Names: **ESS 315**

Lab # 1 Seismic Hazards along the Cascadia Subduction Zone

Seismic Hazards along the Cascadia Subduction Zone

Seismographs located throughout the Pacific Northwest record thousands of earthquakes each year in Washington and Oregon. Between one and two dozen of these earthquakes cause enough ground shaking to be felt by residents, though few cause any damage. However, based on the history of past damaging earthquakes and our understanding of the geologic history of the Pacific Northwest and of the interaction between the Juan de Fuca (oceanic) and North American (continental) plates, it is inevitable that damaging earthquakes (magnitude 6 or greater) will recur in our region. To date, we have no way to predict whether this event will occur today or many years in the future.

Earthquakes are driven by geologic processes that produce stress in the earth. In the Pacific Northwest, the ocean floor is being subducted beneath the North American continent along a major plate boundary parallel to the coast of Washington and Oregon. The boundary, called the *Cascadia Subduction Zone* lies about 50 miles offshore and extends from the middle of Vancouver Island in British Columbia past Washington and Oregon to northern California. Damaging earthquakes occur in the continental crust and deep in the subducted oceanic plate as well as along the subduction zone (Fig. 1-1).

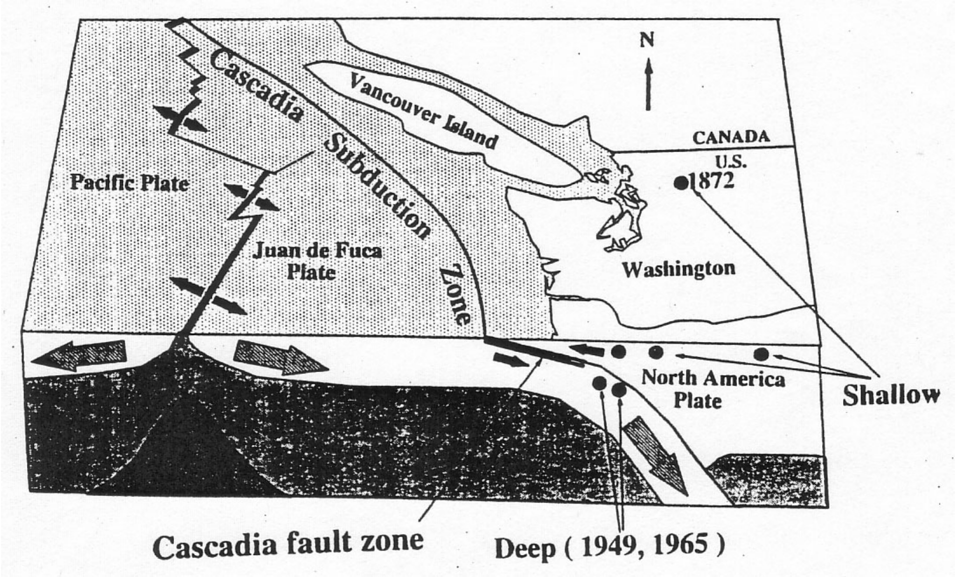


Figure 1-1: Earthquakes along the Cascadia Subduction Zone

Deep earthquakes in the subducted oceanic plate: The three most recent damaging earthquakes in Washington, 2001 (M 6.8, near Olympia) 1965 (M 6.5, located between Seattle and Tacoma) and 1949 (M 7.1, near Olympia), were approximately 30-40 miles deep, within the oceanic plate where it lies beneath the continent. These earthquakes caused serious damage, and were felt as far away as Montana. Other sizable events that were probably deep occurred in 1882, 1909, and 1939.

Shallow earthquakes in the continental crust: The largest historic earthquake in Washington or Oregon occurred in 1872 in the North Cascades. This earthquake had an estimated magnitude 7.4 and was followed by many aftershocks. It was probably at a depth of 10 miles or less within the continental crust. In 1993, crustal earthquakes in Oregon caused over $30 million in damages, and in January 1995 a magnitude 5.0 crustal earthquake was widely felt and did minor damage in the Puget Lowland. There are many crustal faults in Washington and Oregon that could produce damaging earthquakes. Geologic evidence indicates that a large shallow earthquake took place within the central Puget Basin 1,100 years ago along what is now called the Seattle Fault, causing massive block landslides into Lake Washington, a tsunami in Puget Sound which left sand deposits at West Point in Seattle and at Cultus Bay on Whidbey Island, and large rock avalanches on the southeastern Olympic Peninsula.

Subduction Zone megathrust earthquakes: Although no large earthquakes have happened along the offshore Cascadia Subduction Zone since our historic records began in 1790, similar subduction zones worldwide do produce “great” earthquakes - magnitude 8 or larger. These occur because the oceanic crust “sticks” as it is being pushed beneath the continent, rather than sliding smoothly. Over hundreds of years, large stresses build which are released suddenly in great earthquakes. Such earthquakes typically have a minute or more of strong ground shaking, and are quickly followed by damaging tsunamis and numerous large aftershocks. The M 9.2 Alaskan earthquake of 1964 was a great subduction zone earthquake (as was the recent M 9.0 earthquake in Indonesia). Geological evidence shows that the Cascadia Subduction Zone has also generated great earthquakes, and the most recent one was about 300 years ago. Large earthquakes also occur at the southern end of the Cascadia Subduction Zone (near the Oregon-California border) where it meets the San Andreas Fault system: including a magnitude 7.1 earthquake in 1992, and a magnitude 6.8 (estimated) earthquake in 1873.

Seismic Waves

There are three main types of seismic wave energy generated by earthquakes, and each travels through the earth a different velocities. P- (compressional) and S- (shear) waves are both body waves, which will travel outward from the point of origin (e.g., like light or sound waves) and will propagate through the earth. Compressional waves deform rock through a change in volume while shear wave deform material through a change in shape. P waves are the fastest seismic waves, traveling at about 6.0 km/sec through the Earth’s crust. S-waves travel at about 3.5 km/sec through the Earth’s crust. Surface waves (analogous to ocean waves), the slowest seismic waves, are restricted to the Earth’s surface and are associated with the greatest ground shaking.

Because P-waves travel faster than S-waves, they arrive sooner at any given distance from the origin of the earthquake. The greater the distance from the origin, the greater the lag time between the arrivals of the P- and S-waves. This fact is important to locating the epicenter of an earthquake--that point on the Earth’s surface which lies directly above the focus of seismic energy release.

Locating earthquake epicenters

If a seismic event has been recorded by at least three or more seismographs, its epicenter can be determined using simple calculations. In today's lab you will determine the location of the epicenter using seismic data from one of two earthquake seismograms shown below (Fig. 1-2).

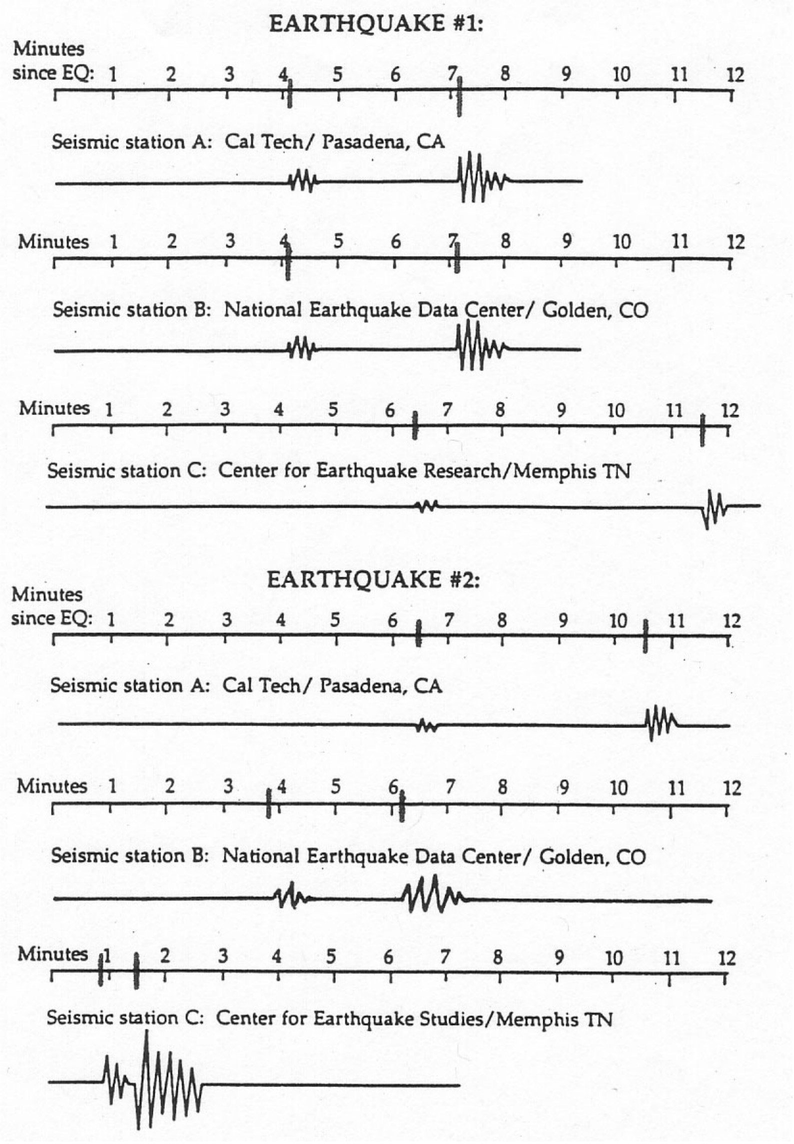


Figure 1-2 (above): Seismograms for two earthquakes in North America.

STATION	Time of P arrival (min)	Time of S arrival (min)	P-S lag time (min)	Distance from epicenter (km)
A				
B				
C				

Table 1-1 (above)

1. Determine the distance between the seismograph and epicenter. This is accomplished by comparing the arrival times of the P- and S- waves (See Fig. 1-3) using average travel-time curves for each respective wave. The greater the difference between arrival times, the greater the corresponding distance from the seismic station and epicenter. Record this information for each of the three seismic stations in the Table 1-1. Convert the lag times to distances from the epicenter using the lowermost curve in Fig. 1-3.

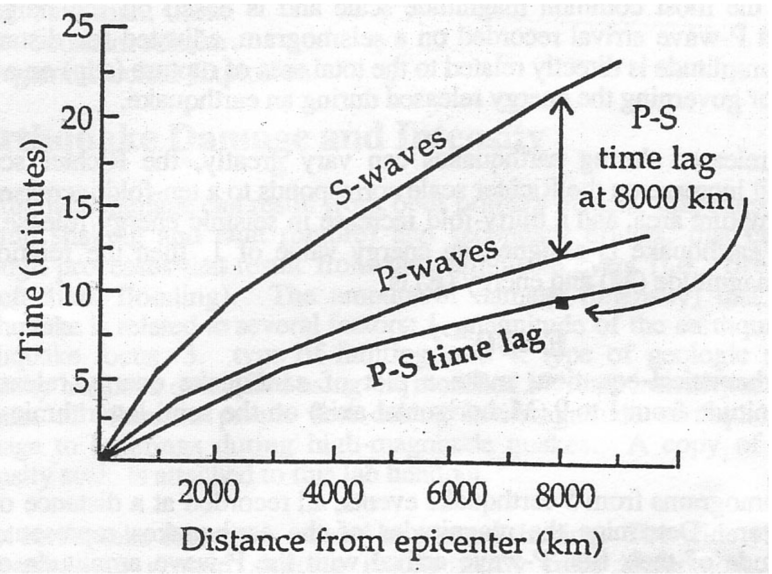


Figure 1-3

2. Using a compass and pencil draw three circles (or arcs) on the North American map (Fig. 1-4) centered on the seismic stations with radii equal to the distance from the epicenter.

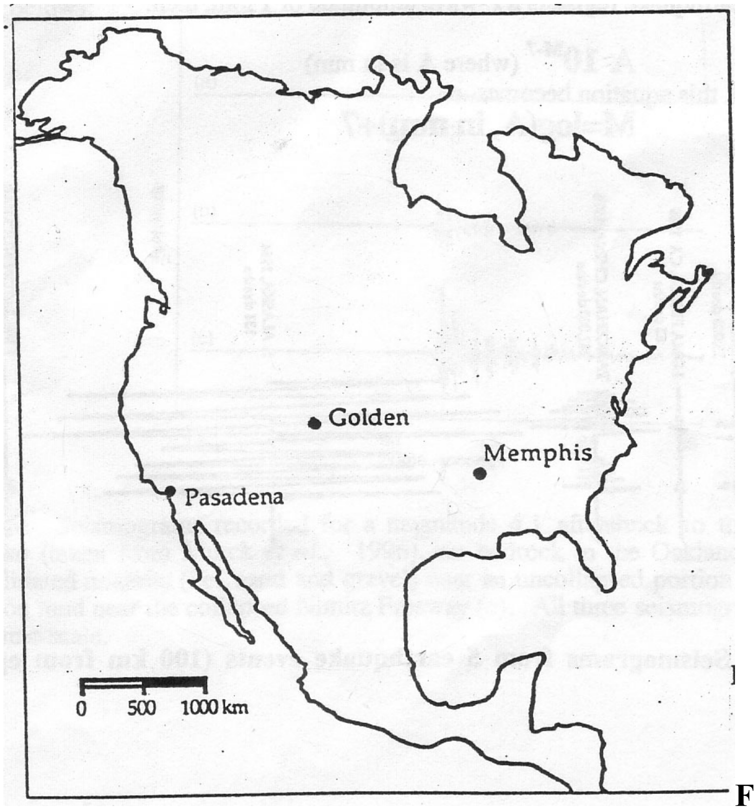


Figure 1-4

3. Is the epicenter of your earthquake near a plate boundary? If so, what type of plate boundary?

Assigning Earthquake Magnitudes

The magnitude of an earthquake is the quantitative description of the energy it releases. The Richter scale is the most common magnitude scale and is based on the height, or amplitude, of the first P-wave arrival recorded on a seismogram, adjusted for distance to the epicenter. Wave amplitude is directly related to the total area of rupture (slip) on a fault, which is a major factor governing the energy released during an earthquake.

Because the energy released during earthquakes can vary greatly, the Richter scale is logarithmic. Each unit increase on the Richter scale corresponds to a ten-fold increase in P-wave amplitude and rupture area, and a thirty-fold increase in seismic energy release. If a Richter magnitude 1 earthquake is assigned an energy value of 1, then the relationship between earthquake magnitude (**M**) and energy (**E**) is:

$$E=30^{M-1}$$

Using the above mathematical equation, make a plot of earthquake energy release (E, vertical axis) vs. magnitude from 1 to 9 (M, horizontal axis) on the semi-logarithmic graph paper provided.

Figure 1-5 shows seismograms from 5 earthquake events, all recorded at a distance of 100 km from the epicenter. Determine the magnitudes of the earthquakes represented by comparing the amplitude of their first P-wave arrival with the P-wave amplitude on the record for the devastating 1988 magnitude 7 earthquake in Armenia. Remember that 10-fold increase in P-wave amplitude (A) corresponds to a 1 unit increase in magnitude, so if a magnitude 7 earthquake registers a P-wave amplitude of 1 mm, then:

$$A=10^{M-7}$$ (where **A** is amplitude in mm)

Solving for M, this equation becomes

$$M=\log(A, \text{in mm})+7$$

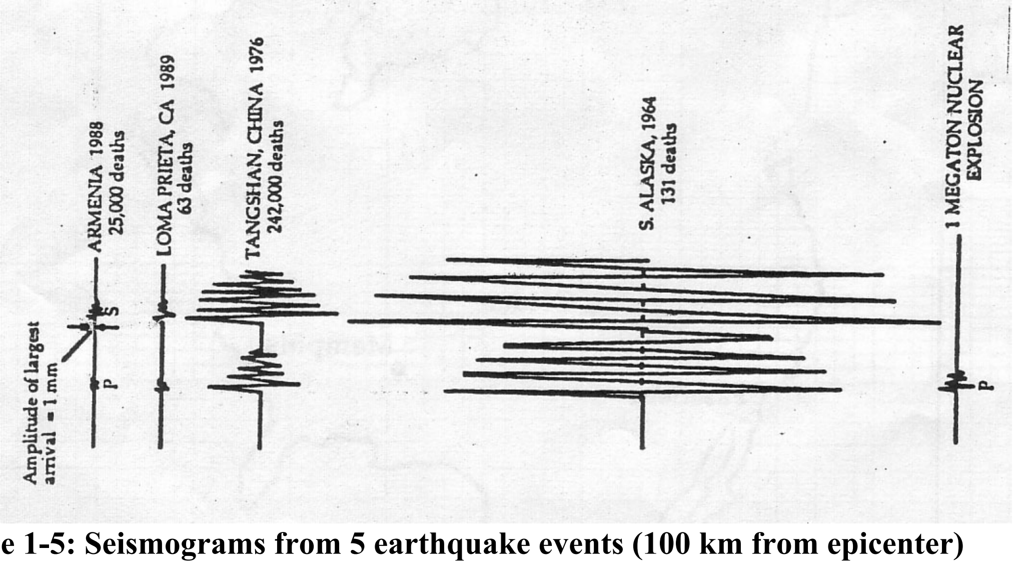
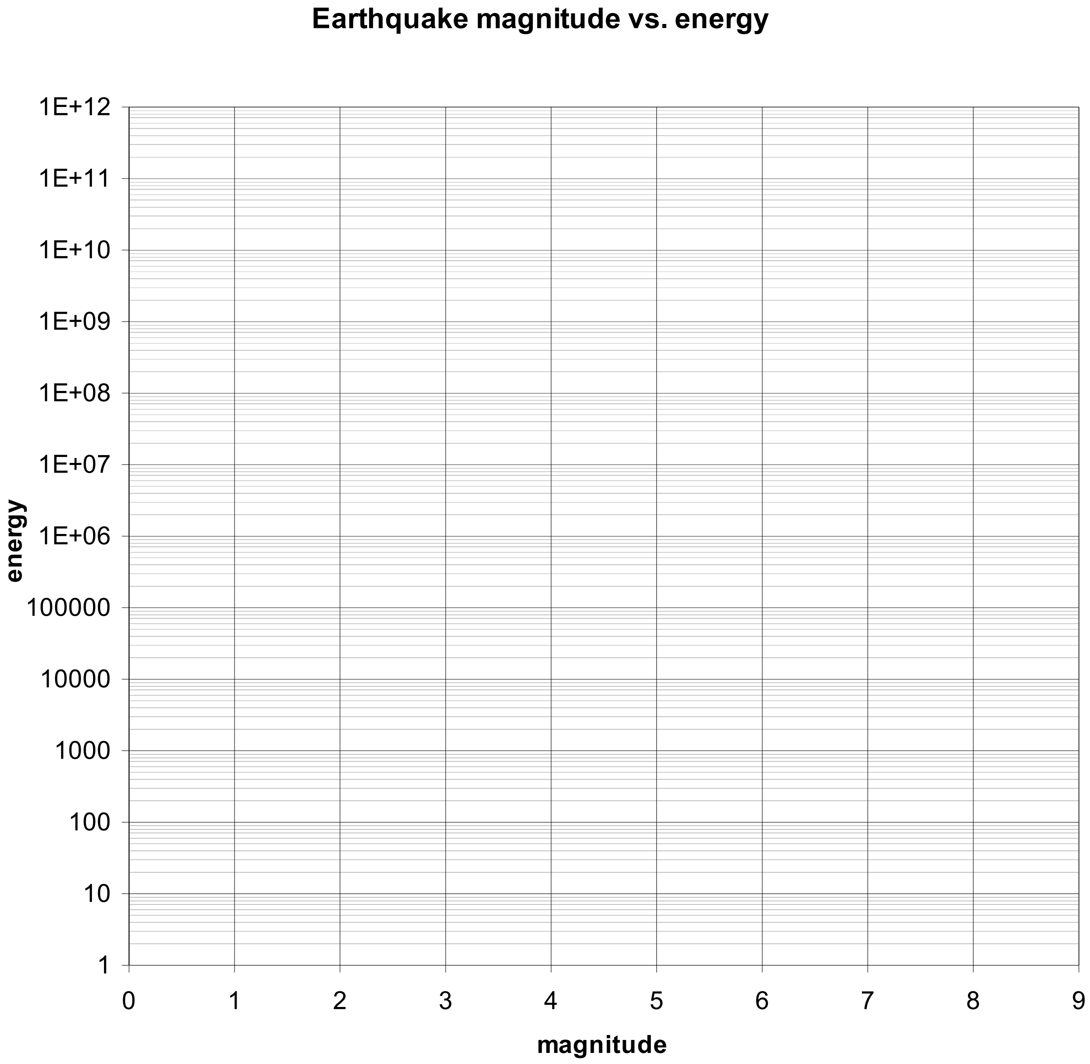


Figure 1-5: Seismograms from 5 earthquake events (100 km from epicenter)

Enter the P-wave amplitudes and magnitudes in **Table 1-2** below then plot these earthquakes on your magnitude vs. energy release graph below.

EVENT	MAXIMUM AMPLITUDE	MAGNITUDE
1988: Armenia	1.00 mm	7.0
1989: Loma Prieta, CA		
1976: Tangshan, China		
1964: Southern Alaska		
1 Megaton Nuclear Explosion		

Table 1-2



Earthquake Damage and Intensity

Earthquake damage can result from both primary effects, that cause damage directly (i.e., ground shaking and fault rupture) and secondary effects, that cause damage indirectly through processes that result from the earthquake event (i.e., fire, landslides, tsunamis, liquefaction, flooding). The amount of damage (intensity) that results from a given earthquake is related to several factors: 1) magnitude of the earthquake, 2) distance to the earthquake focus, 3) type of faulting, and 4) type of geologic substrate. Earthquake intensity has been quantified using the modified Mercalli intensity scale that is based on the amount of vibration people feel during low-magnitude earthquakes and the extent of damage to buildings during high-magnitude quakes (see the Mercalli scale in **Table 1-3** at the back of this handout).

Most earthquake damage is caused by ground shaking. The wide variety of effects caused by earthquake ground shaking results partly from differences in the way geologic substrates transmit seismic waves. Unconsolidated sediments will tend to amplify seismic waves, particularly soft sediments like artificial fill and fine-grained muds or clays (See Fig. 1-6 below).

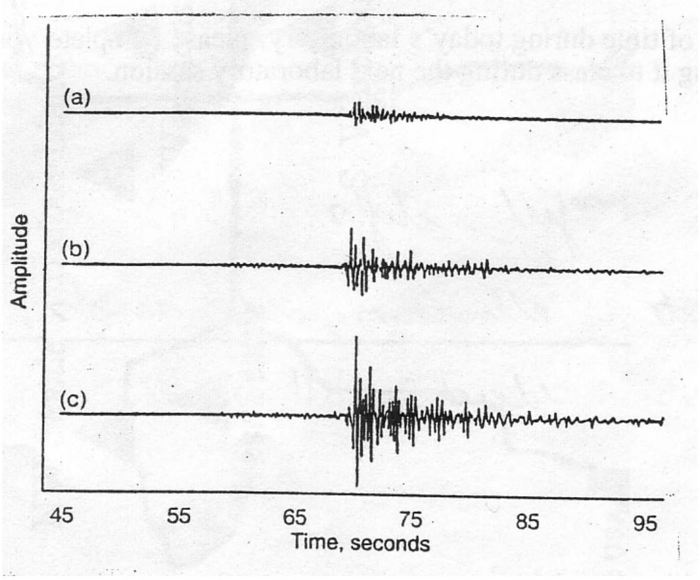


Fig. 1-6: Seismograms recorded for a magnitude 4.1 aftershock to the Loma Prieta earthquake (taken from Murck *et al.,* 1996), on bedrock in the Oakland Hills (a), on unconsolidated material (i.e., sand and gravel) near an uncollapsed portion of the freeway (b), and on mud near the collapsed Nimitz Freeway (c). All three seismograms are plotted on the same scale.

We have provided seismograms of the magnitude 3.5 Beacon Hill Earthquake for various regions of downtown Seattle (**Figure 1-7 and 1-8**). Based on your knowledge about the relationship between substrate and seismic wave amplification, determine which three seismograms represent locations overlying artificial fill. _______________, _______________, and _____________. One of the locations overlies Tertiary bedrock. Which seismogram do you think represents a bedrock location? ________________. Find this location on the Preliminary geologic map of Seattle (Waldron, Liesch, Mullineaux and Crandell, 1962). What is the substrate that underlies this seismogram?

________________. Use this geologic map to determine the substrate that Seattle University and the Space Needle overlie ______________.

We have copied a portion of the surficial geologic map of Seattle (**Figure 1-9**). We would like you to develop a seismic risk map for this part of Seattle. We would like you to subdivide your risk map into three different risk-levels (III-high, II-moderate, and I-low), based mainly on substrate conditions and potential for seismic-induced landslides. Use a red pencil crayon to color in all of your high risk areas, orange pencil crayon for moderate risk areas and yellow for lower risk areas.

Which of Seattle's famous landmarks located in high risk locations?

____

____.

What is the earthquake risk for the location where you live _____ and work ______? (Look on the surficial geologic map in the laboratory).

Figure 1-7

Mag 3.5 Beacon Hill Earthquake, 10 Feb 1997

S-wave ground velocity recorded by 2 Hz N-S seismometers

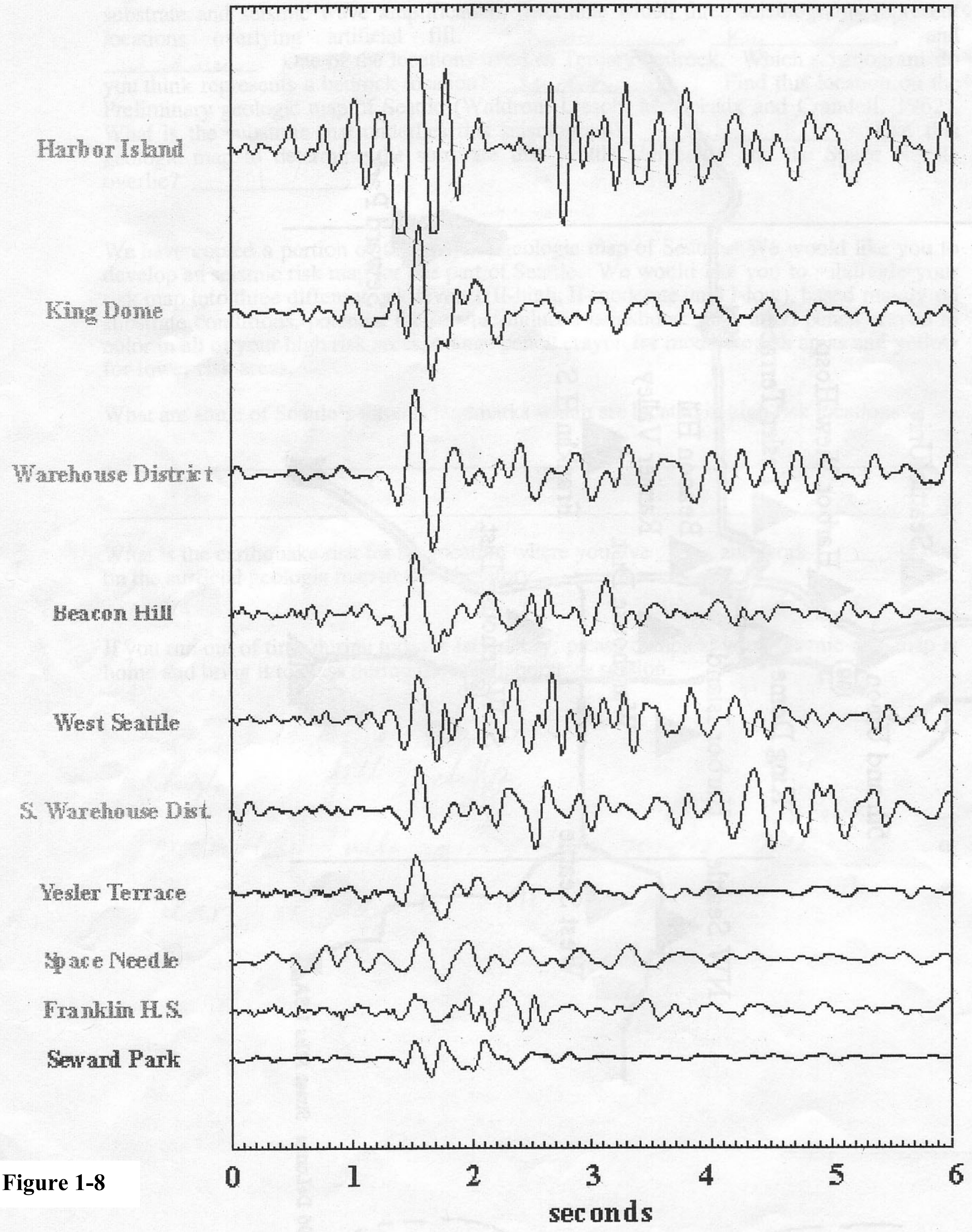


Figure 1-8

This earthquake occurred directly under the urban area where it was

http://groundmotion.cr.usgs.gov/Seattle/presscon97/0410426p.gif

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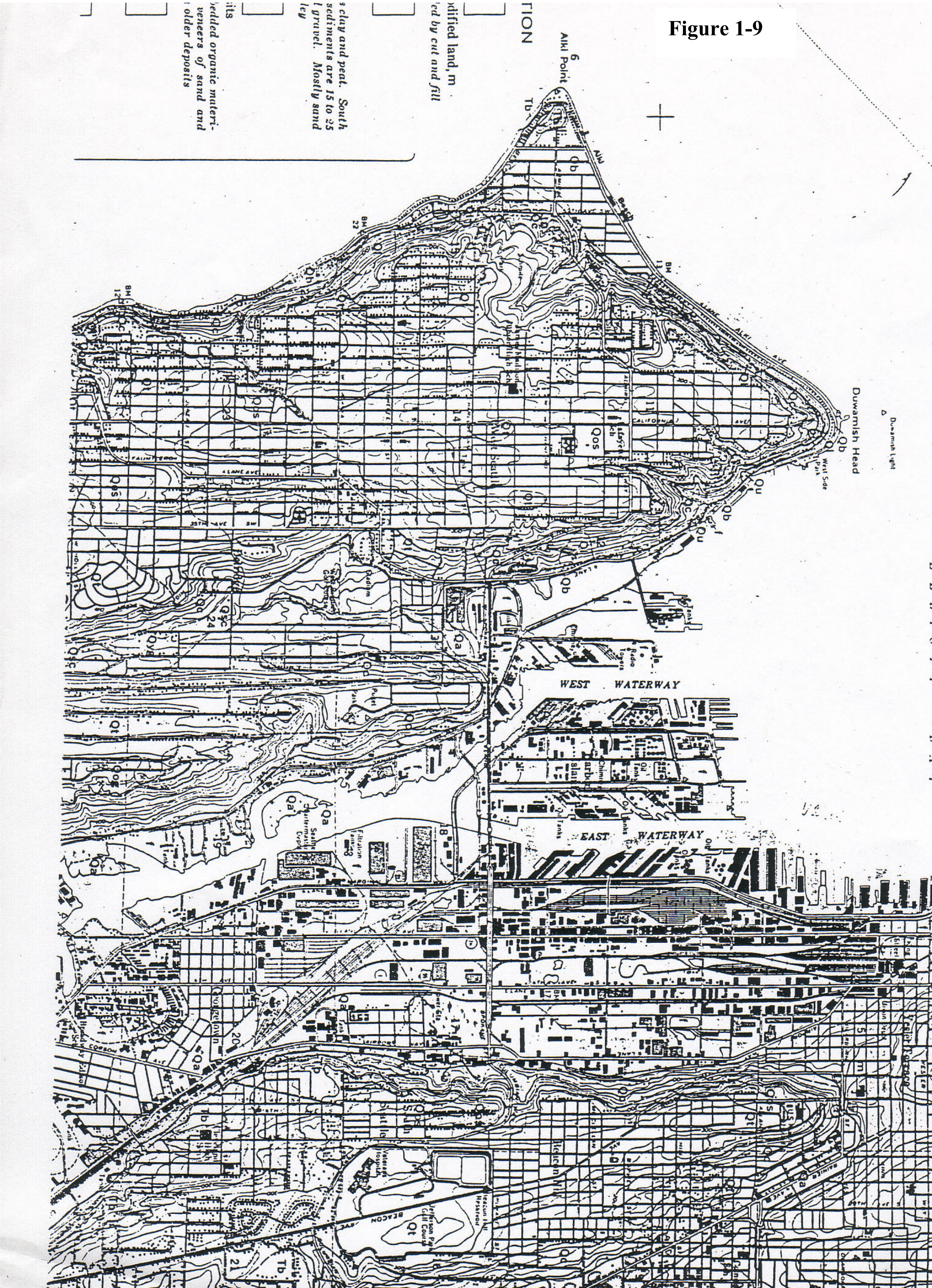
Figure 1-9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Duwamish Head
Duwamish Light
Qb
Qos
Qu
Qa
Qt
Tb
WEST WATERWAY
EAST WATERWAY
ALKI AVE
CALIFORNIA AVE
35TH AVE SW
Georgetown
BEACON
Jefferson Park Golf Course
Veterans Hospital
Radio Towers
Oil Tanks
Filtration Plant
Seattle Quartermaster Depot

TABLE 1-3 -- MODIFIED MERCALLI INTENSITY SCALE

MMI value	Summary description	Full description
I	Not felt	Not felt. Marginal and long period effects of large earthquakes.
II		Felt by persons at rest, on upper floors, or favorably placed
III		Felt indoors. Hanging objects swing. Vibration like passing of light trucks. Duration estimated. May not be recognized as an earthquake
IV		Hanging objects swing. Vibration like passing of heavy trucks; or sensation of a jolt like a heavy ball striking the walls. Standing motor cars rock. Windows, dishes, doors rattle Glasses clink. Crockery clashes. In the upper range of IV, wooden walls and frame creak.
V	Pictures move	Felt outdoors; direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters, pictures move Pendulum clocks stop, start, change rate.
VI	Objects fall	Felt by all. Many frightened and run outdoors. Persons walk unsteadily. Windows, dishes, glassware broken. Knickknacks, books, etc., off shelves. Pictures off walls. Furniture moved or overturned. Weak plaster and masonry D* cracked. Small bells ring (church, school). Trees, bushes shaken (visibly, or heard to rustle).
VII	Nonstructural damage	Difficult to stand. Noticed by drivers of motor cars. Hanging objects quiver. Furniture broken. Damage to masonry D, including cracks. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices (also unbraced parapets and architectural ornaments). Some cracks in masonry C. Waves on ponds; water turbid with mud. Small slides caving in along sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged
VIII	Moderate damage	Steering of motor cars affected. Damage to masonry C; partial collapse. Some damage to masonry B; none to masonry A. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed piling broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes.
IX	Heavy damage	General panic. Masonry D destroyed; masonry C heavily damaged, sometimes with complete collapse; masonry B seriously damaged (General damage to foundations.) Frame structures, if not bolted, shifted off foundations. Frames racked. Serious to reservoirs. Underground pipes broken. Conspicuous cracks in reservoirs. Underground pipes broken. Conspicuous cracks in fountains, sand craters.
X	Extreme damage	Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, embankments. Large landslides. Water thrown on banks of canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land. Rails bent slightly.
XI		Rails bent greatly. Underground pipelines completely out of service.
XII		Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown into the air.

*Masonry A: Good workmanship, mortar, and design; reinforced, especially laterally, and bound together by using steel, concrete, etc.; designed to resist lateral forces.

Masonry B: Good workmanship and mortar; reinforced, but not designed in detail to resist lateral forces.

Masonry C: Ordinary workmanship and mortar; no extreme weaknesses like failing to tie in at corners, but neither reinforced nor designed against horizontal forces.

Masonry D: Weak materials, such as adobe; poor mortar; low standards of workmanship; weak horizontally.

Full descriptions are from: Richter, C.F., 1958. Elementary Seismology. W.H. Freeman and Company, San Francisco, pp. 135-149; 650-653.