most important surface wave types are named after the 19th century scientists that first described them.

   These waves are generated when P- and S-waves arrive at the Earth's surface. The energy can not continue on into air, so some are reflected back down and the rest of the energy pushes and pulls the particles of the ground near the surface resulting in generation of Rayleigh and Love waves. They then travel along the surface, causing the damage we are all so worried about. Surface waves are much slower than body waves, and the energy carried by them can not depart from the surface along which they are traveling.

1. When a **Rayleigh wave** (referred to as **vertical surface waves** in *Keller et al.*) travels, particles experience a rotating motion that is in line with the wave's direction. These are the waves that cause the most damage because they are largest, and they are most clearly felt because they travel along the Earth's surface. Rayleigh waves are those experienced by witnesses who say they felt as if they were in the ocean. View the Rayleigh wave animation below.

2. As a **Love waves** (referred to as **horizontal surface waves** in *Keller et al.*) passes, particles experience a side-to-side motion that is perpendicular to the wave's direction. Unfortunately we don't have an animation of Love waves.

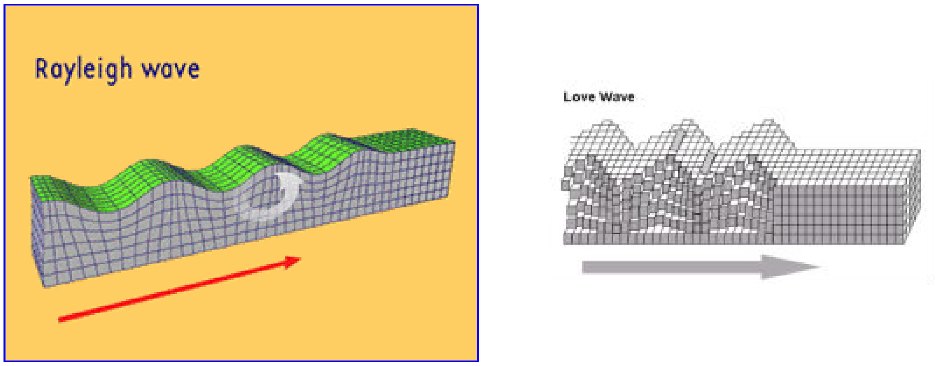


Figure EQ.29 (Left panel) Particles experience a rotating motion in line with a Raleigh wave direction of travel. Click on the image to view the animation. (Right panel) Particles oscillate horizontally and perpendicular to the direction of a passing Love wave. Unfortunately, there is no animation for the Love wave.

Click here PLAY VIDEO to view an animation of the 4 wave types from *Keller et al.*. Note that in these animations, *Keller et al.* refer to Rayleigh waves as *vertical surface waves* and Love waves as *horizontal waves*. These labels refer to the PLANE of motion and DO NOT refer to the direction of movement of the waves! Rayleigh waves cause motion in the x-z plane, which is "vertical" to the surface plane of the Earth. Love waves cause motion in the x-y plane, which is "horizontal" to the surface plane of the Earth.

All 4 wave types travel at their own velocity, and the whole pattern of energy resulting from an earthquake becomes very complicated very soon after the event. The animation below shows a simplified view of this complexity, allowing for a more comprehensive understanding of what ground motion is.

View more animations of the 4 wave types here PLAY VIDEO from the website of L. Braile from Purdue University.

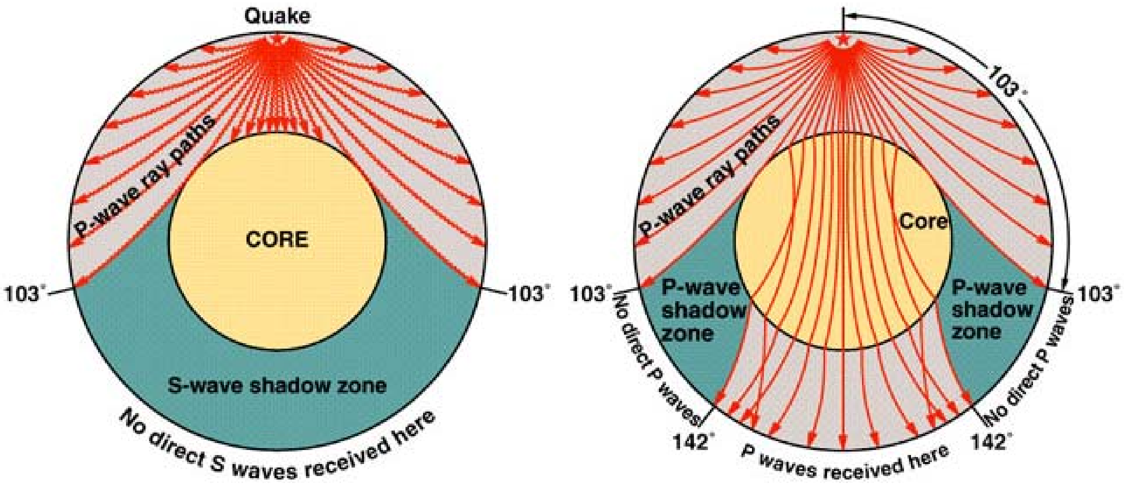


Figure EQ.30 Paths traveled by P- and S-waves within the Earth.

Click here PLAY VIDEO ▶ to view an animation of the images above.

CHECK YOUR UNDERSTANDING:

1. Which earthquake wave travels the fastest?

a. P-waves b. S-waves c. Rayleigh waves d. Love waves

2. Match the following descriptions to the correct wave type:

A. first wave recorded on a seismogram
B. travels through solids only
C. surface waves with a rolling motion
D. slowest and most damaging seismic waves
E. surface waves with a side-to-side motion

1. P waves
2. S waves
3. Rayleigh waves
4. Surface waves
5. Love waves

Having learned the types of seismic waves, you might want to review how these ground motions are observed. This was covered in the first unit, so refer to the discussion and images of seismometers in Unit A section 2.

4a. Characterizing seismic waves

The waves we have described are characterized in the same way as all types of waves (sound, electromagnetic, etc). Three related parameters that describe waves are **frequency**, **velocity**, and **wavelength**.

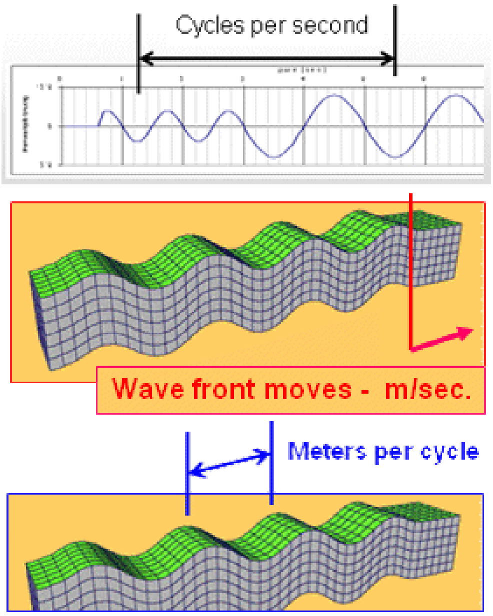


Figure EQ.31 Defining frequency (top panel), velocity (middle panel), and wavelength (bottom panel) of a wave. Note the units for these parameters.

The concepts of frequency, wavelength, and velocity may be more familiar in the context of musical tones. Sound is essentially a P-wave in air, and the same physics applies to studies of seismic waves and sound waves. A comparison of one tone "Middle C" and seismic signals in bedrock reveals that pressure waves travel 20 times faster in rock than in air. Seismic energy is generally at a much lower frequency than audible sound, and wavelengths are correspondingly much longer (see Table EQ.1 below).

Table EQ.1 Comparison of musical sound wave and seismic wave

	Musical Middle C	**Seismic Waves in Bedrock**
Frequency, *Hz*	262.63	10
Velocity, *m/sec*	345.0	6500
Wavelength, *m*	1.32	650

The complex nature of seismic signals can be understood better, when we compare them to complicated sound signals. A musical sound made by an instrument is generally much more complicated than a simple sinusoidal wave. A picture of a trombone's sound and the pattern of a seismic signal is shown next to it. Although the patterns appear very similar, note that the seismic signal lasts for a much longer time compared to the sound wave which lasts for a few seconds at most.

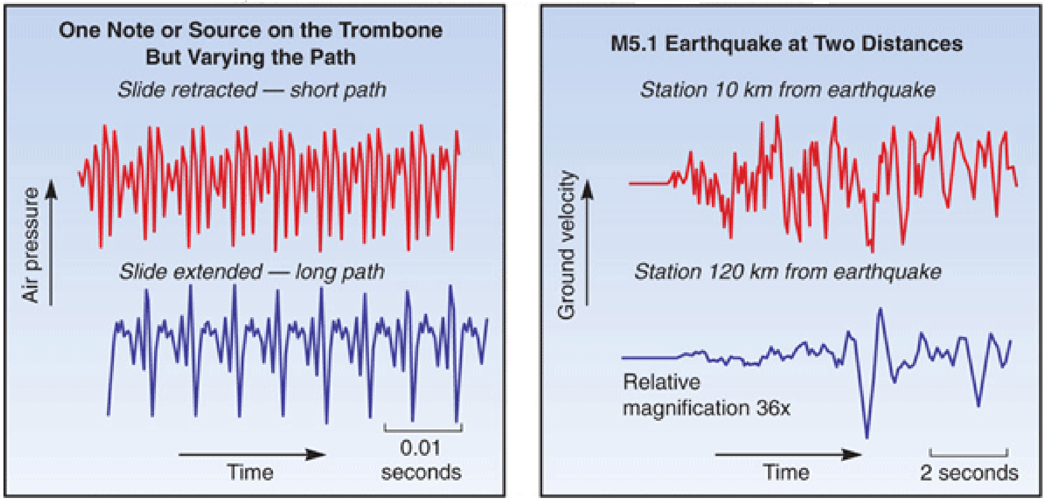
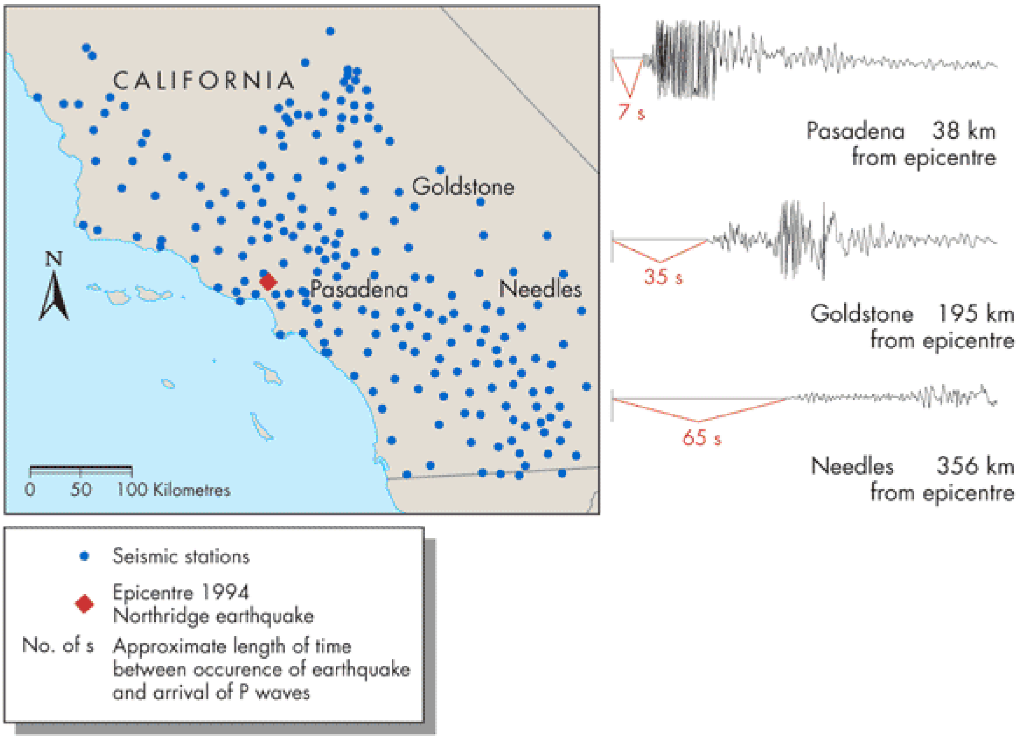


Figure EQ.32 Seismic waves are complex ... like music sounds. Visit the USGS web site to learn about and listen to sounds of earthquakes at http://quake.usgs.gov/info/listen/.

4b. How far can seismic energy travel

When waves travel, its energy dissipates because rocks are not perfectly elastic. Seismic wave energy starts out as a very complicated mixture of all frequencies. The highest frequencies dissipate more quickly as waves travel through Earth's materials.

This means that signals detected at greater distances will look different compared to signals recorded nearer the source. The signals detected there will consist primarily of the lower frequency components. The figure below illustrates this with actual recorded signals from the Northridge, California earthquake of 1994. Waves recorded nearby include high frequencies, whereas those recorded at locations that are more distant consist only of lower frequency waves. The more distant signals are also weaker, but this may not always be easy to tell since amplifiers are used to boost the traces.



Keller et al. Figure 2.16d **Three seismograms of the 1994 Los Angeles (Northridge) earthquake, recorded at different distances from the epicentre. The seismic waves take much longer to reach the seismograms and their amplitudes decrease with increasing distance from the epicentre. The greater the amplitude of the waves, the stronger the ground shaking.**

4c. Seismic waves at boundaries

As seismic waves travel across boundaries between differing materials (for example from cooler, brittle materials of the crust to warmer, softer materials of the mantle), their velocity changes.

The figures below illustrate how, as for all wave energy, seismic signals are reflected (echo) or refracted (bent), depending on how the material properties change as they travel across boundaries. This is not unexpected. We all are aware of echoing sound, and light refracting as it passes from water into air. In the photographs on the right, which image illustrates which phenomenon?

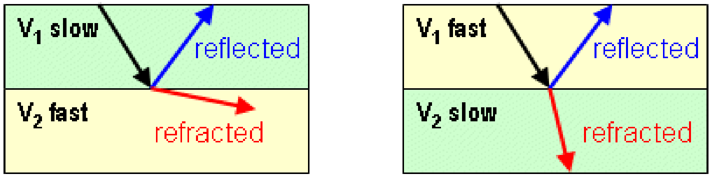


Figure EQ.33 Wave direction is bent when it travels across a boundary between materials with different elastic properties.

4d. Seismic waves in the deep Earth

Changes in wave direction imposed by changes in materials affect how seismic waves travel throughout the Earth. This is an important concept to know because it means waves don't travel straight through the planet.

Examples of material boundaries in the Earth's interior include the boundary between the lithosphere and the mantle, the boundary between the mantle and the core, or boundaries (however smooth and subtle) between warmer upwelling mantle material (such as under a hotspot) and cooler downwelling or sinking, mantle material.

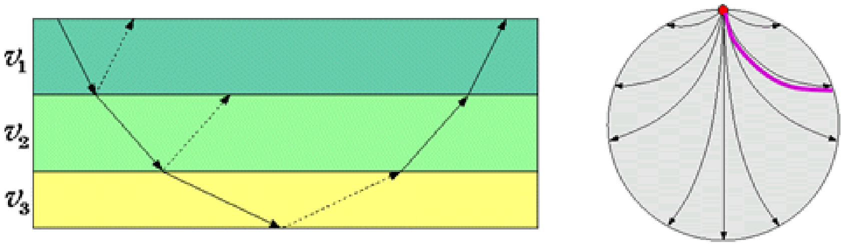


Figure EQ.34 Reflection and refraction in continuously changing media. The result is seismic waves tend to travel along curved pathways within the Earth. Of course, in reality distinct layering within the Earth makes these pathways much more complicated.

The most important consequence of changes in direction of travel is that seismic waves do not propagate in straight lines through the entire planet. The pathways are curving because of the general increase in velocity with depth inside the Earth. Also, waves are bent and reflected at boundaries. We will see later that analysis of the pattern of change from observations of a large number of seismic signals allows scientists to know details about the internal structure of our planet without ever having to travel there.

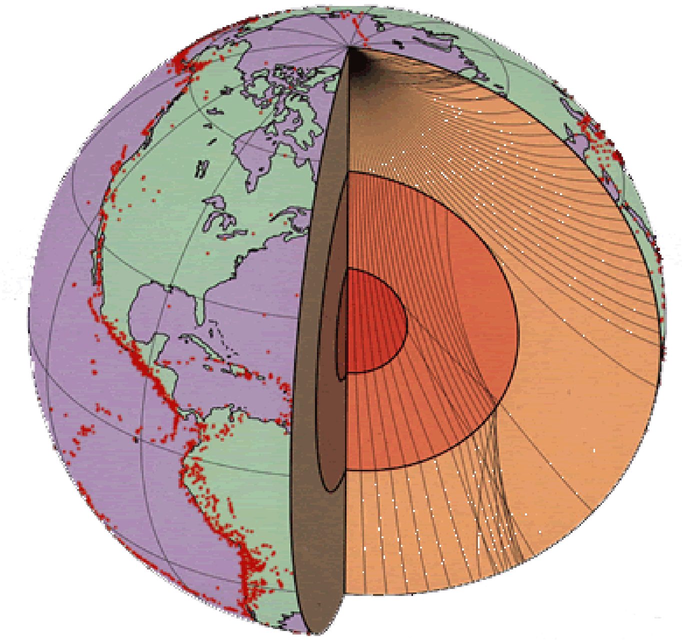


Figure EQ.35 Pathways of seismic waves in the interior of the Earth are gently curving, reflecting the general increase in velocity with depth.

One more important aspect of wave travel not shown in the images above is that shear waves (S-waves) **cannot** travel through liquids. On planet Earth, this means that these body waves cannot pass through the liquid outer core. Hence the shadow zones depicted in the wave path animation shown in a previous section (Click here PLAY VIDEO ▶ to view it again).

---

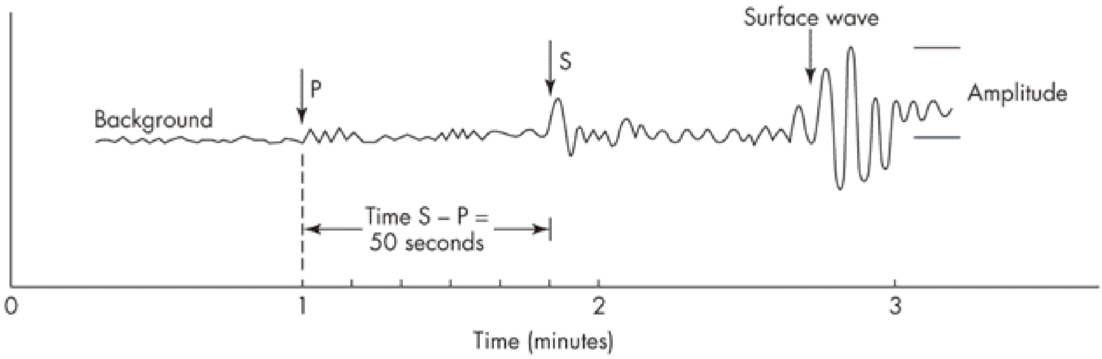
5. Using seismic waves

We now know enough to understand how seismic signals can be used. There are many aspects of earthquake science that depend upon the use of seismic signals:

- determining the location of distant earthquakes
- estimating earthquake magnitudes
- learning about our planet's internal structure

Before we can use seismic signals they must be analysed. Once the signals have been recorded, their pattern must be analysed, and important features identified.

Key features to determine from an analysis are the relative times of arrival of P-waves and S-waves. Figure EQ.36 illustrates how this is done.



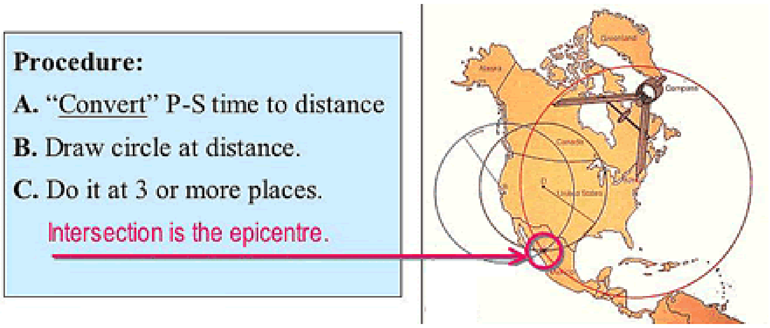
Keller et al. Fig 2.16b **The recording drum of a seismograph at the Pacific Geoscience Centre near Victoria, B.C. showing the seismogram of the Washington State earthquake of February 28, 2001 (M6.8).**

5a. Finding earthquake locations

The main features that must be identified to locate an earthquake are the **relative times that P-waves and S-waves arrive**. P-waves travel about 1.7 times faster than S-waves. Thus, the greater the difference in arrival times between these 2 wave types, the farther away the recording is from the earthquake origin. These arrival times *do not represent* the amount of time it took for signals to travel from the earthquake to the seismometer. At this stage of the process we don't yet know where the earthquake occurred, so all we can do is notice how much time *separates* the P-wave and S-wave arrivals.

Identifying these signals is not always easy. In the example shown below, the P-wave and S-wave arrivals can be clearly noted. Often however, the experts are challenged to identify exactly which wiggle represents the particular type of wave energy.

Once the relative times of arrival of P- and S-waves have been identified, we can proceed to locate the earthquake's epicentre. The concept used to accomplish this is shown in Figure EQ.36. If one distance is estimated, the earthquake location could be anywhere on a circle with radius equal to the distance from the seismometer (equivalent to the compass's point in the figure). If three distances (epicentre to seismometer) can be estimated, the resulting three circles will intersect at the only possible location of the epicentre. Clever... but there is one tricky part. That is, how does one convert relative arrival times into distances? This is the kind of problem scientists enjoy solving.



Procedure:

A. "Convert" P-S time to distance

B. Draw circle at distance.

C. Do it at 3 or more places.

Intersection is the epicentre.

Figure EQ.36 Locating the source of an earthquake requires analysis of seismograms from at least three widely separated locations. Also refer to *Keller et al. Figure 2.17*.

Converting seismic wave time into distance is done as follows. Consider the seismogram in Figure EQ.36 above. What do we know and what do we need to solve for?

1. We know the speed of the wave and the time it traveled, we know how distance, time and velocity are related:

   $$v = \frac{d}{t}$$

   or

   $$d = v \times t$$

   where *v* is velocity, *d* is distance, and *t* is time. Recall the units for velocity is *metres/second*, distance is *metres*, and time is *seconds*

2. Let us assume that we know the velocity of seismic waves

3. Do we know *t* ? Well, not really, because we don't know what time the energy started traveling (on the X-axis of the seismogram).

4. BUT we do know TWO "relative" times and that the distance traveled, *d*, is the same for both P- and S-waves. Therefore, we can manipulate the arithmetic as shown below to calculate what we need, *t*, travel time:

   From the equation for velocity, the arrival times for the P- and S-waves can be calculated as

   $$t_P = \frac{d}{v_P} \text{ and } t_S = \frac{d}{v_S}$$

   We do know the difference between the two relative times such that:

   $$\Delta t = t_S - t_P$$

   and

   $$t_S - t_P = \left[\frac{d}{v_S} - \frac{d}{v_P}\right] = d\left(\frac{1}{v_S} - \frac{1}{v_P}\right)$$

   thus

   $$d = \frac{\left(t_S - t_P\right)}{\left(\frac{1}{v_S} - \frac{1}{v_P}\right)}$$

5. We have now converted the time difference into a distance measurement.

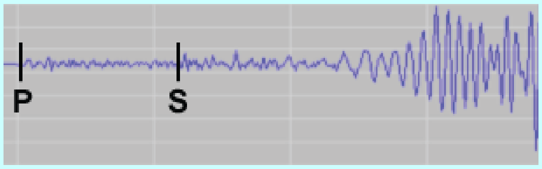
The result is that the desired distance can be found with a simple formula involving a time difference we can measure on seismograms, and velocities that are "known" from textbooks or journal articles - i.e., from previous observations. This is an excellent example of how scientists use observations, logic, and clearly stated questions to come up with ways of providing information that is useful to society.

Click here PLAY VIDEO ▶ to view an animation of the procedure described above.

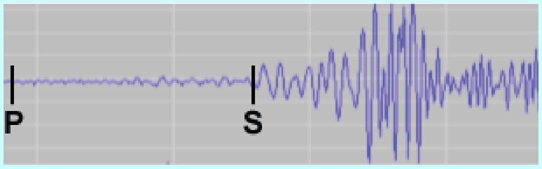
CHECK YOUR UNDERSTANDING:

Which of seismograms below was recorded furthest from the earthquake?

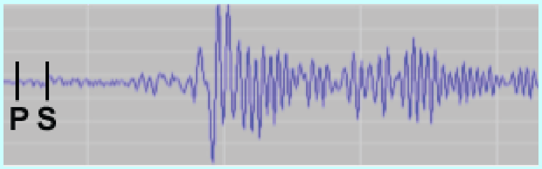
a.



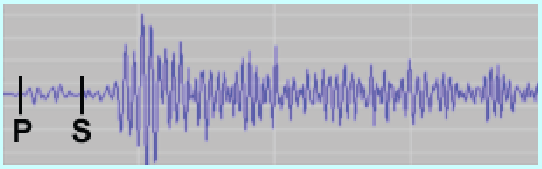
b.



c.



d.



5b. Calculating earthquake magnitude

The amount of energy released by an earthquake is obviously of interest. But how can magnitude (energy at the focus) be estimated when all we can directly observe is ground motion at the instruments? This is like trying to estimate the wattage of a light bulb from across the room.

You would have to take into account your distance from the light bulb, the material through which the light traveled, and the physics of how the light spreads out from its source. Thus, earthquake magnitude can be estimated by:

1. observing the amount of ground motion,
2. taking into account the materials through which waves traveled,
3. the distance traveled, and
4. the physics of wave propagation.

The process is conceptually simple, but details are tricky because exactly how much contribution to the final calculation should be attributed to each factor depends on many factors. The figure below illustrates this (more information in the caption!).

This example shows the **nomogram** (and equation) used to find the "Richter magnitude", which, strictly speaking, is **correct only if a particular type of seismometer was used, and if were in Southern California**.

Other nomograms or equations (similar but with different coefficients) would be needed to find magnitude from seismograms in different situations, or if a different part of the seismogram was to be used (such as the P-wave amplitude or the S-wave amplitude rather than surface wave amplitude).

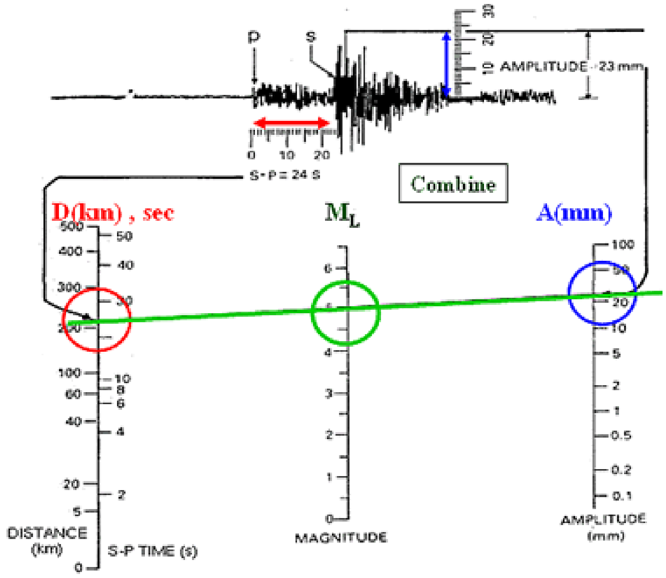


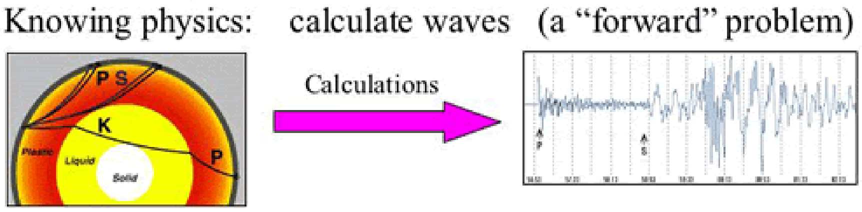
Figure EQ.37 Estimation of earthquake magnitude using a nomogram, a graphical solution to the equation

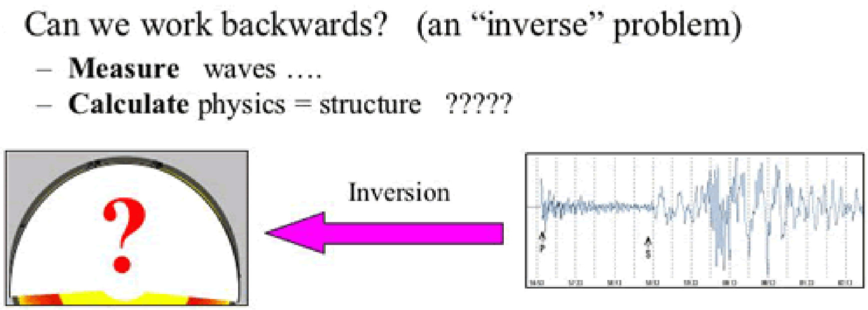
$$M_L = 2.76\log_d - 2.48 + \log A$$

This illustrates the concept behind the old Richter magnitude calculation. First find the distance d (red) on the left-most scale. Next find the maximum amplitude of surface waves A (blue) on the right-most scale. Draw a line connecting these 2 points and read the value of magnitude (green) off the center scale.

5c. Earth's structure from earthquakes

In Figure EQ.38 two common types of thinking are illustrated. Both are used by scientists to come to grips with challenging questions such as "What is inside the Earth?" In earlier examples we learned how data analysis (velocities of P- and S-waves) lead to the answer for critical questions such as "Where did the earthquake occur?"





Can we work backwards? (an "inverse" problem)

- **Measure** waves ….
- **Calculate** physics = structure ?????

Figure EQ.38 An illustration of two modes of analysis of scientific problems.

What if we could make the measurements but we weren't sure of the Earth's velocities? Then the question should be "What are the parameters of the Earth that describe its materials and structures?" This type of question is called an **inverse** question because it involves using measurements to figure out structure or material properties.

Can this type of problem be solved? Yes! We will need data from a lot of seismic events. We do realize that this is not easy to accomplish. However, if a great many measurements are made then all those measurements will begin to produce patterns that can be analysed.

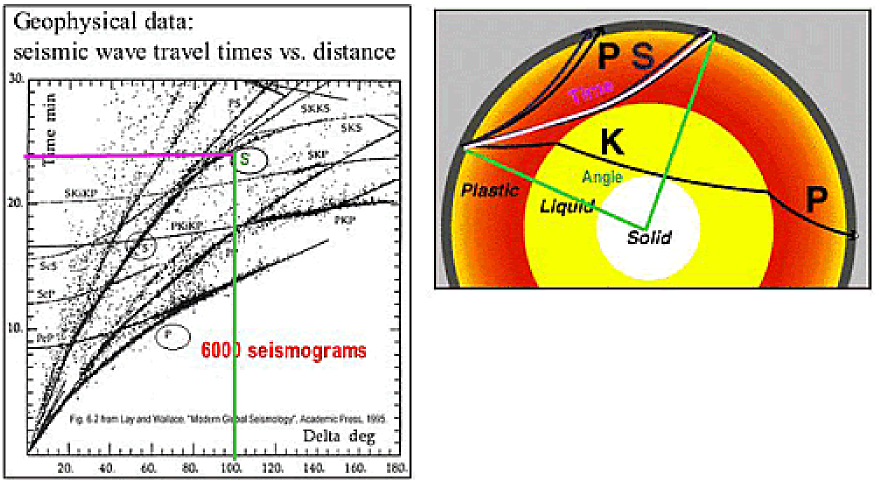


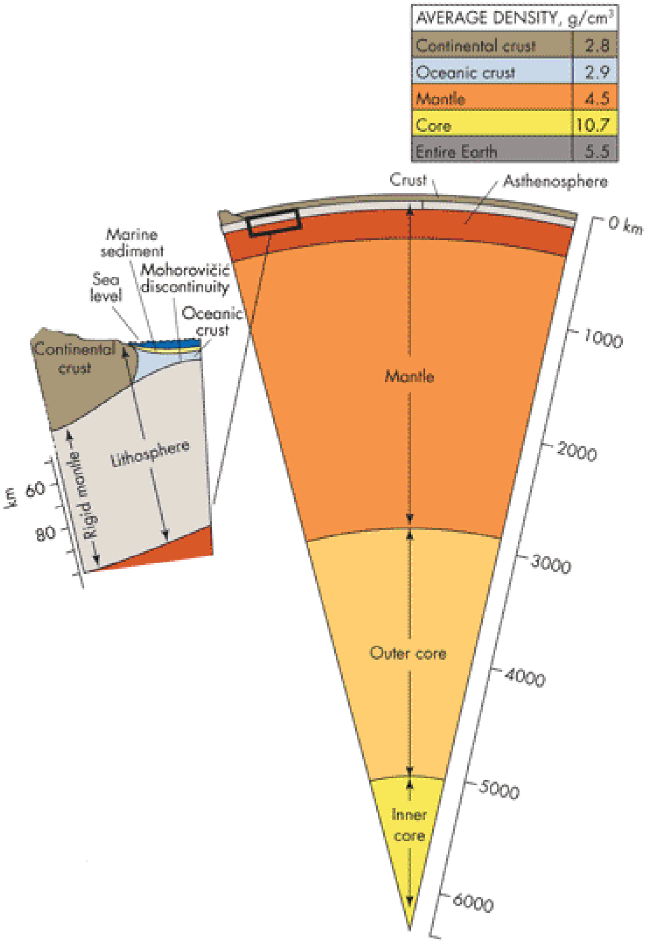
Figure EQ.39 The plot on the left shows one dot for every earthquake in a collection of 6000 events. On this plot, each dot is placed depending upon its seismic signal travel time and the distance between the instrument and earthquake. Inverse analysis works because global signal paths for seismic waves are affected by changes in material properties. The patterns of travel time versus distance on the graph tell us about what's hidden inside the Earth.

Figure EQ.39 above shows a plot of travel time for seismic signals (vertical axis) versus distance between source and measurement (horizontal axis). These are two parameters that can be measured. The unknown that we need to derive concerns how these two are related. That means velocity. This approach is more complicated than it looks because the seismic signals travel at different velocities through different materials. When seismic signals travel through several materials before being recorded, then the relationship between time and distance becomes even more complex.

In summary, the patterns on the plot of seismic travel times vs. distance can be analysed in order to determine a simplified model of the Earth, as shown in the next figure, taken from *Keller et al. Figure 1.6b*.

Keller et al. Figure 1.6b **(right) The structure of the Earth from its centre to its surface. Densities and thicknesses of the different layers have been estimated from the patterns and velocities of earthquake waves within Earth, from rocks formed within the**

lithosphere that have reached Earth's surface by tectonic processes, and from meteorites, thought to be pieces of old, Earth-like planets.



As a result of analysis of detailed and complicated data sets such as the one shown above, the concentric structure of our planet has become evident. It has a thin, hard outer crust floating on top of the lithosphere, which overlies the asthenosphere. The asthenosphere lies on top of the mantle, which overlie the two layers of core at the centre. This type of analysis, which yields a new understanding about the planet's structure, could not be done without earthquake seismograms recorded all over the world.

In fact, the simple concentric layered model of our planet is only a first approximation. It is not surprising that details about interior structures are much more complex. Figure EQ.40 illustrates this complexity by showing a cross-section of the Earth's top few zones (from surface to 1600 km depth), under a line drawn through the South Pacific Island region near Fiji and Tonga.

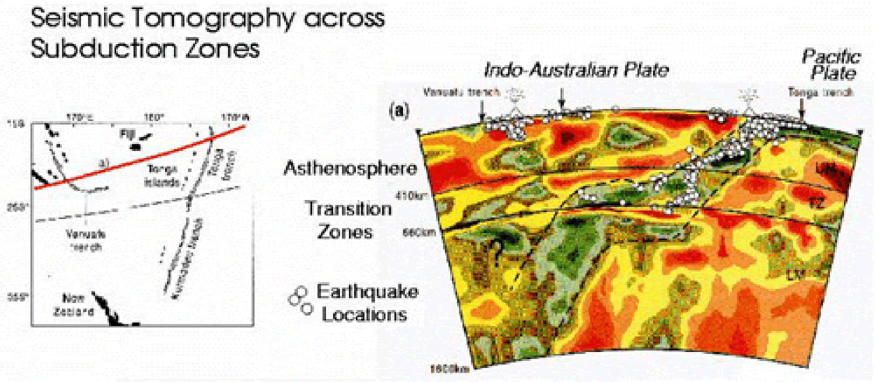


Figure EQ.40 The simplified model of a layered Earth is only a first approximation to its structure. Analysis of data indicate that the Earth's internal structure is more complex.

In the figure above, earthquake locations are shown as little white dots inside the Earth, and regions of lower or higher density are mapped using reds and greens respectively. The Pacific Plate can be seen as it subducts beneath the Indo-Australian Plate and dives down into the warm mantle before becoming consumed.

We have come a long way from Unit A. The remaining units will focus on possibilities and limitations of "prediction" and mitigation (making life safer).

UNIT	TOPIC
D	Forecasting

Outline

This is the fourth of five Units on earthquakes. The topic is prediction and forecasting. What do we need to know?

Prediction is too general a term. It implies making precise statements of what will happen in the future. Definitely not reasonable.

Forecasting is a more reasonable term. Depending on the type of environment, weather forecasting is usually accurate for the next 24 hours, pretty good for 5 days, and begins to get less reliable further into the future. Earthquake forecasting on similar time scales would be quite useful. Anticipating events months or years in advance would be even more useful. So what is the current state of the art?

The first step is to clarify our needs. Prediction/forecasting is needed -- but what do we need to forecast or predict? It is more useful to consider four aspects separately:

1. **Where** will earthquakes occur?
2. **What** effects should we expect when an event occurs?
3. **When** will an earthquake event occur?
    a. **Probability** of occurrence
    b. Possible **precursors**
4. **Specifics** about Cascadia

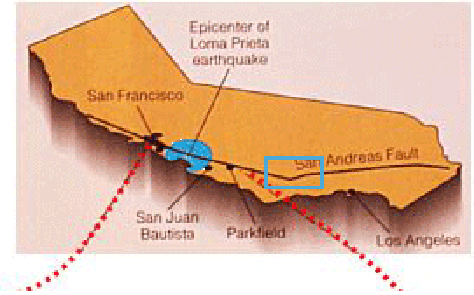
Before proceeding with this Unit, it is interesting to consider the words of Charles Richter, one of the early prominent earthquake scientists:

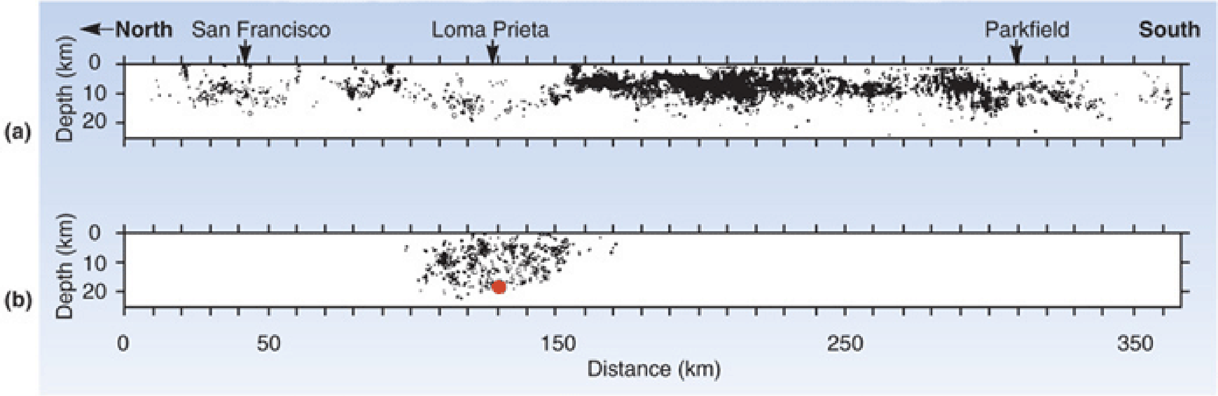
> *"Since my first attachment to seismology, I have had a horror of predictions and of predictors. Journalists and the general public rush to any suggestion of earthquake prediction like hogs toward a full trough."*
>
> Charles Richter, Bulletin of the Seismological Society of America, 1977.

1. Predicting where earthquakes occur

"Predicting" where earthquakes will occur is of course very useful. There are several aspects to the "where" question. We know where most (but not all!) faults are, and our knowledge of plate tectonics is sophisticated enough now that we know where plates move relative to each other. In a few well-studied places there are many observations of motion at a fault. The figure below illustrates how such observations can help suggest where earthquakes will occur "soon".

Figure EQ.41 A portion of the San Andreas fault is shown with 20 years of earthquakes plotted as dots on depth sections along the fault. Areas with relatively few earthquakes are called "seismic gaps". If motion is consistent along the fault, it can be argued that the seismic gaps are the most likely places for earthquakes to occur in the near future.





HOWEVER... very few faults are so well studied.

Additionally, faults are complex. Even the most well studied fault in the world, the San Andreas in California, is a very complicated feature. All known faults around the bend in the San Andreas are shown in the next figure, but there are also hidden faults in this system. So, yes, this fault is active, and earthquakes will occur along it. We have the answer for "Where?", but only to a very rough estimate. "Where exactly?" Which of the many associated branches, parallel and spawned faults will be the next to move?

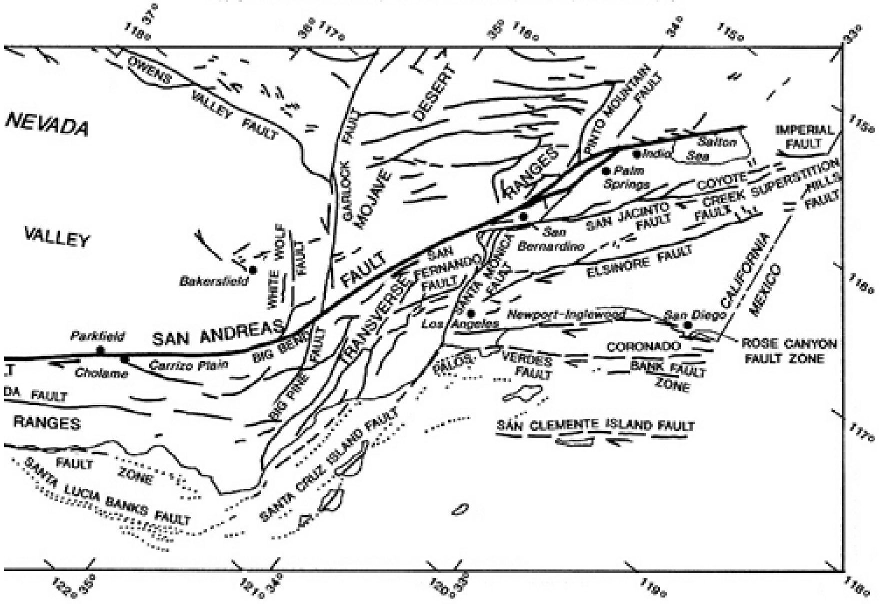


Figure EQ.42 Map of the San Andreas and other faults of Southern California (area enclosed by blue box in previous figure above).

Scientists have recently learned that more sophisticated observations and studies can provide more accurate answers to the question of "Where?" Earlier (Unit B section 4) we saw that the pattern of stress changes as a result of an earthquake, reducing stress in some places and increasing it in others. This type of information helps with forecasting "where". The sequence of images in the figure below illustrates this process.

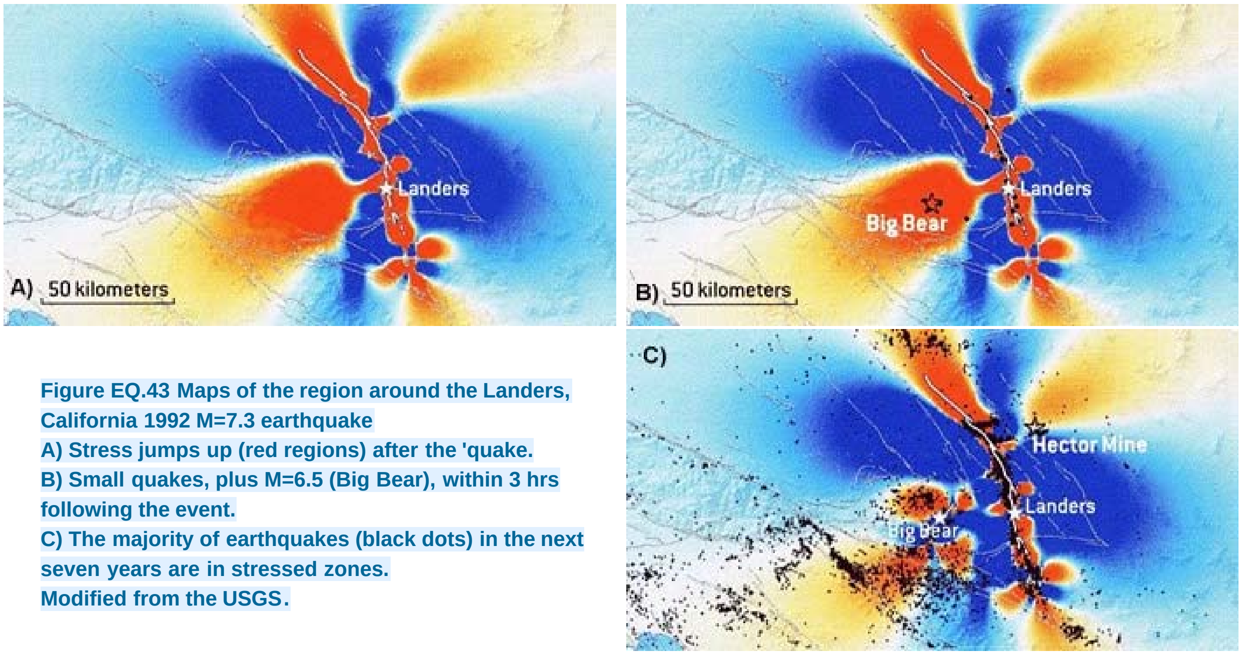


Figure EQ.43 Maps of the region around the Landers, California 1992 M=7.3 earthquake
A) Stress jumps up (red regions) after the 'quake.
B) Small quakes, plus M=6.5 (Big Bear), within 3 hrs following the event.
C) The majority of earthquakes (black dots) in the next seven years are in stressed zones.
Modified from the USGS.

This is a very promising concept. However, the stresses must be monitored (observed) constantly so that changes can be detected, and only well-funded institutes can afford the instrumentation, infrastructure, and full-time experts to carry out such work. Work is being done by scientists elsewhere using less-expensive methods of monitoring changing stresses. In observing very small changes in the ground's shape using satellite-based radar measurements, Canada's RadarSat1 and RadarSat2 are contributors to such work. However these techniques are still in the experimental stages.

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2. Predicting the effects of an earthquake

How will ground move? This is an excellent question of a predictive nature. The answers to this question affect building designs and other engineering decisions. If we knew exactly how the ground will move, and structures could be built to withstand that motion perfectly, then there would be no more worries about living in earthquake prone regions. Can we do it? The answer is sometimes, but usually not very well.

One set of observations that gives hope is a pair of seismograms recorded at exactly the same location for two earthquakes that occurred 12 years apart. They are both shown in the figure below; one in red and the other in black. The correspondence is remarkable.

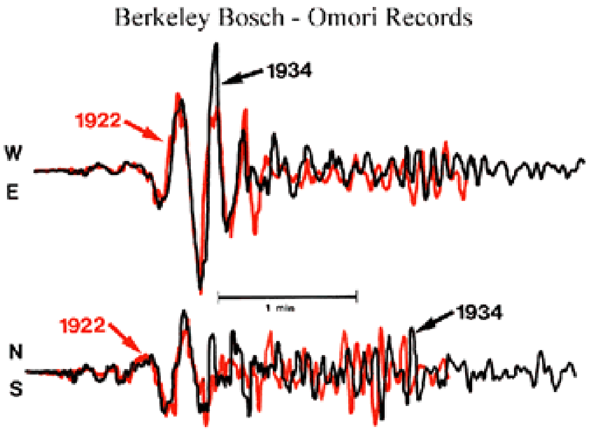
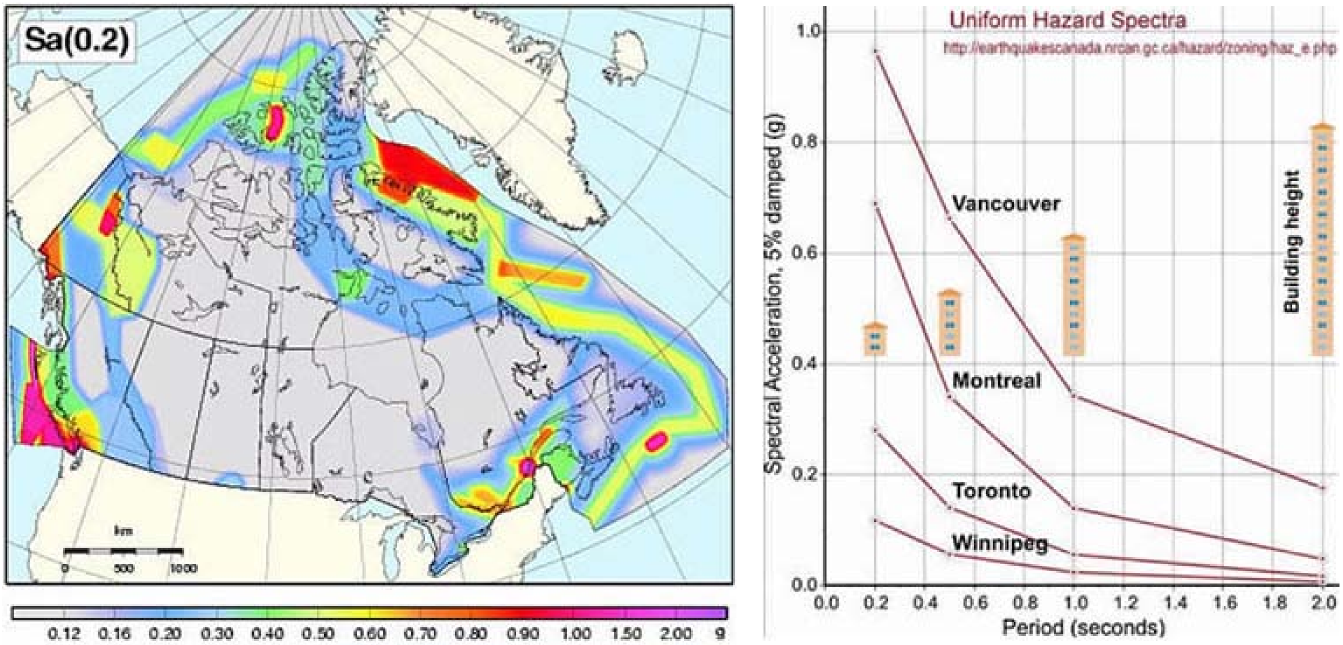


Figure EQ.44 Ground motion at one location for two different earthquakes. The motions are so similar that we might expect the

ground to behave similarly for future earthquakes. Image downloaded from USGS.

Making "predictions" of effects is one thing governments try to do in order to ensure that the construction industry builds to minimize disaster. In Canada, the Geological Survey of Canada (GSC) has a whole department devoted to Seismic Hazard. The figure below is an example of the kind of information produced by the Seismic Hazard group from analyses of large numbers of observations and data.

We saw earlier (Unit C section 2) that ground motion is currently being monitored using many types of instruments. Based upon the data collected and the type of ground, maps are produced showing the likelihood of ground motion strong enough to damage large buildings. A different map would show the same thing for small buildings. Effects of ground type and the buildings themselves will be discussed later. What part of Canada are you most surprised to learn may be seismically hazardous?



A. **B.**

Figure EQ.45 A. This map shows the likelihood of experiencing ground acceleration at one frequency (scale: 1.0g is acceleration equivalent to gravity). This motion has a 2% probability of occurring in 50 years. Sa(0.2) means 0.2 Hertz frequency (which is one oscillation every 5 seconds). B. Graph summarizing seismic hazards for different buildings at four Canadian cities. Small periods indicate high frequency. Note that smaller buildings are at risk from higher frequency ground motion. Images from Natural Resources Canada.

The information above can also be presented as a plot of acceleration versus period (= 1/frequency). The graph in the right panel tells us that larger accelerations can be expected for higher frequencies. Note that taller buildings "resonate" at lower frequencies, a subject we will cover in Unit E of this Module.

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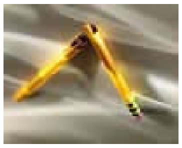
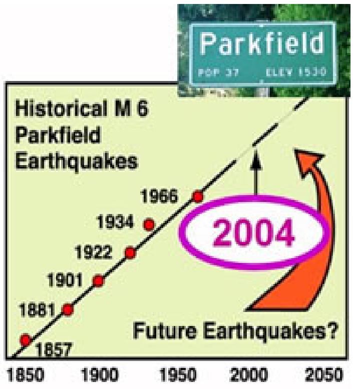
3. Predicting When...



When will an earthquake occur and where will it happen? Tough question! This is like trying to break a stick or pencil and being able to predict the exact moment when the stick breaks. You know it will break, but exactly when is not known.

Again, California leads the world in attempting to make predictions. The Parkfield experiment was established based on predictions of earthquake events. The predicted quake did finally happen on September 2004 but it was about 10 years "late".

The prediction was based on the observed (predictions need observations!) large (all roughly M6.0) earthquakes over the previous century, which occurred with unusual regularity. See the USGS web site for information on the monitoring experiment set up to observe an earthquake "in action".



There are many examples of the dangers of putting all our "trust" in predictions:

- One earthquake was "predicted" successfully in 1975 at Haicheng, China...

  BUT the same group failed terribly a year later when the most devastating earthquake of the century occurred at Tangshan in 1976, causing 250,000 fatalities.

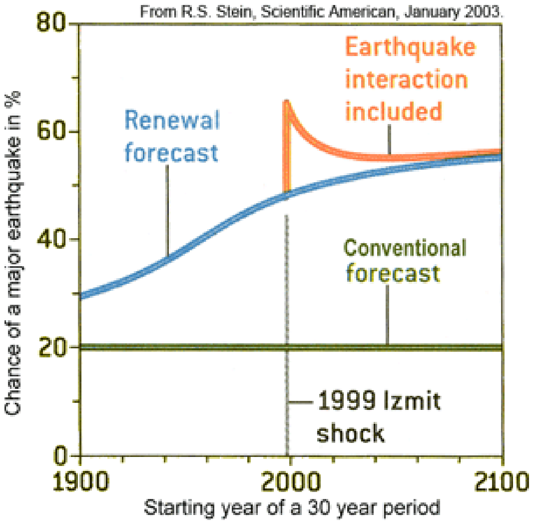
- Prediction efforts in Japan in early 1990's focused upon Tokyo...

  BUT then Kobe was struck catastrophically in 1995.

3a. Predicting when... the probability

More observations must lead to better explanations and hopefully better predictions or forecasts about "when". In the mean time, it is generally considered more useful to think about the **likelihood** of when rather than trying to state categorically when an event will occur.

The concepts underlying probability can get rather mathematical, but it is not hard to gain an appreciation for how the thinking works. The graphs in Figure EQ.46 to the right illustrate several types of probability curves for the areas in the region around Izmit, Turkey. It shows the chance, in percentage, of an event happening within a 30 year time period.


From R.S. Stein, Scientific American, January 2003.

The "Conventional Forecast" (green curve) is an outdated, simplistic approach. It assumes that the chance of an earthquake is constant at 20%. This is not sensible because the Earth is dynamic and constantly changing.

The "Renewal Forecast" (blue curve) is more useful. If we agree that stress increases gradually, then the chance of a shock grows as time passes.

The orange curve is a Renewal Forecast with a consideration of the effect of earthquakes nearby, such as the 1999 event. As we have seen, an earthquake will cause stresses to change. If we are in the "red zone" of an area near a recent earthquake, then the likelihood of an earthquake in our area might spike up soon after a nearby 'quake. If in fact we don't experience one, then the probability might decay because of relaxation in the ground.

How do we build such a curve? Consider the picture below, which shows historic events on a horizontal time scale. The purple bars show large earthquakes that occurred in the Pacific Northwest region of North America. (We will consider how such information was obtained later). Can you estimate a period, or repeat rate in years, for events? Should we do this by taking the average... or picking the shortest ... or the longest interval ...? Let's try the average for now.

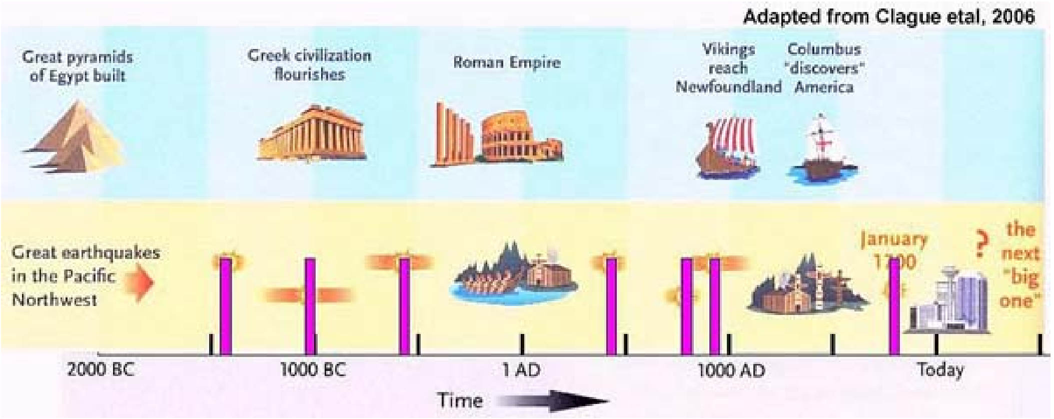
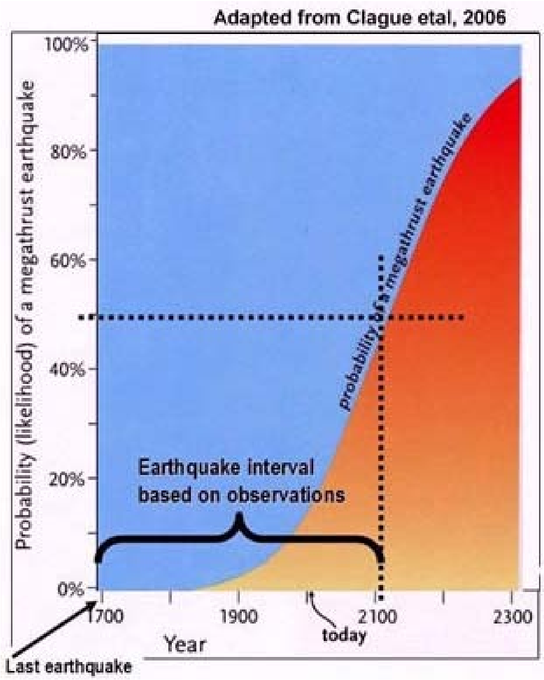


Figure EQ.47 Time scale of large earthquakes over the previous 3,000 years.

Seven events in 3,500 years yields an average of 500 years interval. Let's be pessimistic and say the interval is closer to 400 years because the smallest interval is 100 years. Now let's put the 50% part of a curve at this average interval, then place the curve on a time scale so that this 50% part is 400 years after the most recent event (in this case, the event that was known to have occurred in 1700).



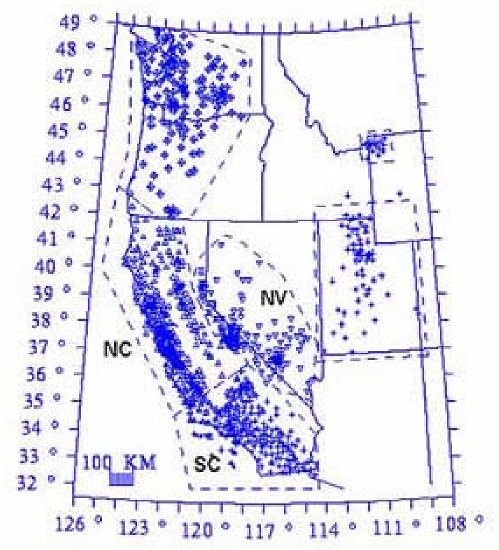
Now from the graph to the right (Figure EQ.48), the chance of a big earthquake occurring today (see "today" on X-axis) is about 15%. BUT...

- What if this curve does not have the right shape?
- What if there are "jumps" in the curve?
- How is a suitable earthquake interval chosen?
- What if there are things going on that we have not yet observed?

Sure there are plenty of uncertainties, but thinking this way is better than not anticipating at all. In a society where decisions have to be made everyday, *it is better to make informed decisions knowing there are uncertainties, than making decisions in total ignorance*. Learning to live with uncertainty is one of the hardest lessons for all scientists (and for everyone).

There are continuing advancements in our understanding of earthquakes. Large numbers of observations are being recorded and experiments are constantly being carried out by academics, government agencies, and engineers. We can be assured that the decision making process is indeed becoming more and more reliable.

One example of enhanced information is the daily earthquake forecasts produced for the State of California. Probability maps are produced daily, based upon many measurements. A map showing the location of recording instruments and another showing the forecast for aftershocks following the September 28, 2004 Parkfield earthquake are shown in Figure EQ.49. The ground shaking predicted is based on the Mercalli scale (introduced in the next section). You can see today's forecast for California at the USGS website.



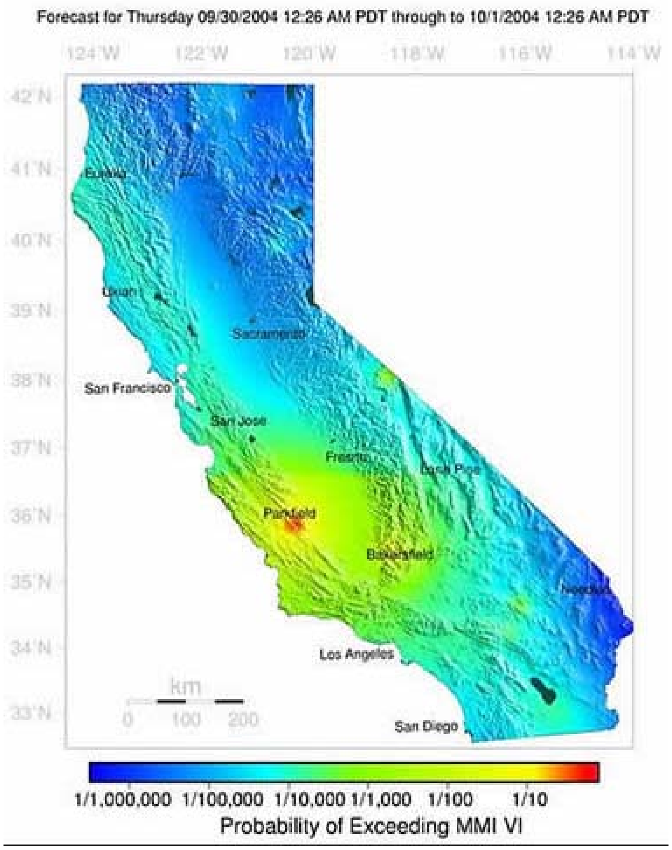
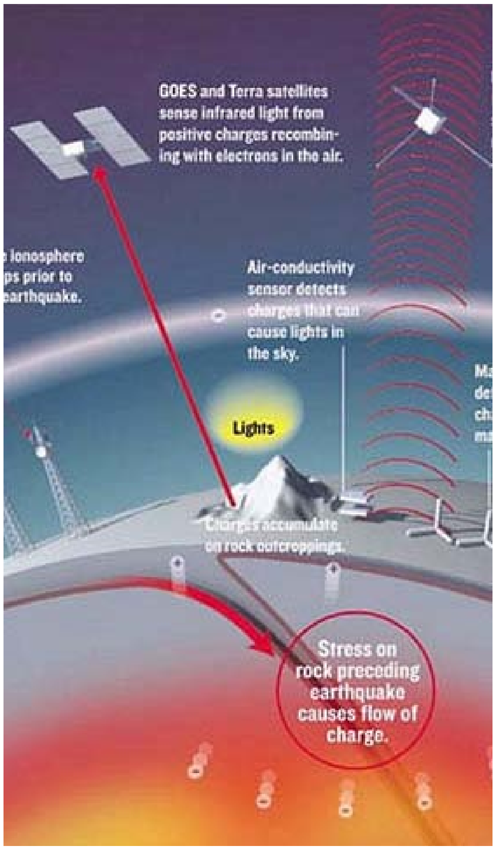


Figure EQ.49 (Top panel) Locations of instruments used to support daily probability forecasts in western US States. (Right panel) Map of forecast for aftershocks around Parkfield two days after the September 2004 event. Maps from USGS Earthquake Hazards Program.

3b. Predicting when... possible precursors



There are many different types of observations that have been suggested as indicators of imminent earthquakes. The challenge is to sort out the foolish and the merely speculative from those that might actually have some merit.

Some observations that have been attributed to impending earthquakes involve observations of electrical phenomena:

- Lights in the sky
- Changing electrical resistivity in ground, air, and ionosphere
- Spontaneous radio noise
- Changing height of the ionosphere
- Changes in infrared light visible from satellites

These and related ideas were reported in the December 2005 edition of Spectrum, the prestigious monthly journal of the IEEE (the Institute of Electrical and Electronic Engineers).

A possible explanation for these observed phenomena is that changes in tectonically active regions cause charges to build up and propagate. "Moving charges" is the definition of an electric current, and varying currents cause electromagnetic signals such as radio signals. These are readily observable on the ground and/or from low orbit space-based platforms.

The December 2005 article generated many letters to the Editor arguing various aspects of this topic. One writer wrote that " ...incredible claims call for incredibly strong data and theory... but (that) rather than view it as a problem, this set of observations must be treated as a challenge". More observations and experimentations are necessary. It is hoped that in the future, measurements can be made that will serve as reliable warnings of impending events. But we are not there yet.

For more information on this topic, read the Spectrum article online. The discussions generated by the article are available here and here.

There are other predictive "observations" that have been reported. Some of these are:

- Ground behavior (uplift, tilt, creep, ground water levels)
- Seismicity (patterns of small quakes and motions)
- Radon emission
- Animal behaviour

How should we assess the legitimacy of such claims? Before relying on any form of information, many observations and experiments are required so that there is a thorough, reliable understanding of what's going on. This requires careful recording of all information before, during, and after earthquake events worldwide. Such data acquisition is expensive, complex, and time consuming. But whatever the challenges and difficulties, high-quality analyses of the data must be performed BEFORE prediction and recommendation can be carried out!

In the mean time, it is probably fair to say that prevention may be more cost-effective than prediction.

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4. Prediction: Cascadia

Will there be a **Big One** in the Pacific Northwest? Is the **Mega-Quake** imminent? By now you should be able to consider this question in a sensible and scientific way. Are there observations that relate to these questions? What evidence is there that a large earthquake is imminent? Is there adequate understanding about the tectonics of this region?

There is now a large body of knowledge about earthquakes in Cascadia. Scientific evidence of a mega-quake includes:

- The tectonic setting is clearly optimal for large subduction zone earthquakes
- Evidence of a very large 'quake exists in tree rings, sediments on the shores of inlets and salt marshes, and geologic evidence of landslips and fault motions
- There are real-time measurements of tectonic deformation
- Historic tsunami records from Japan suggest a large event occurring hours after a seismic event
- Oral history of local native peoples also confirms an event

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4a. Cascadia: The tectonic setting

First, the tectonic setting suggests there is great potential for a large earthquake in Cascadia. Figure EQ.50 shows where large earthquakes have occurred in this region. The figure is a reminder that the Juan de Fuca plate is subducting under the North American plate and we know from global earthquake distributions that all the world's largest earthquakes occur at subduction zones. This is the first aspect of prediction: comparing events at similar settings. Cascadia's tectonic setting is similar to those of Alaska, Chile, and other locations where many recent mega-quakes (earthquakes with magnitude greater than 8.0) have occurred.

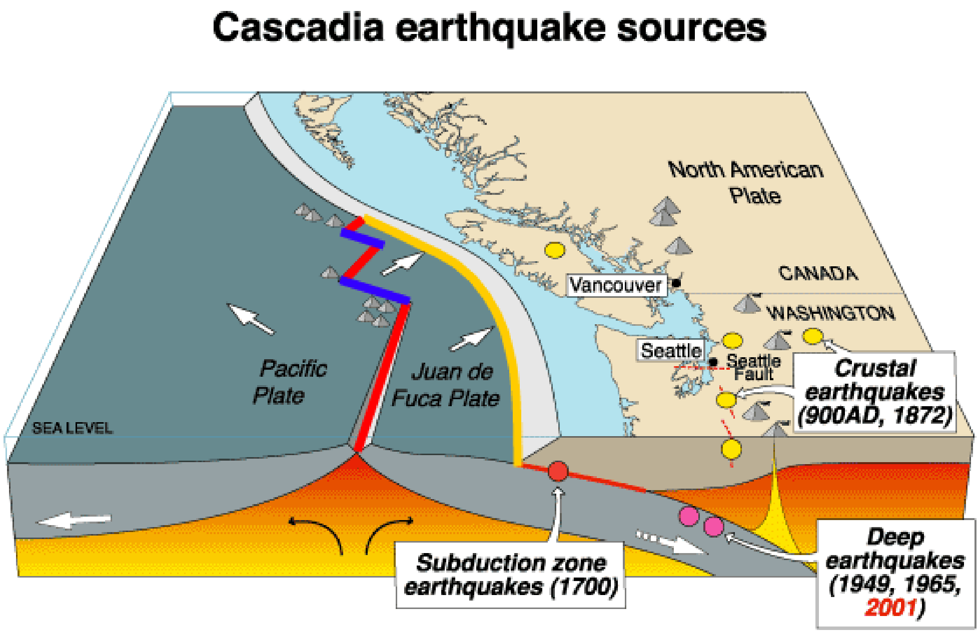
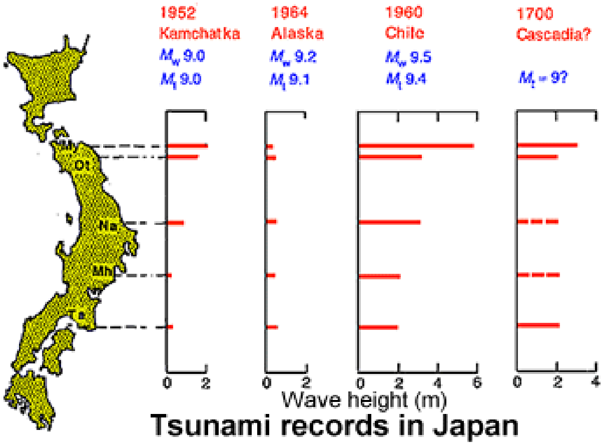


Figure EQ.50 The Cascadia tectonic setting includes mid-ocean ridges, transform faults, and subduction zones. Schematic courtesy of Natural Resources Canada.

Humans have been recording earthquakes only for a few centuries, a very short span of time on a geological scale. So, is it possible to determine whether earthquakes have occurred in this part of the world before records were kept? Yes! In fact, there is overwhelming evidence of a mega-quake occurring on January 26, 1700, at 9:00 PM. This seems awfully precise, and indeed it is. Evidence for this event includes:

- **Tree rings**: at several locations along the B.C., Washington, and Oregon coasts there are regions where land appears to have dropped suddenly to slightly below sea level killing all trees in the area. Tree ring dating shows this event to have occurred in the winter of 1699-1700.
- There is also evidence of changing **sediment deposition** along the coast indicating periodic uplift and sinking. These geologic events can be dated, and they occurred at the same time as events dated in tree rings. In fact, there was a series of similar events going back in time at intervals varying between about 300 and 900 years. This is the source of data for Figure EQ.48 shown in Unit D section 3a.
- There are also records in Japanese coastal communities of a **tsunami** occurring at around this time. Computer modeling can be used to establish exactly when the earthquake occurred if its location could be assumed. This is how the precise time of 9:00 PM, January 26, 1700 comes about. Figure EQ.50 includes an image of the computer modeling process, as well as tsunami records from Japan showing how known earthquakes caused observations very similar to the 1700 event.



source: K. Satake

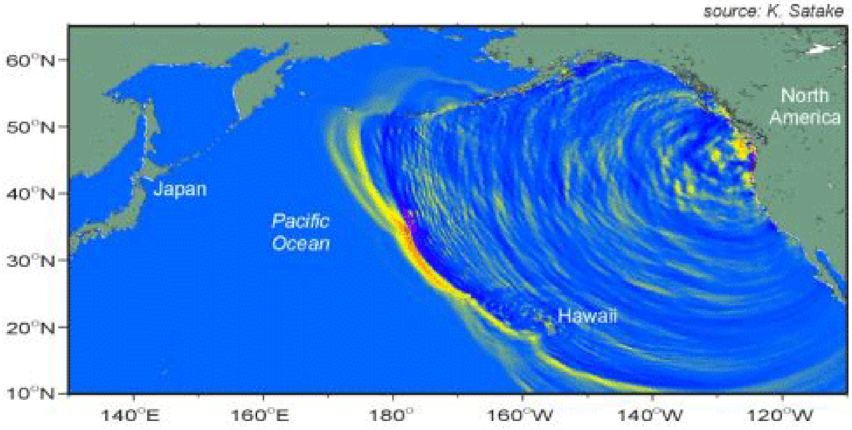


Figure EQ.51 A snapshot of a computer model illustrating a tsunami propagating from the source region next to southern Vancouver Island. History from coastal communities in Japan point to the arrival of a tsunami at a time consistent with an earthquake occurring opposite SW Vancouver Island.

Oral historical accounts by coastal native communities including that of a small community being devastated by a tsunami on the west side of Vancouver Island. Knowing the family history of those with these stories allows the dating of these events to within a year or two. People spoke of *"... the most important story the Huu-ay-aht people have ... "* and *"... it was at night time that the land shook"*. These accounts agree with the 9:00 PM time calculated from computer modeling. For more on oral history see Steven Earle's web site at Vancouver Island University, Nanaimo, BC.

4b. Cascadia: recent and current research

Finally, recently (2002) published results of investigations at the GSC describe in detail the real-time motion of the western edge of the North American Plate (Vancouver Island). Figure EQ.52 below is a composite image showing the tectonic setting and the GPS (Global Positioning Satellite) tracking system installed permanently in various locations on the plate. These monitoring devises record their positions relative to a reference location at Princeton, BC.

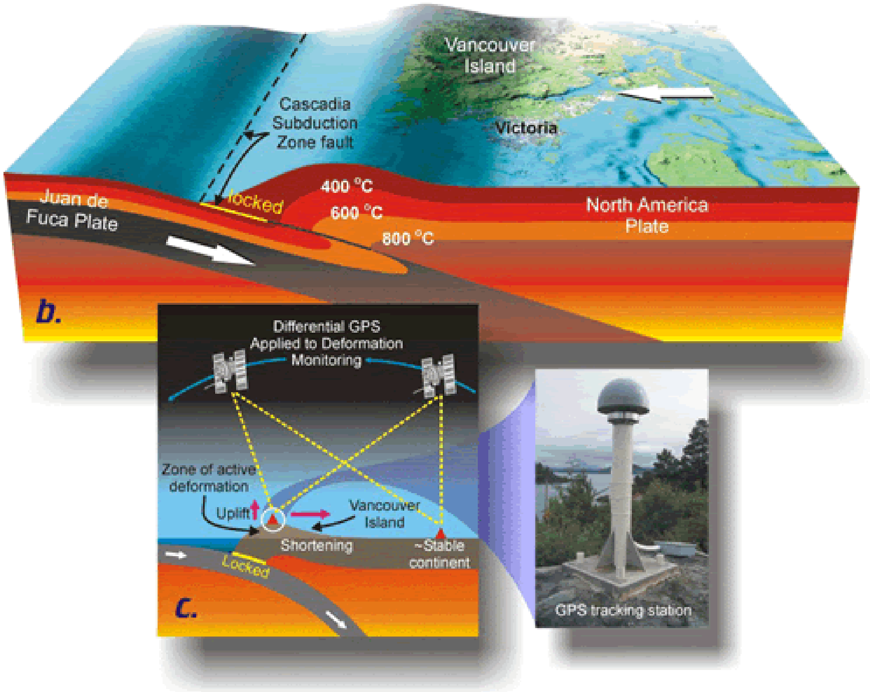
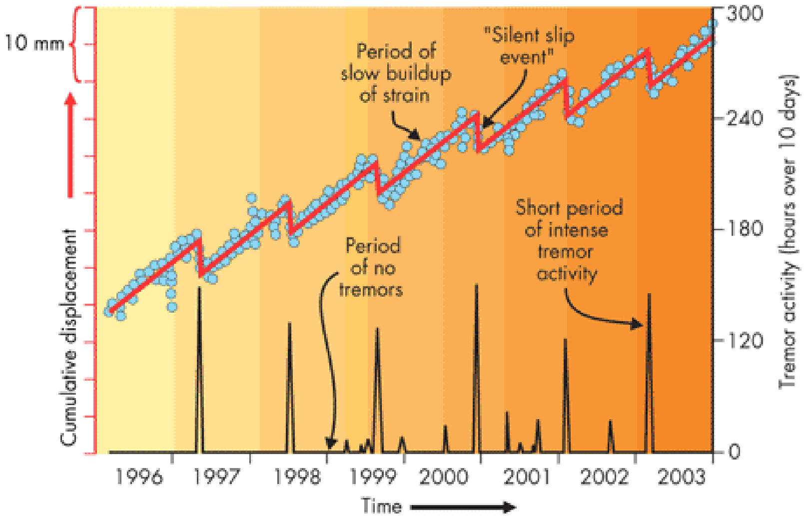


Figure EQ.52 Composite figure showing how GPS satellite technology allows scientists to make extremely accurate measurements of very slow plate movement such as that of the Juan de Fuca Plate relative to the North American Plate along the Cascadia Subduction Zone. Downloaded from Natural Resources Canada.



◀ **FIGURE 2.42 SILENT SLIP** Slow slip events along the deep portion of the Cascadia subduction zone and non-earthquake tremor activity recorded in the Victoria area. The blue circles represent day-to-day changes in the position of a GPS site at Victoria with respect to a GPS site near the inland city of Penticton, British Columbia, which is assumed to be stationary and fixed to the North America plate. The red line segments show the progressive movements between slip events, marked by reversals every 13 to 16 months. Since 1996 Victoria has moved 50 mm closer to Penticton. The bottom graph shows the total number of hours of tremor activity per 10-day period for southern Vancouver Island. Slip events have an average duration of 10 days. *(Clague, J., C. Yorath, R. Franklin, and B. Turner. 2006. At risk: Earthquakes and tsunamis on the west coast. Vancouver, BC: Tricouni Press)*

Data gathered from the Victoria area recording plate motion (*Keller et al. Figure 2.42* above) shows interesting features of the Cascadia subduction zone. One of the remarkable observations is that this portion of the western edge of the North American plate has long term motion that is **not steady**. It is mainly steady at speeds of about 10 mm per year in an eastward direction, but with sudden westward jumps ("silent slip" events) roughly every year. These jumps coincide exactly with periods of increased seismic activity. This activity involves unusual ground motion that is not detectible except with very careful measurements.

Analyses of these observations show that the North American Plate is being slowly pushed eastward and slightly upwards by the force of the subducting Juan de Fuca plate. However, the "sticky" junction between the two plates periodically slips as the stresses accumulate to a point where the plates can no longer hold together. The periodic slip events appear to be releasing stress in a benign way, thus perhaps reducing the chance of a major earthquake.

However the situation may not be this simple. If stress is being regularly released in some regions of this subduction zone, there must be accompanying increases in stress at other locations. The entire situation appears complicated, and it is currently being studied by large groups of scientists to attempt to understand better the implications on the potential of major earthquakes off the coast of the Cascadia region. For more information, go to the Geodynamics Division of the Geological Survey of Canada.

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5. Prediction: Summary

To summarize, we have outlined 3 aspects of prediction and some complications for each.

1. **Where** will earthquakes occur?

   At faults, *but geometry and physics are complicated*.

2. **What effects** can be anticipated *if* an event occurs?

   Knowing how ground moves allows us to build better buildings.

3. **When** will an event occur?

   Estimating probability is more helpful than trying to forecast times. *But... reliable records exist for only the past 100 years.*

Other possible precursors exist... *but we still need data and explanations on how these are related.*

Finally, we asked what about **Cascadia ...**

- Large 'quakes have occurred and scientific evidence exist
- Oral history confirms the most recent event occurred on January 26, 1700
- Plate dynamics is being carefully studied to inform us about Cascadia

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UNIT	TOPIC
E	Engineering for Survival

Outline

We have arrived at the last Unit of this Module: Engineering for Survival. This is where we discuss recommendations that can be made based on observations and understanding.

What are the "needs" driving these issues?

1. How can we say **"Earthquakes don't kill..."**?
2. What **breaks** buildings and structures?
3. How best should we describe **Intensity**?
4. How can a building's design **minimize earthquake damage**?
5. How do we characterize other contributors to **Catastrophe**?

We will cover the first two topics rather quickly and devote more time on carefully explaining exactly what affects "felt intensity" as compared to "earthquake magnitude". Structure and building design are important topics affecting our ability to live safely in earthquake zones. The last item in the list ensures we don't forget to mention aspects that affect safety other than the buildings themselves.

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1. How can we say "*Earthquakes don't kill...* "?

The heading above appears contradictory but if you think about it, if an earthquake does not damage or collapse structures (roads, dams, bridges, buildings, etc.) it could be argued that there was no "catastrophe".

Figure EQ.53 below shows two examples to emphasize this point: a moderate earthquake very near the city of Kobe, Japan (1995) caused tremendous destruction, whereas the second largest earthquake on record did much less damage, except in the city of Anchorage, which was not near the epicentre.

Figure EQ.53 The figure on the left shows some of the damage and destruction in Kobe, Japan after the earthquake in 1995, M_W=7.2. The damage to infrastructure was estimated to be $2.7 billion and cost 6,425 lives. The figure on the right shows an intertidal platform that was uplifted 33 feet during the 1964 Good Friday earthquake in Prince William Sound, Alaska, M_W=9.2. The damage caused by the earthquake was estimated to be between $300-400 million but only cost 116 lives in Alaska. Basic information on these and other earthquakes may be found at the USGS website.

An example from more recent events is a pair of earthquakes that hit Alaska on October-November 2002 only 2 weeks apart. One was a M6.2 and the second M7.9, no lives were lost, and cost relatively little in damage. Were it not for a major road connecting Anchorage and Fairbanks with the Trans-Alaska Pipeline running right through the area, these earthquakes would not have been noticed except by the local wildlife. No major damage to the pipeline was reported, although the road did need some repair.

The pipeline was not damaged because of its engineering design. Because the fault was already known to exist, the pipeline was mounted on rails parallel to the fault (visible in the aerial photo below left). When the 2002 earthquake occurred, the earth moved the rails under the pipeline roughly 2.5 m but did not cause any damage to the pipeline. Careful observations and analyses, coupled with proper designs based upon an understanding of earthquakes allowed this infrastructure to survive in the presence of a dynamic and possibly dangerous Earth.

Figure EQ.54 Map showing location of 2 earthquakes occurring in Alaska in October-November 2002. Photo on right shows the Trans-Alaska Pipeline running parallel to the fault. Note the rails supporting the pipeline.

Consider the potential for catastrophe had these earthquakes occurred on a fault near a city. The photo below shows the effect of a non-catastrophic landslide caused by an earthquake. A remote glacier in the mountains near the earthquake's epicentre was covered. This and many other resources are on the web, illustrating the types of changes to ground, mountains, glaciers, roads, and oil pipeline. One example is the Denali Fault Earthquake Information of the Alaska Department of Natural Resources.

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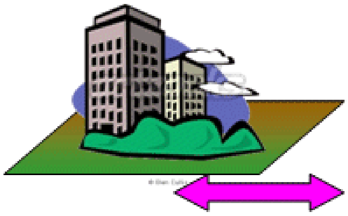
2. What breaks buildings and structures?



How does ground motion break a structure? By applying a force to it. Moving ground causes the structure to accelerate, This means velocity changes from zero to something larger, and back again to zero. Recall that force F is related to the mass and acceleration via the equation:

$$F = m \cdot a$$

The force applied to a structure is proportional to the structure's acceleration and mass.

Which types of seismic waves are the most hazardous? To answer this question we must know which, vertical or horizontal acceleration (motion), will be worst for structures.

Structures are built to withstand acceleration in the vertical direction. In fact they continuously withstand the acceleration of gravity which is 9.8 m/s^2 = 1.0 g. Small deviations from that value due to seismic wave motion will not have a large effect on a building.

However, structures are NOT built to withstand horizontal acceleration. Normally they do not experience any at all, i.e. 0.0 m/s^2. So, a change in horizontal acceleration represents a significant change from normal. (Note that a turning train or boat experiences roughly 0.1 g or 0.2 g of sideways acceleration). In other words most structures are much less able to withstand changes in horizontal motion.

Now recall the maps we showed earlier (Unit D section 2) when we discussed "predicting" the effects of ground motion. The maps showed the likelihood of experiencing a certain acceleration considered hazardous to particular building types.

Now back to the question about which seismic wave types are most dangerous. Figure EQ.55 is a review of the various types of seismic waves. Which of these waves cause the most significant side-to-side motion at surfaces? **Rayleigh** and **Love** waves. In addition, these are the waves with the largest amplitude of motion. *These waves cause the most damage*.

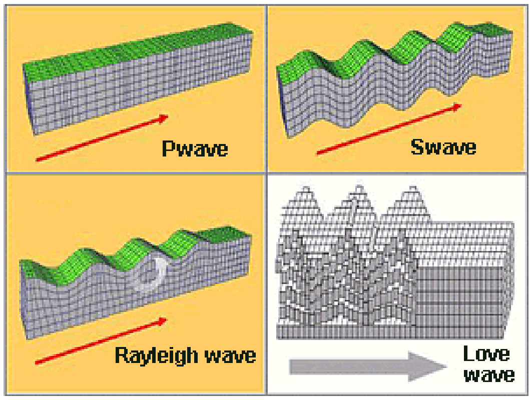


Figure EQ.55 (left) A review of particle motion during the transport of seismic waves. (right) A video clip from a convenience store's security camera during an earthquake. It clearly shows the direction of destructive ground motion: side-to-side motion. Click on the image to view the video.

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3. Magnitude vs. Intensity

Before continuing it is important to clarify the distinction between earthquake **magnitude** and **intensity** of ground motion. Figure EQ.56 uses the analogy of a light bulb to make the point. The amount of energy at the source describes the magnitude (wattage of the light bulb), whereas the experience felt as a result of that energy is the "**felt intensity**" (amount of light at the place it is used).

For example, the magnitude of the December 26, 2004 earthquake in Indonesia was 9.1, but the intensity of felt motion for that earthquake in North America was close to zero.

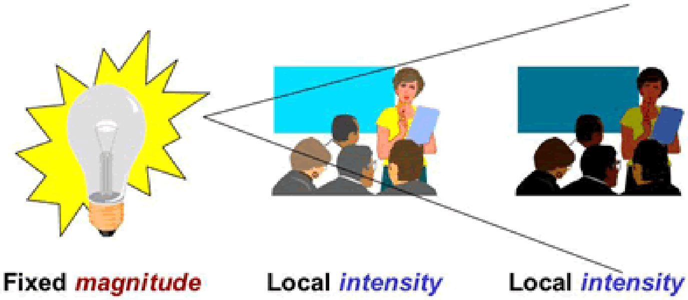


Figure EQ.56 Relating magnitude (energy at source) to intensity (what was experienced).

3a. Characterizing intensity

How is intensity characterized? The map shown below was introduced in Unit C section 2. It shows how ground motion is felt. A colour scale based on the Mercalli scale, which is a qualitative characterization of the type of motion experienced, is now shown. Such a map can only be built by interviewing a large number of people to record their "felt intensity" or by recording large scale motions with appropriate instruments.

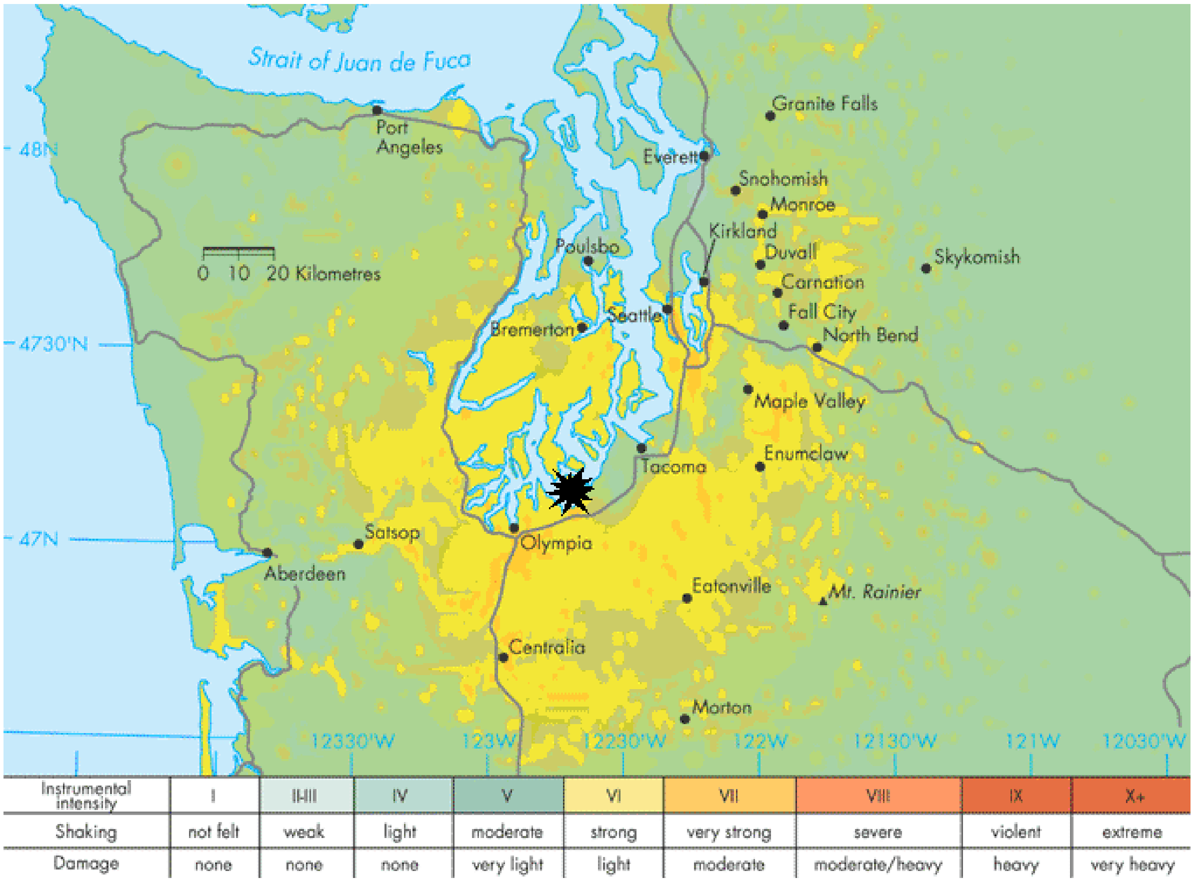


Figure EQ.26 The felt zone map for the Nisqually earthquake, February 28, 2001. Epicentre (point on the ground above the hypocentre or focus) is indicated by the black exploding star. Red/orange to yellow regions are those where motion was experienced. Figure modified from *Keller et al. Figure 2.7b*.

3b. Factors influencing intensity

What factors influence intensity of ground motion? This is of course an important question. It is related to real needs of those living in earthquake zones, and involves both observations and development of understanding. There are five important factors.

a. Earthquake magnitude

b. Duration of shaking

c. Distance from epicentre/hypocentre

d. Ground type

e. Building characteristics

a. Earthquake magnitude This topic has already been discussed. Larger earthquakes have a much greater capacity to be catastrophic. However, this is only true if they occur near human activity. We have seen several examples, two are given in the following figure.

Figure EQ.57 (Left panel) Anchorage Alaska, 1964; M_W=9.2. This earthquake was the 2nd largest ever recorded! (Right panel) Smaller earthquakes can be more devastating! Bam, Iran, 2003; M_W=6.6. A much smaller earthquake, but it ruined many more people's lives.

b. Duration of shaking Longer shaking will cause more damage. Again this is common sense -- a useful tool in all scientific investigations!

c. Distance to/depth of epicentre/hypocentre The "felt zone" for Nisqually was shown in Figure EQ.26. It is clear in this instance that the closer to the epicentre/hypocentre, the more likely that intensity is large. However, this is definitely not always true. Other factors do affect intensity.

d. Ground type is very important. Harder rocks are stiffer and generally experience smaller motions. Additionally, all frequencies of a seismic signal (high and low) pass more easily in hard rocks. Softer rocks in the same location, however are likely to experience larger motions. Higher frequencies also tend to decay more quickly in softer rocks. The image below shows an excellent set of observations that support these ideas.

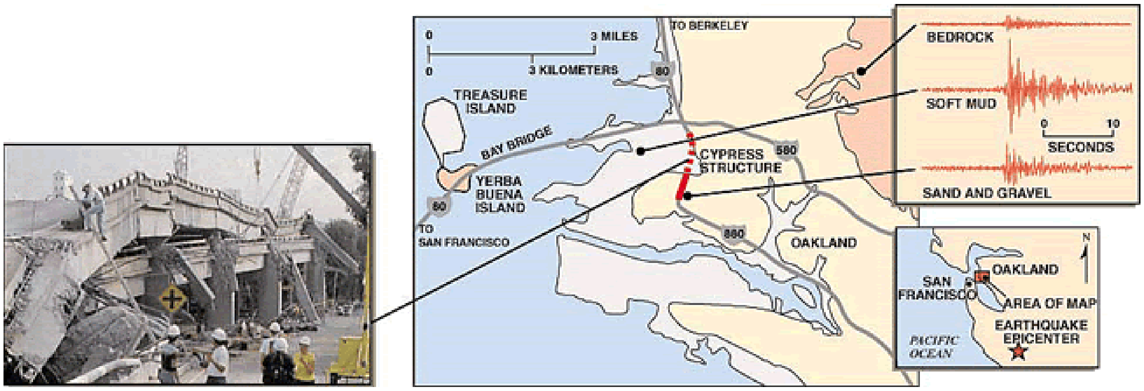


Figure EQ.58 Seismograms showing ground motion for the same earthquake measured on three types of ground. Note the difference in frequencies of the signals recorded. Which portion of the overhead freeway was destroyed (see photo on left panel)? From the seismograms, we can see that it was the portion built on the softest ground, shown as the dotted portion of the red line on the map.

Where in the Vancouver area are rocks hard and where are they soft? Think in terms of rocky and mountainous regions versus regions that are flat and filled with recent river sediments. The likelihood of liquefaction in B.C.'s Lower Fraser Valley is shown in Figure EQ.67 in Unit E section 5, Other Contributors to Catastrophe.

3c. Building characteristics and felt intensity

e. Building characteristics One more very important aspect of felt motion, and breaking structures, is the buildings themselves. Of course, stronger buildings will suffer less than poorly constructed ones. However, another factor, which is equally important, is resonance.

Every object wobbles at its preferred frequency. Strings in a musical instrument oscillate (wobble) at a rate dependent on its length and tension. If you hold a pencil vertically by its tip and allow it to wobble, it will do so at a preferred oscillation frequency. A yardstick will have a preferred oscillation frequency that will be slower than that of the shorter pencil. This illustrates resonance. The frequency at which an object prefers to wobble is called its "resonant" frequency.

Just like an object, buildings also have a resonant frequency. A 1-story house wobbles at about a tenth of a second per cycle. A 30-story building sways at about 3 seconds per cycle. Factors other than height determine resonant frequency. For example, stiffer buildings have higher resonant frequencies, more flexible buildings have lower resonant frequencies, and increased mass (related to its weight) lowers the resonant frequency.

What is the significance of a building's resonant frequency? If the building is made to shake at exactly it's resonant frequency, the building's motion will increase rapidly, causing it to break much more quickly than if it is forced to move at a rate that is not close to it's resonant frequency.

Unfortunately, ground motion from earthquakes can be very similar to the resonant frequency of many buildings. This is why the seismic hazard maps such as the one introduced in unit D section 2 (Figure EQ.45) are given in terms of a particular frequency of ground motion. Refresh your understanding by reviewing that page.

One other important aspect of a building's response to earthquake ground motion is the behaviour of adjacent buildings. The figure below shows examples of what can happen when two buildings adjacent to each other have different resonant frequencies and interact during an earthquake event.

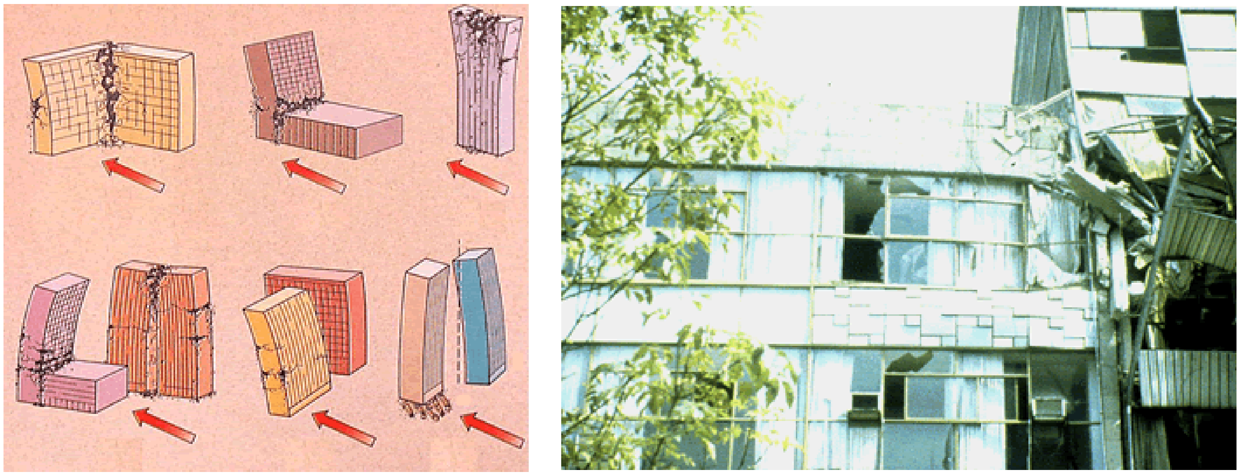
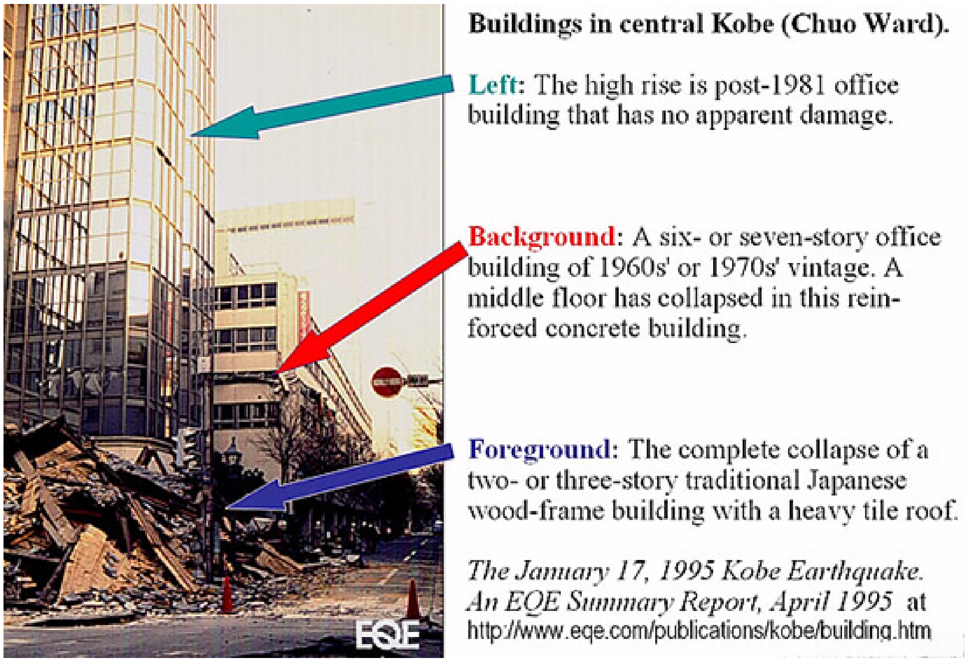


Figure EQ.59 (Left panel) Schematic of response of various types of buildings. (Right panel) Mid-floor failure of building at right from repeated pounding from building on left. The natural periods of the buildings were close to the period of the earthquake causing lateral displacements large enough to allow them to "hammer" each other. Photo credit: C. Arnold, Building Systems Development, Inc. See also *Abbott Figure 6.6 (Figure 5.6, 5th edition)*.

Resonance and building interactions are some of many factors that affect the likelihood of a building to be damaged. Modern engineering designs ensure buildings will withstand the shaking that can be expected. There is more about these engineering and design practices in the next unit of the earthquakes lesson, but for now, an example of how different buildings might respond is given in the following photograph.



Buildings in central Kobe (Chuo Ward).

Left: The high rise is post-1981 office building that has no apparent damage.

Background: A six- or seven-story office building of 1960s' or 1970s' vintage. A middle floor has collapsed in this reinforced concrete building.

Foreground: The complete collapse of a two- or three-story traditional Japanese wood-frame building with a heavy tile roof.

The January 17, 1995 Kobe Earthquake. An EQE Summary Report, April 1995 at http://www.eqe.com/publications/kobe/building.htm

Figure EQ.60 Effect of building type on earthquake damage, Kobe, Japan 1995. Photo credit: ABS Consulting.

This concludes our discussion about magnitude vs. intensity and the five factors affecting intensity of ground motion. Next, we can put some of this new knowledge to work explaining how damaging effects are minimized by engineering practices.

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4. Mitigation... making it safe

Mitigation means "*To act in such a way as to cause an offense to seem less serious*". In other words, mitigation aims to minimize bad effects. Both infrastructure (roads, dams, slopes, etc.) and building designs are of interest.

Let us start with an example of a seismic hazard reduction project with long-term relevance to communities, the Seymour Falls Dam Seismic Upgrade project in Vancouver's local region. This project involves upgrading an earth-filled and concrete dam, which holds one of Vancouver's main water reservoirs. The structure is strong, but its foundations may weaken if a large earthquake causes it to shake.

The dam foundation is being re-built by dynamic compaction (blasting and dropping large weights). Such "blast densification" is a relatively new process in British Columbia. The method involves setting off explosions, which cause soil layers to settle and become dense. Dense layers will not flow when the Earth shakes.

Figure EQ.61 Seymour Falls and the planned upgrades projected for completion by 2007. The upgrades will ensure that the Dam performs safely in the event of a major earthquake. Photo from Metro Vancouver.

4a. Static methods to strengthen buildings

We saw in a previous unit how earthquakes can break buildings. The side-to-side motion of surface waves causes buildings to be shaken in the direction where they are weakest. Techniques used to strengthen buildings where they need it most are most easily described with pictures. The next three sets of figures illustrate these concepts.

There are two general approaches to making buildings better able to withstand side-to-side stresses:

1. static methods and
2. dynamic methods

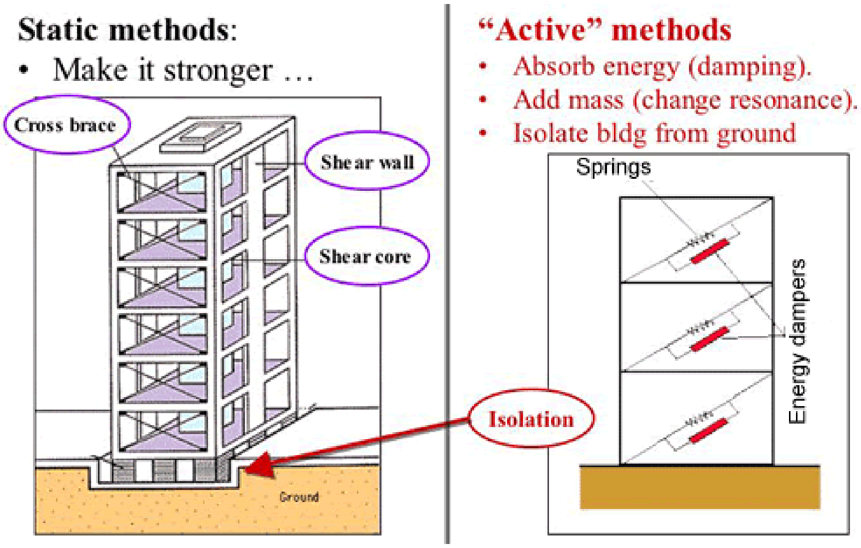

Figure EQ.62 Static and active methods to retrofit buildings to better withstand shaking.

Static methods involve simply adding strength in the form of cross braces, shear walls (walls with good shear or side-to-side strength), and shear cores (a central zone with added shear strength). It is not uncommon for the bottom floor of a building to be surprisingly "weak" (i.e., a "soft" storey) with respect to side-to-side forces. It is not difficult to brace buildings, bridges, and other structures after they have been built as shown in the examples on the UBC campus below. Also shown is damage to a building with a "soft" storey.

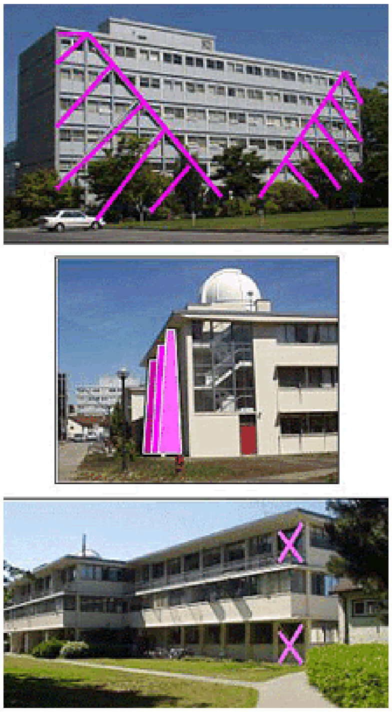

Figure EQ.63 (Top panel) Damage to a building with a "soft" storey. (Right panel) Examples of how selected buildings on UBC campus have been strengthened (braces are highlighted in magenta).

4b. Dynamic methods to strengthen buildings

Dynamic methods involve one or more of three mechanisms:

a. **Absorbing energy** if shear motion occurs. Use of springs and shock absorbers (dampers) allows some of the energy of swaying to be dissipated in the same way the shock absorbers in your car help damp out the up and down motion of rough roads.

b. Changing the **resonant frequency** of the building. Adding **mass** has the effect of reducing the resonant frequency. This is done when the building sways preferentially at the speed expected for ground motion. Rather than completely re-designing the building, it is sometimes sufficient to simply add mass at the correct location within the building so that it will not be shaken to pieces when the expected ground motion occurs.

c. **Allowing the earth to move** without dragging the structure with it. This so-called "isolation" at the foundation of a structure can be done with huge rubber foundation blocks. This technique was employed to isolate the Trans Alaska pipeline as we saw in Unit E section 1.

There is always more to learn about how best to make structures of all types stronger using cost effective measures. UBC's Civil Engineering Department has a dynamic group of structural engineers who have been conducting research on a wide range of topics related to cost-effective seismic design and retrofit methods. Results from their research projects have benefited residents of British Columbia and the rest of the world. One of the research projects being conducted focuses on establishing best practices for making strong shear walls out of indigenous materials for Third World countries.

An important research component of the UBC facility is the large shaking table (see photo on right) that can be made to shake side to side and up and down in exactly the same manner as a real earthquake. This is very useful for testing new structures in controlled and repeatable ways that are excellent simulations of real conditions.

Finally, here are a few images illustrating the importance of employing good general construction practices. Some of the aspects engineers must consider include:

- **Firmly attach cosmetic brick** facing to buildings so these are not easily detached during shaking
- **Use reinforced concrete properly**. The bridge pylons in the example below were reinforced but were weak at the joins causing the entire upper section to collapse during an earthquake
- **Use of shear walls.** This could be as simple as a sheet of plywood added to a timber frame home to give it side-to-side strength
- **Hillsides can be dangerous** especially if they slip when shaken

Figure EQ.64 (Top left panel) Bricks that fell because they were not properly attached to a building near the Washington Capitol Building in Olympia, WA causing damage to cars and other properties on the ground. Photo retrieved from the U.S. Geological Survey and The Nisqually Earthquake Information Clearing House (Top right panel) Concrete failure at the join between two sections of reinforcing, Interstate 880 in California.
(Bottom right panel) Slope damage near a home following a landslide caused by an earthquake.

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5. Other contributors to catastrophe

In this section, we will discuss two more aspects of catastrophe:

a. destruction of **infrastructure**, and

b. **liquefaction**

a. Destruction of infrastructure. When an urban setting is badly shaken there will always be the possibility of dangerous fires because gas lines will be broken, or open flames moved around (in kitchens, workshops, etc).

In addition, the extent of the catastrophe will always be increased when important services are interrupted. If infrastructure and utilities such as communications (telephone, internet), utilities (water, electricity), and transport (roads, vehicles, airports, etc) can be "hardened" (i.e., made more resistant to ground motion), the risk of living in earthquake prone regions will be significantly reduced.

Figure EQ.65 (Top left panel) An entire city block in Kobe, Japan burns following the 1995 M_W6.9 earthquake. Photo from City of Kobe, Japan
(Top right panel) Map showing areas devastated by fire, Kobe, Japan, 1995.
(Bottom right panel) Side view of support-column failure and collapsed upper deck, Cypress viaduct, Oakland, California. Photo credit: H.G. Wilshire, U.S. Geological Survey.

b. Liquefaction of soils. The next figure illustrates the consequences of building on (or with) materials prone to **liquefaction**. What does liquefaction mean? Soft materials like sands or soils are often perfectly strong enough to support buildings or dams, so long as they are kept still. But if these materials are full of water (saturated) and they are shaken, it is possible for the particles of the material to get shaken apart within the fluid (water) and thus loose their strength. This causes structures built on the material to sink, or the material to slump.

Figure EQ.66 (Left panel) Photo of buildings that were destroyed because of liquefaction following an earthquake near Niigata, Japan, 1964. (Right panel) Photo of an earth dam that was very nearly breached (water breaking through) as a result of liquefaction caused by earthquake shaking. Less than a minute more of shaking and the

valley below would have been devastated.

The map below shows where ground may be prone to liquefaction within British Columbia's Lower Fraser Valley region. Red areas are where ground is made from fine sediments deposited by the Fraser River within the last 10,000 years or so. Yellow areas are older, harder glacial deposits and black areas are bedrock. Both glacial deposits and bedrock are much less prone to be shaken to the point of losing strength.

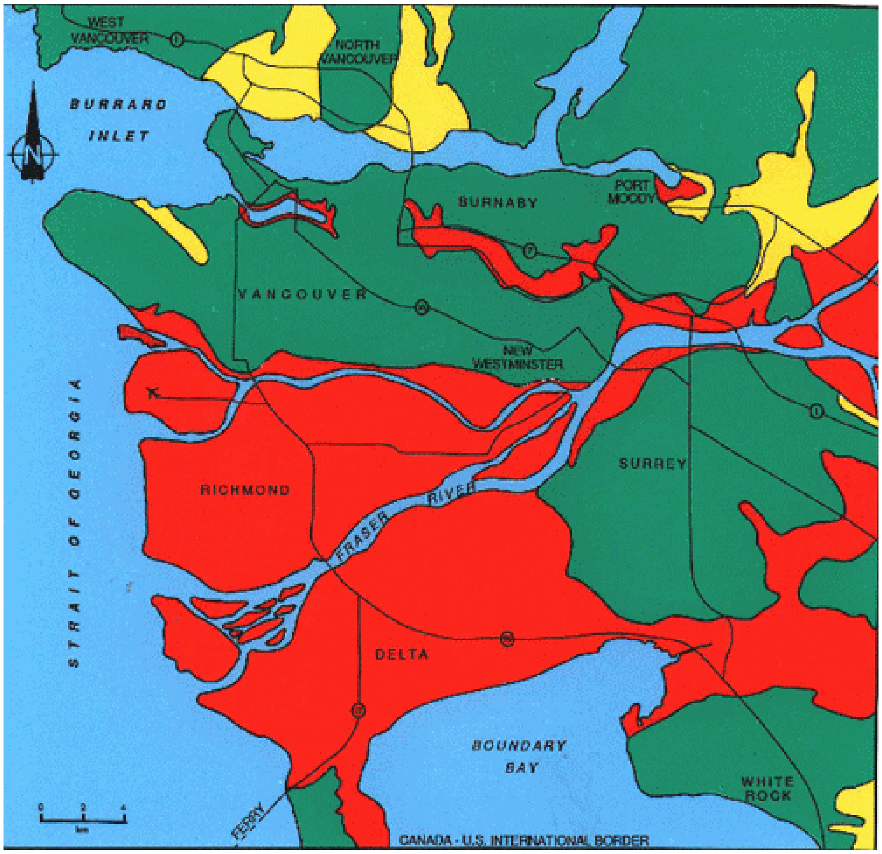

Figure EQ.67 The map of Greater Vancouver Illustrates three simplified geological zones that are incorporated into the National Building Code of Canada for use in the design of large structures. Green: compact or stiff soils <15m thick and bedrock. Yellow: compact or stiff soils >15m thick; and loose or soft soils <15m thick. Red: Loose or soft soils > 15m thick. Figure from BC Ministry of Energy, Mines and Petroleum Resources.

The red areas in the map above encompass the largest delta in Canada, the Fraser River delta, which is undergoing rapid urban development. Approximately 250,000 people live on the delta proper, and it is the region receiving most of the recent population increase.

In addition to this urbanization, the delta is host to a $74M/year farming industry, expanding industrial capacity, the Vancouver International Airport, the busiest ferry terminal in the world, the largest shipping facility in Canada, a $260M/year fishery, and a submarine hydroelectric cable corridor which supplies power to Vancouver Island and the capital city of the province.

State-of-the-art geological, geophysical, and geotechnical technologies have been applied to investigate the stability of the delta in terms of its liquefaction potential and ground surface response in the event of an earthquake.

Click here PLAY VIDEO ▶ to view an animation of the liquefaction at the particle level. Animation from *Keller et al.*.

It must be mentioned that NOT all earthquakes are caused naturally (i.e. only by plate movement). Observations show that earthquakes have been caused by human activity! Some of these events are:

Building a dam and flooding a valley

- Injecting liquid waste deep into the ground
- Detonating underground explosions

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6. Safety and Survival

Your actions before, during, and after an earthquake can significantly reduce death, major injuries, and even damage to property. What should you do?

a. BEFORE an earthquake. Look around you!

- Retrofit your home: put secure latches on cabinet doors; connect bookcases and wall units to the wall; store breakable or heavy objects on lower shelves; put anti-skid pads under heavy objects such as TVs, microwaves, etc.
- Keep your home safe: learn how to shut off the gas, water, and electricity; strap water heaters to walls; keep flammable and other hazardous liquids away from the house
- Identify safe spots - under a sturdy desk
- Prepare an earthquake kit. Here are some items to consider including in your kit:

- Determine seismic hazard at your site. More details are available at Earthquakes Canada.
- refer to *Keller et al.* page 68 for other tips

b. DURING an earthquake.

- Stay calm: DON'T PANIC
- Get out of areas where flying objects could cause injury (for example the kitchen, study/library, areas with glass windows)
- Stay under strong tables or desks (remember: Duck, Cover, Hold)
- Failing that, stand under archways or the inside corner of a room
- Avoid doorways!
- Do not move until the shaking stops

c. AFTER an earthquake.

- Deep breaths!
- Help the injured (or get help)
- Get out of damaged buildings
- Do not use the phone if possible
- Be prepared to survive on your own; Help might not be available for at least 3 (or more) days

  - Find food, water, supplies, equipment to help the injured
  - Fill a bathtub with water as your reserve
  - Use other sources of water: water heaters, melted ice cubes, the toilet tank

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Conclusion

This concludes the earthquake portion of the course. We have covered a lot of ground. Here as a reminder of the outline of our topics for this Module.

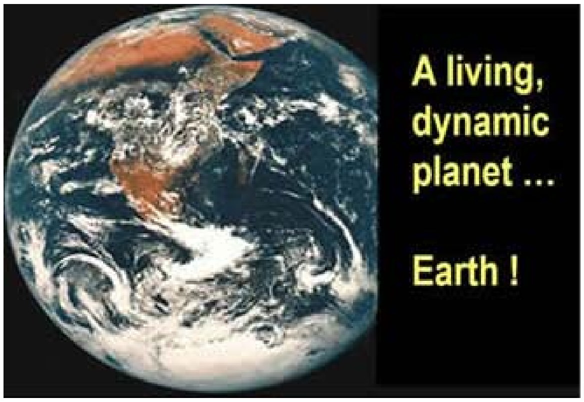
Unit	Topic
A	**Global Distribution:** Where and how often do earthquakes occur, especially in the Pacific Northwest?
B	**Earthquake Sources:** What observations and explanations do we have about the source of an earthquake?
C	**Seismic Energy and Waves:** What observations and understanding do we have about the energy that travels away from earthquakes?
D	**Forecasting:** What is the difference between "prediction" and "forecasting"? How can we use current understanding to forecast where and when an earthquake occurs and what effects it will cause?
E	**Engineering for Survival:** How is current knowledge used to make recommendations about how to survive with modern infrastructure in earthquake zones?

If there is "one moral of the story", it is that ***earthquakes do not kill...***. Inadequate preparation for earthquakes kills thousands worldwide per year. Fortunately, for all of us, proven scientific and engineering principles can minimize damage and destruction. The effort and commitment to apply these principles must be employed at all levels: the individual, community, national, and global levels.

We must also remember that in any scientific discussion, whether it is among experts in the field, or amongst professionals in non-scientific disciplines, the debate must always account for each aspect of

Observations... Explanations... Predictions... Recommendations

Making or using predictions or recommendations can not be done reliably or usefully without considering all relevant observations and explanations.


A living,
dynamic
planet …

Earth !