ANNOUNCEMENTS

- Remember Quiz week
- Next Volcanoes, flooding and tsunamis
-
  - https://www.nytimes.com/2017/09/08/world/americas/mexico-earthquake.html
  - http://www.sciencemag.org/news/2017/09/unusual-mexico-earthquake-may-have-relieved-stress-seismic-gap (good article to read after we are done discussing these things as it has a lot of terms should know by the end of this week)
- I am getting a lot of questions on topics I covered in the Welcome post on Avenue. Please read it if you haven't.


EARTHQUAKES

Learning Objectives

- Know what an earthquake is and how seismologists determine its magnitude
- Understand earthquake processes, such as faulting, tectonic creep, and the formation and movement of seismic waves
- Understand which regions are most at risk for earthquakes and why

Learning Objectives, cont.

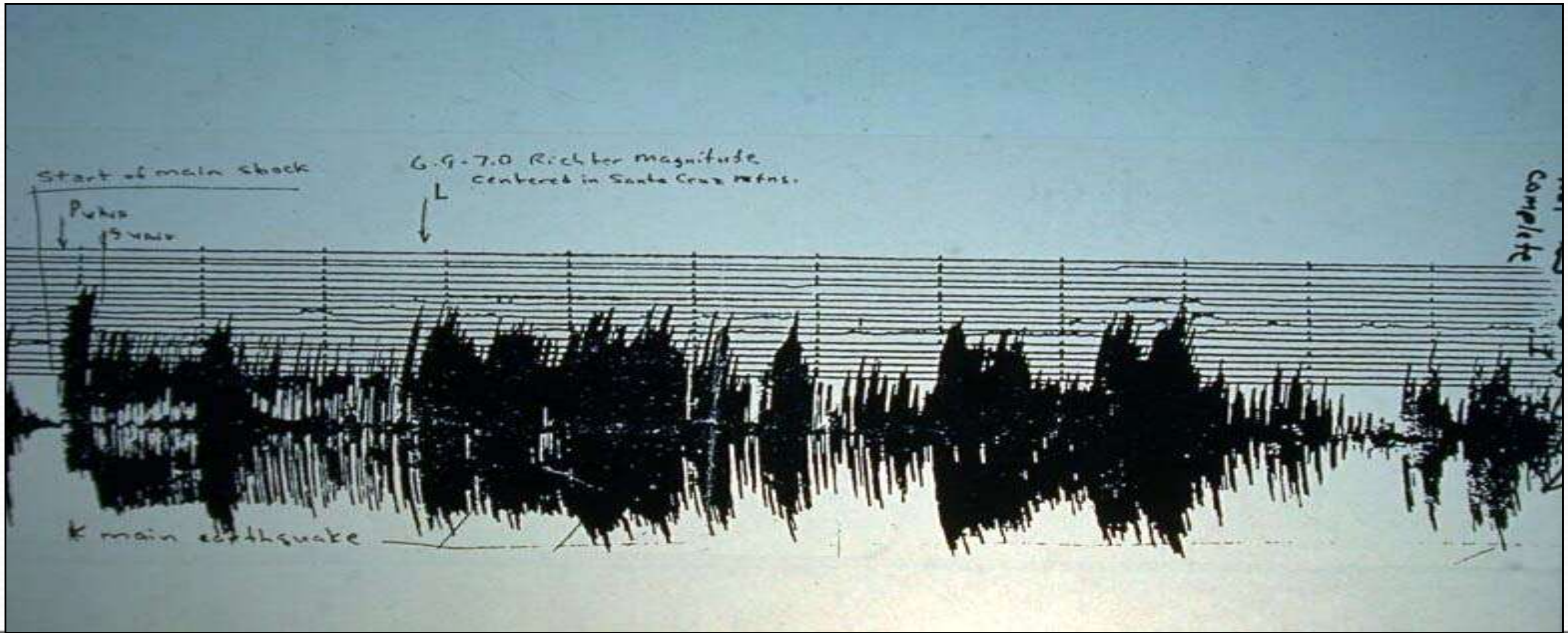
- Understand the effects of earthquakes such as shaking, ground rupture, tsunamis, and liquefaction
- Identify how earthquakes are linked to other natural hazards
- Know the important natural service functions of earthquakes
- Understand how people can minimize earthquake risk, and take measures to protect themselves

What is an earthquake?

Earthquake –

Motion or trembling of the ground caused by sudden displacement of rock

Trembling isn't moving; it's just moving in the same spot



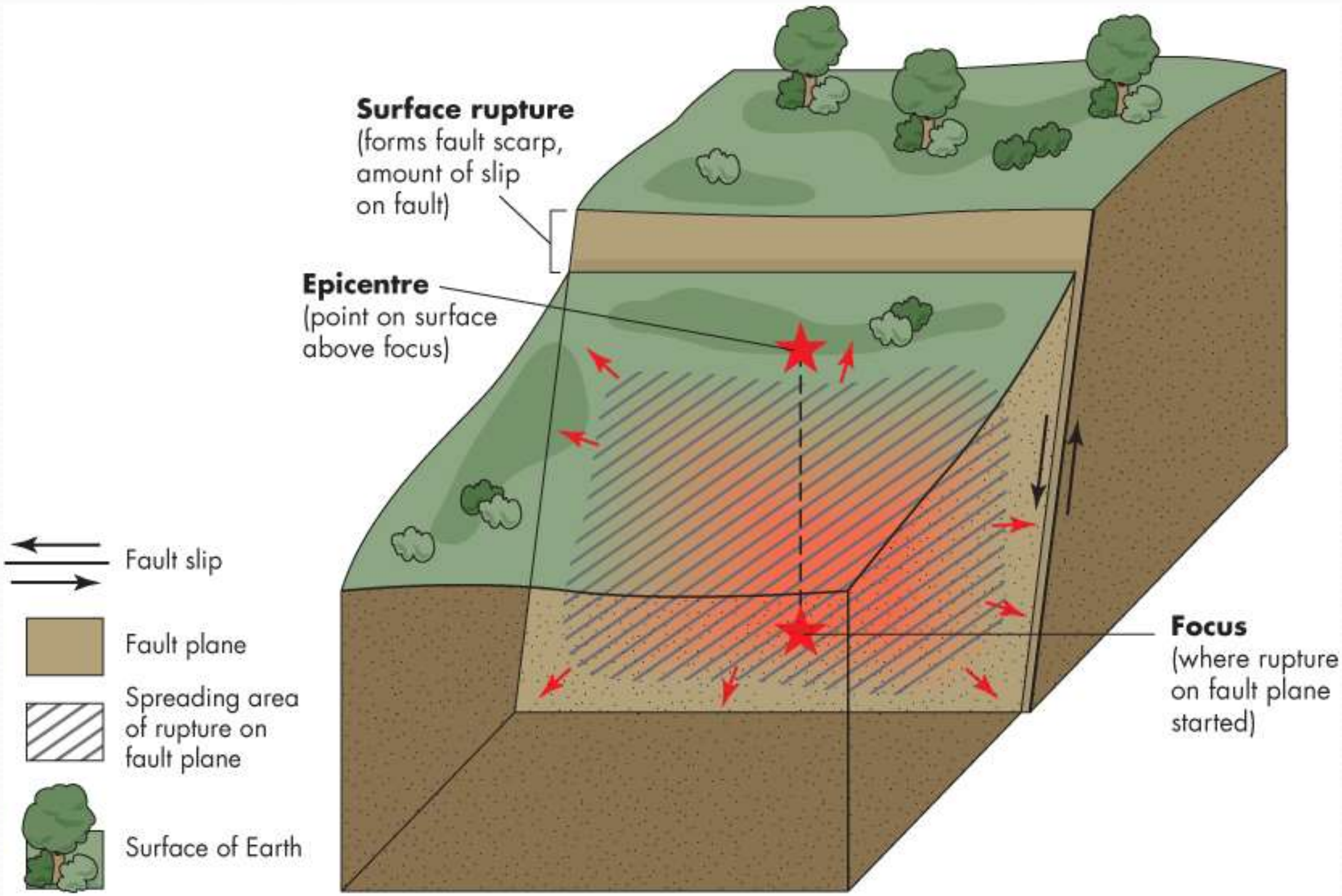
The Toll of Earthquakes

- The consequences of an earthquake depend on:
  - Magnitude
  - Depth
  - Direction of fault rupture
  - Distance from populated areas
  - Nature of the local earth materials
  - Engineering and construction practices

- Differences in some of these factors explain why a **M** 7.0 earthquake in Haiti (2010) killed ~ 240,000 people but a **M** 6.9 earthquake in California (1989) killed less than 70.

Earthquake Introduction

- Result from the rupture of rocks along a **fault**
  - Energy is released in the form of seismic waves
- Mapped according to the epicentre
  - The focus is directly below the epicentre
- Measured by seismograph
- Compared based on:
  - Magnitude
  - Intensity



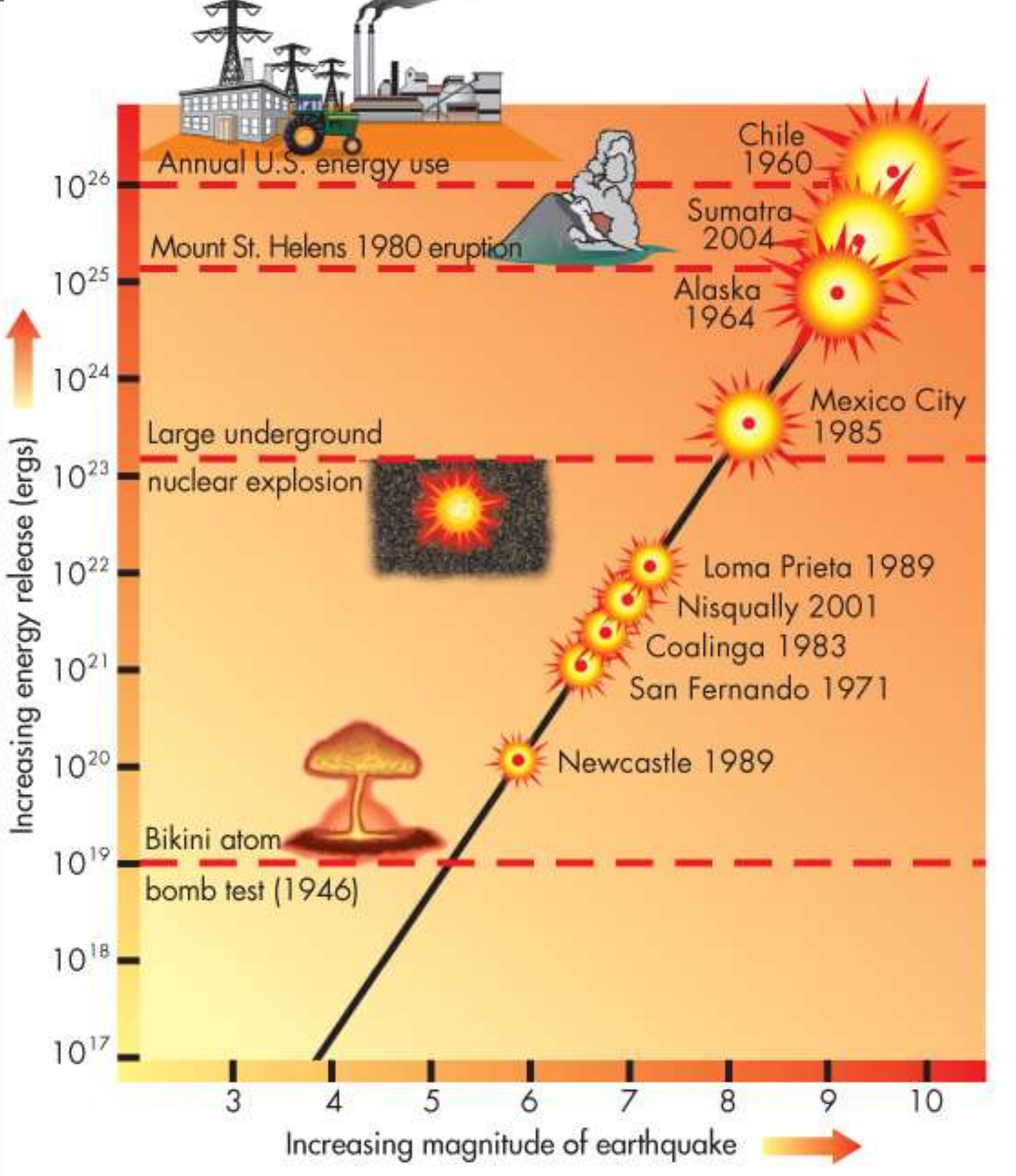
▲ **FIGURE 3.2 BASIC EARTHQUAKE NOMENCLATURE** This block diagram shows a fault plane (light tan surface), amount of displacement, rupture area (closely spaced diagonal lines), focus (lower red star), and epicentre (upper red star). The rupture starts at the focus and propagates up, down, and laterally along the fault plane (red arrows). During a great earthquake, slip may be 10 m to 30 m along a fault length of several hundred kilometres, and the rupture area may be more than 10 000 km^2.

TABLE 3.2 Major Earthquakes in Canada and the United States

Year	Location	Damage (U.S. $millions)	Number of Deaths
1811–1812	New Madrid, Missouri	Unknown	Unknown
1886	Charleston, South Carolina	23	60
1906	San Francisco, California	524	3000[1]
1925	Santa Barbara, California	8	13
1929	Sea floor off Newfoundland	Unknown	28
1933	Long Beach, California	40	115
1940	Imperial Valley, California	6	9
1946	Vancouver Island, British Columbia	Several million	2
1949	Haida Gwaii, British Columbia	Sparsely populated area	0
1952	Kern County, California	60	12
1959	Hebgen Lake, Montana (damage to timber and roads)	11	28
1964	Prince William Sound, Alaska (includes tsunami damage near Anchorage and on the Pacific Coast of Canada and the United States)	500	128
1965	Puget Sound, Washington	13	7
1971	Sylmar (San Fernando), California	553	65
1983	Coalinga, California	31	0
1983	Central Idaho	15	2
1987	Whittier, California	358	8
1989	Loma Prieta (San Francisco), California	6000	63
1992	Landers, California	271	1
1994	Northridge, California	20 000	60
2001	Nisqually, Washington	2000	0
2002	South-Central Alaska	Sparsely populated area	0
2012	Haida Gwaii, British Columbia	Sparsely populated area	0

[1]Deaths from the earthquake and subsequent firestorm.

Source: U.S. Geological Survey Earthquake Hazards Program. http://earthquakes.usgs.gov. Accessed July 28, 2013.



Chile 1960
Sumatra 2004
Alaska 1964
Mexico City 1985
Loma Prieta 1989
Nisqually 2001
Coalinga 1983
San Fernando 1971
Newcastle 1989
Annual U.S. energy use
Mount St. Helens 1980 eruption
Large underground nuclear explosion
Bikini atom bomb test (1946)
10^{26}
10^{25}
10^{24}
10^{23}
10^{22}
10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
Increasing energy release (ergs)
3
4
5
6
7
8
9
10
Increasing magnitude of earthquake

Earthquake Magnitude

- Measured by **moment magnitude (M_w)**

- The scale is logarithmic and based on powers of ten
  - Ground motion for a **M** 3 is 10 times that of a **M** 2.
  - Amount of energy released for a M 3 is 32 times that of a **M 2**

- Smaller earthquakes are more frequent than larger ones

TABLE 3.3 Relationships among Earthquake Magnitude, Displacement, and Energy

Magnitude Change	Ground Motion Change (Displacement[1])	Energy Change
1	10 times	About 32 times
0.5	3.2 times	About 5.5 times
0.3	2 times	About 3 times
0.1	1.3 times	About 1.4 times

[1]Displacement, vertical or horizontal, that is recorded on a standard seismograph.

Source: U.S. Geological Survey. 2009. "Earthquakes, facts and lists." http://neic.usgs.gov/neis/eqlists/eqstats.html. Accessed July 28, 2013.

TABLE 3.4 Magnitude and Frequency of Earthquakes Worldwide

Descriptor	Magnitude	Average Annual Number of Events
Great	8 and higher	1
Major	7–7.9	15
Strong	6–6.9	134
Moderate	5–5.9	1319
Light	4–4.9	13 000 (estimated)
Minor	3–3.9	130 000 (estimated)
Very minor	2–2.9	1 300 000 (estimated) (approximately 150 per hour)

Source: From the U.S. Geological Survey. 2009. "Earthquakes, facts and lists." http://neic.usgs.gov/neis/eqlists/eqstats.html. Accessed July 28, 2013.

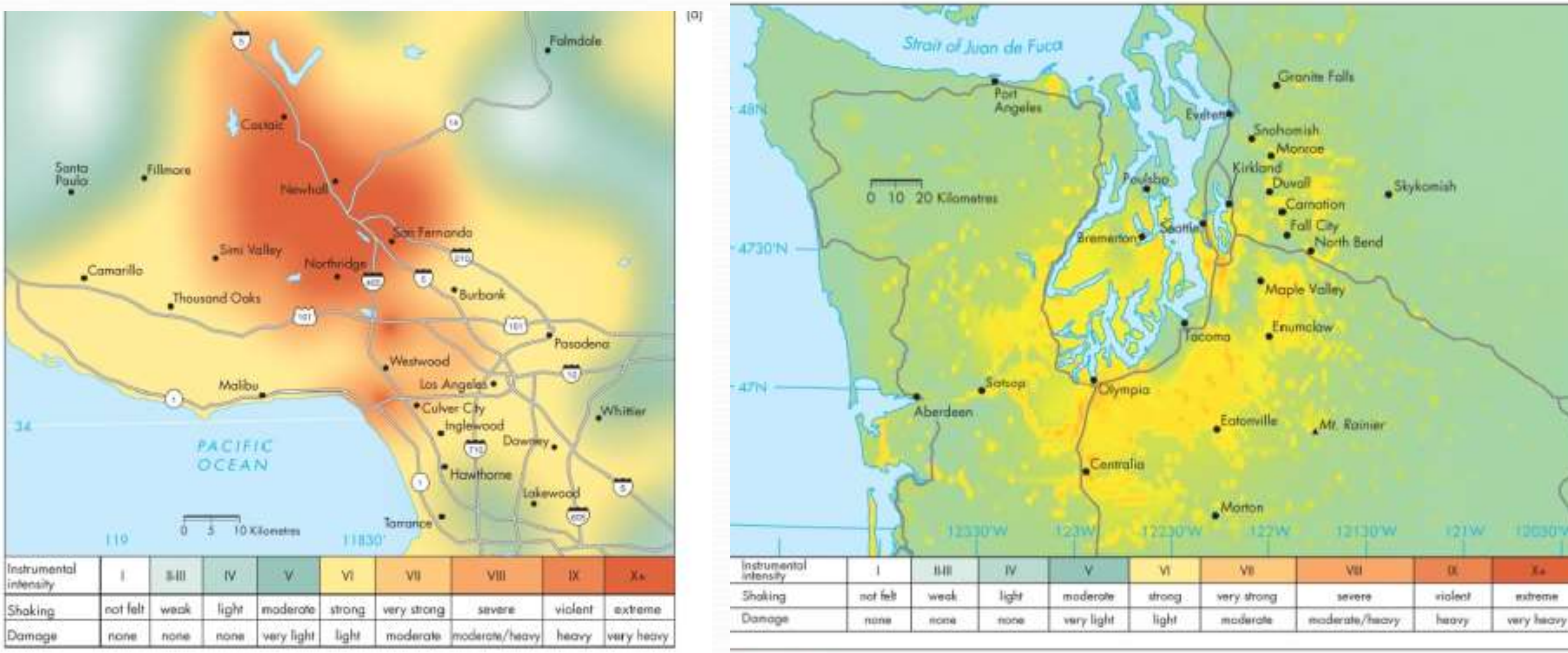
Earthquake Intensity

- Measured by the **Modified Mercalli Intensity Scale**
- The scale is qualitative and based on damage to structures and people's perceptions
- Modified Mercalli Intensity maps show where the damage and perceived shaking is most severe
  - Data is now collected using the Internet.
- Shake maps use seismograph data to show areas of intense shaking.

TABLE 3.5 Modified Mercalli Intensity Scale (abridged)

Intensity	Effects
I	Felt by very few people.
II	Felt by only a few people at rest, especially on upper floors of buildings. Delicate suspended objects may swing.
III	Felt noticeably indoors, especially on upper floors of buildings, but many people do not recognize the shaking as an earthquake. Stationary cars may rock slightly. Vibration feels like the passing of a truck.
IV	During the day, felt indoors by many, outdoors by few. At night, some people awakened. Dishes, windows, doors disturbed; walls make cracking sound. Stationary cars rock noticeably. Sensation is that of a heavy truck striking a building.
V	Felt by nearly everyone; many people awakened. Some dishes and windows broken; a few instances of cracked plaster; unstable objects overturned. Disturbances of trees, poles, and other tall objects are sometimes noticed. Pendulum clocks may stop.
VI	Felt by all; many people frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage is slight.
VII	Almost everybody runs outdoors. Damage is negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by people driving cars.
VIII	Damage slight in specially designed structures; considerable in ordinary substantial buildings, with partial collapse; great in poorly built structures. Panel walls thrown out of frames; chimneys, factory stacks, columns, monuments, and walls collapse; heavy furniture overturned. Sand and mud ejected in small amounts; changes in well water. Disturbs people driving cars.
IX	Damage considerable even in specially designed structures; great in substantial buildings, with partial collapse. Well-designed frame structures thrown out of plumb; some buildings are shifted off foundations. Ground cracks conspicuous. Underground pipes are broken.
X	Some well-built wooden structures are destroyed; most masonry and frame structures with foundations destroyed; ground badly cracked. Train rails bent. Many landslides from riverbanks and steep slopes. Some sand and mud liquefies. Water is splashed over banks.
XI	Few, if any, masonry structures remain standing; bridges are destroyed. Large fissures open in ground. Landslides are common.
XII	Damage is total. Waves are seen on the ground surface. Lines of sight distorted. Objects are thrown into the air.

Source: U.S. Geological Survey Earthquake Hazards Program. http://earthquake.usgs.gov/learning/topics/mercalli.php. Accessed July 28, 2013.

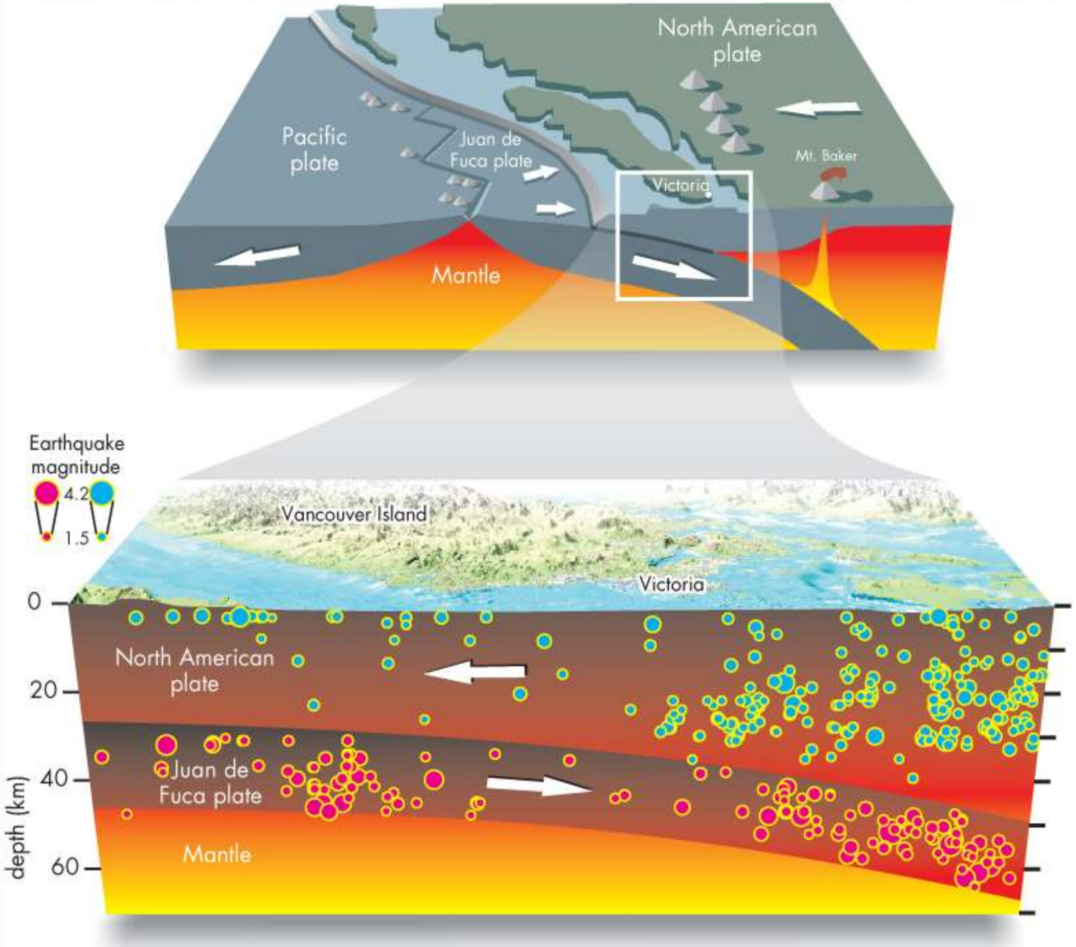


▲ **FIGURE 3.4 SHAKE MAPS** Instrumental intensity maps of (a) the 1994 Northridge, California, earthquake (**M** 6.7) and (b) the 2001 Nisqually, Washington, earthquake (**M** 6.8). *((a) U.S. Geological Survey; courtesy of David Wald. (b) Pacific Northwest Seismograph Network, University of Washington)*

Earthquake Processes

- Earthquakes commonly occur at or near plate boundaries
- Plate boundaries may contain faults
- Friction along plate boundaries exerts strain or deformation
- When stress on rocks exceeds their **strength**, the resulting rupture produces **seismic waves**

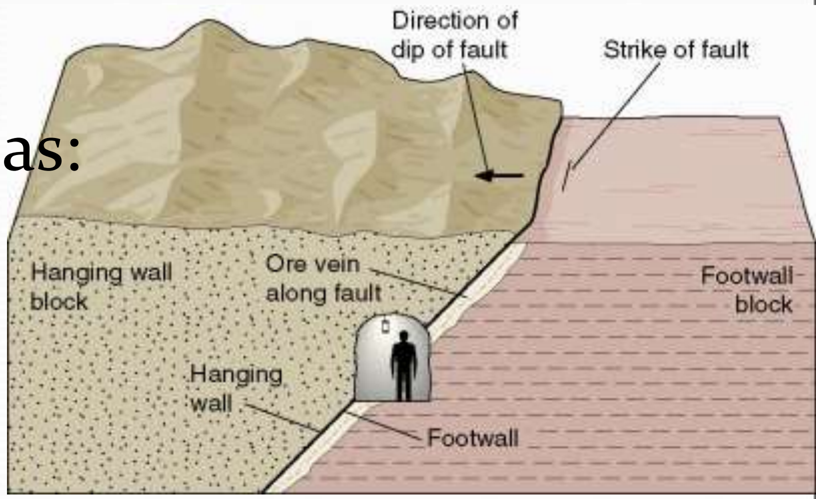
▲ **FIGURE 3.5 GLOBAL EARTHQUAKE DISTRIBUTION** A map of global seismicity (1963–1988, M 5+), showing epicentres of plate-boundary earthquakes (heavy concentration of dots within red zones) and intraplate earthquakes (isolated dots). Locations of plate boundaries are shown in Figure 2.5. Black square shows location of Figure 3.6. *(U.S. Geological Survey National Earthquake Information Center)*



◀ **FIGURE 3.6 TECTONIC PLATES AND EARTHQUAKES, SOUTH-COASTAL BRITISH COLUMBIA** Section of Earth's lithosphere through southern Vancouver Island and the northern tip of Olympic Peninsula showing sources of earthquakes within the North American plate (blue dots) and the Juan de Fuca plate (red dots). White arrows show relative directions of plate motion. *(Based on Clague, J., C. Yorath, R. Franklin, and B. Turner. 2006.* At Risk: Earthquakes and Tsunamis on the West Coast. *Vancouver, BC: Tricouni Press)*

Fault Types – Dip Slip

- Vertical movement
- Three types of dip-slip faults based on which way the bounding earth materials move
- Walls on an incline are defined as:
  - Hanging Wall
  - Football Block



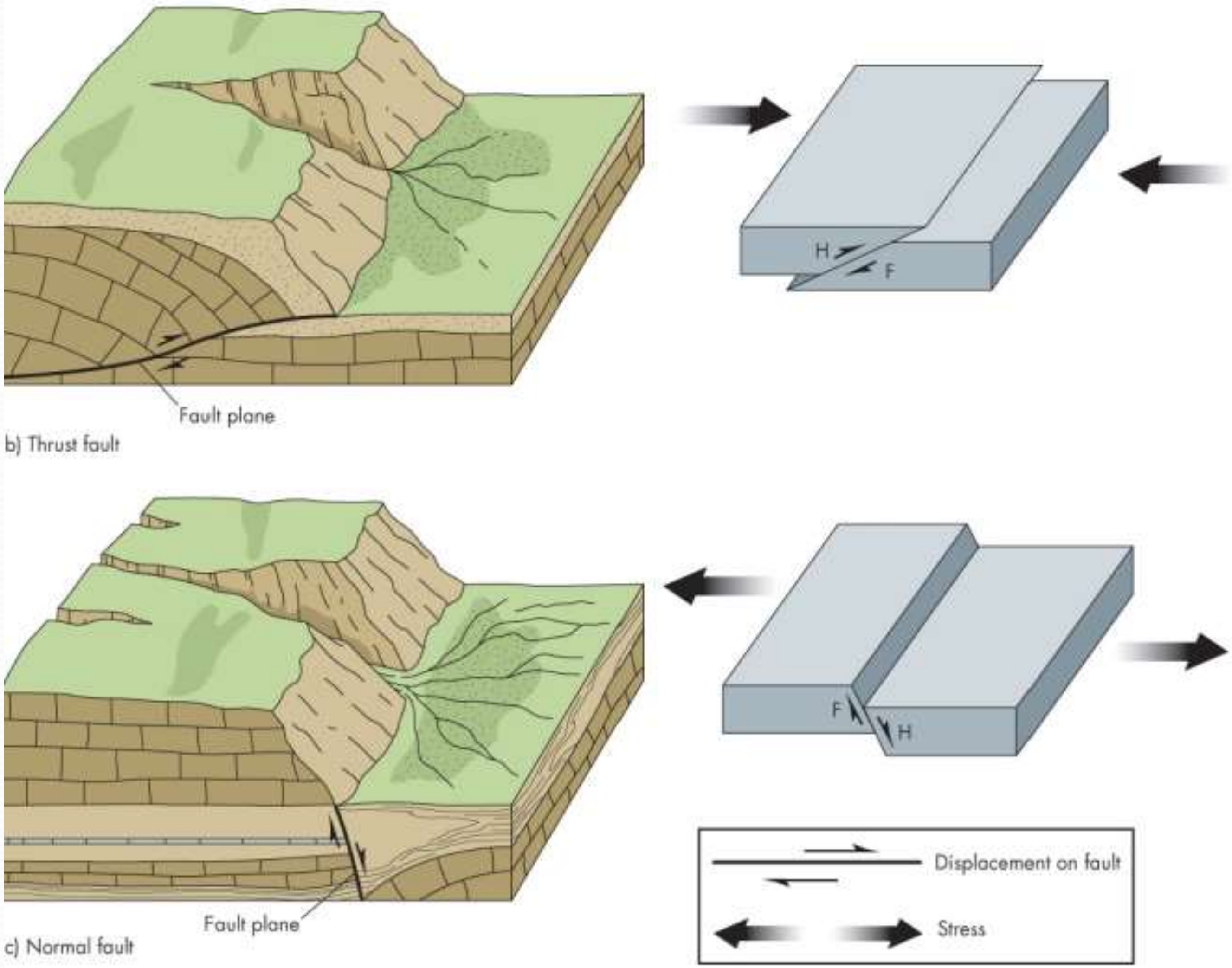
Hanging Wall is hanging on the Football Block

Fault Types – Dip Slip, cont.

- **Normal fault**
  - The hanging wall has moved downward relative to the footwall.

    Occurs at divergent plate boundaries
- **Reverse fault**
  - The hanging wall has moved up relative to the footwall.
  - If the fault plane angle is 45° or less, it is a **thrust fault**.

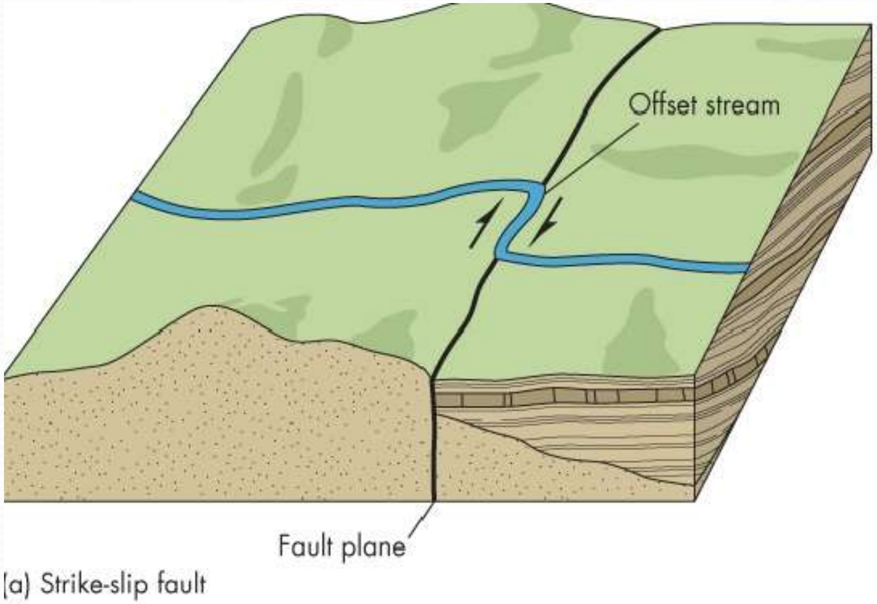
    Occurs at convergent plate boundaries
- **Blind faults** do not extend to the surface.

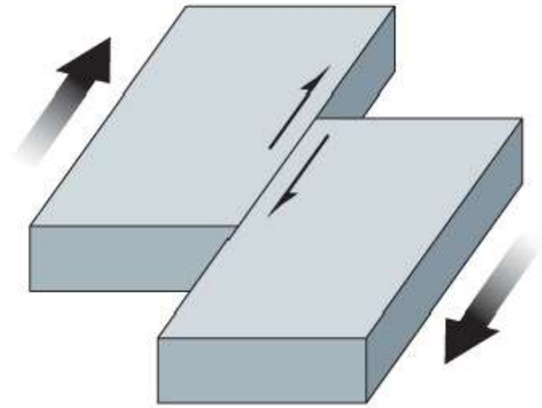


▲ **FIGURE 3.7 TYPES OF GEOLOGIC FAULTS** These schematic diagrams show the three common types of faults and their effects on the landscape. a) Strike-slip fault with horizontal displacement along the fault plane. (b) Thrust fault in which the hanging wall (H) has moved up and over the ootwall (F). (c) Normal fault in which the hanging wall (H) has dropped down. The coloured diagrams on the left show the landscape after movement along the fault (thick black line). The grey diagrams on the right show directions of stress (thick arrows) that produce the displacements (thin half arrows).

Fault Types – Strike Slip

- Horizontal movement





Fault Activity and Tectonic Creep

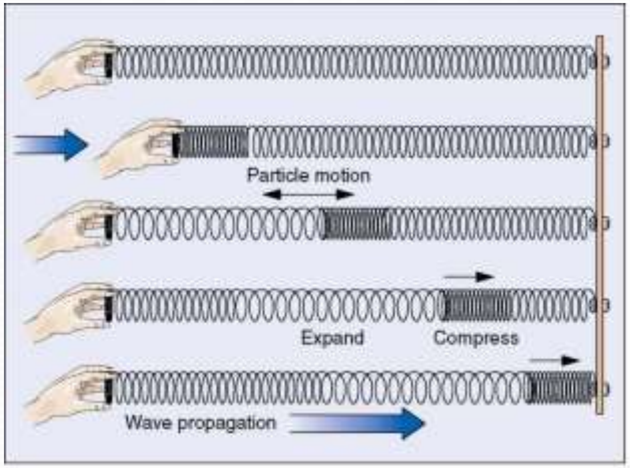
- **Active faults** - movement during the past 11,600 years
- **Potentially active faults** - movement during the past 2.6 million years
- **Inactive faults** - no movement during the past 2.6 million years

- Tectonic Creep occurs when movement along a fault is so gradual that earthquakes are not felt
  - Can slowly damage infrastructure

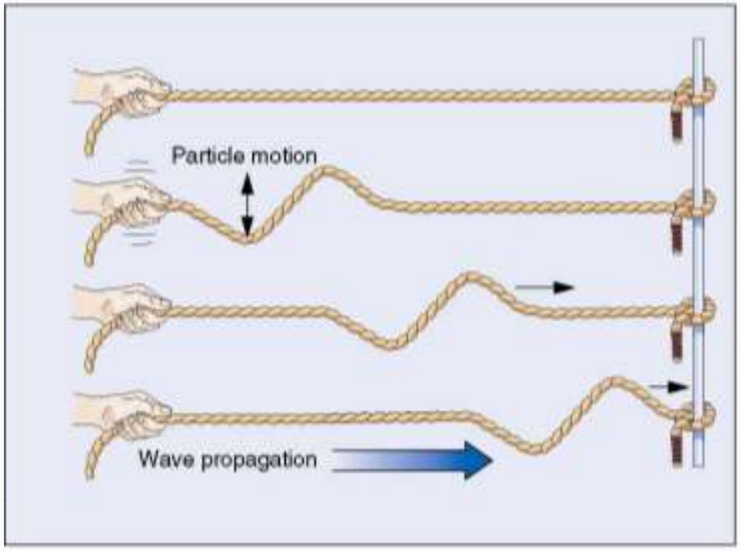
Seismic Waves - Body Waves

- Travel within the body of the Earth

- Two types:
  - **P waves** (primary or compressional waves)
    - Move fast with a push/pull motion
    - Can travel through solid, liquid, and gas
  - **S waves** (secondary or shear waves)
    - Move slowly with a back-and-forth motion at right angles to the direction the waves are moving.
    - Can travel only through solids



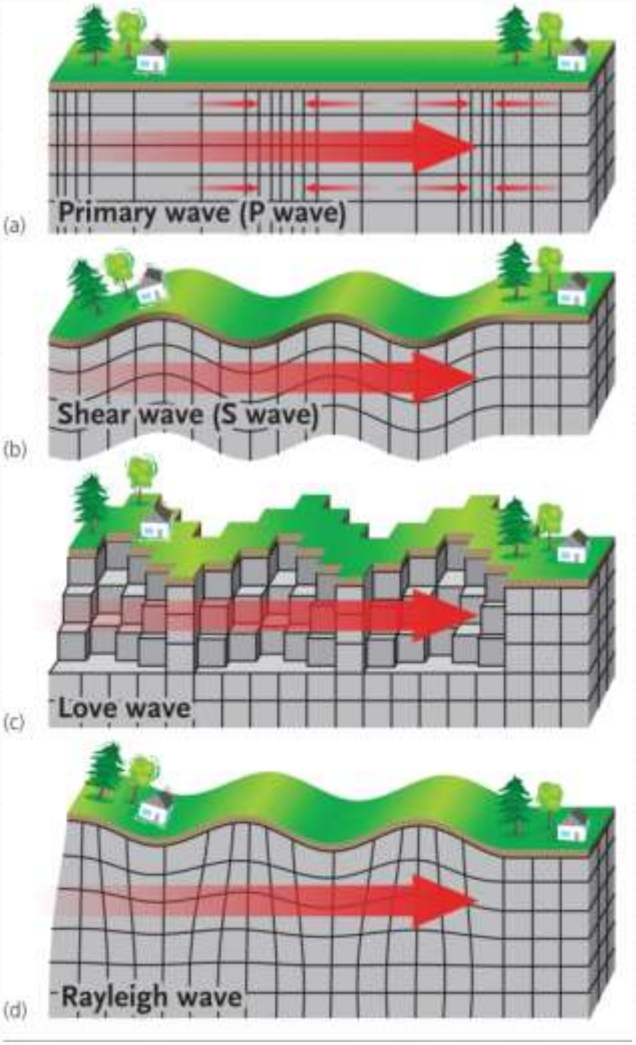
A Primary wave



B Secondary wave

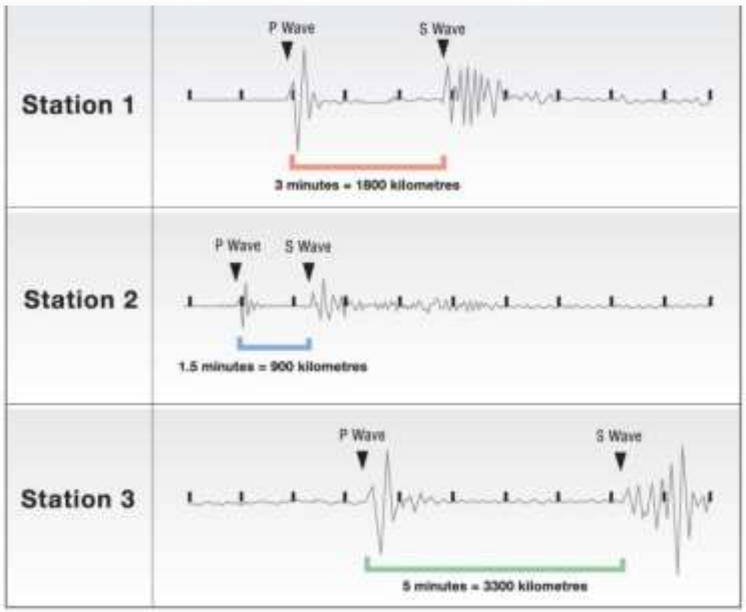
Seismic Waves - Surface Waves

- Travel along Earth's surface horizontally and vertically and can produce rolling motion
- Move more slowly than body waves
- Are responsible for damage near the epicenter
- Two types:
  - **Love waves** - cause horizontal shaking
  - **Rayleigh waves** - rolling waves, elliptical motion



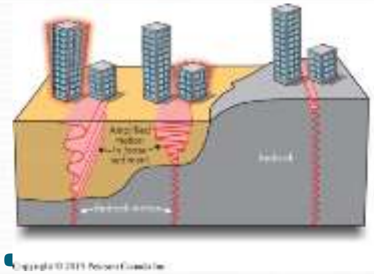
Earthquake Shaking: Distance to the Epicentre and Focal Depth

- **Seismographs** record arrivals of waves to station sites
- P waves and S waves travel at different rates and arrive at each station at different times
- Distance to the epicentre can be found by comparing travel times of the waves using **triangulation**
- **Focal depth** influences amount of shaking due to **attenuation**



▲ FIGURE 3.10 **LOCATING AN EARTHQUAKE** The epicentre of an earthquake can be determined from the arrival times of P and S waves at three or more widely separated sites. P and S waves travel at different velocities; thus the time between their first arrivals at a site provides a measure of the distance from the recording seismograph to the epicentre. A circle with a radius equal to the distance from the epicentre is drawn around each seismograph station. The intersection of the three circles is the epicentre. *(Adapted from How Are Earthquakes Located? IRIS Education & Outreach Series, No. 6. http//www.iris.edu)*

Need 3 spots that have access to a time travel curve to find the epicentre of a earthquake

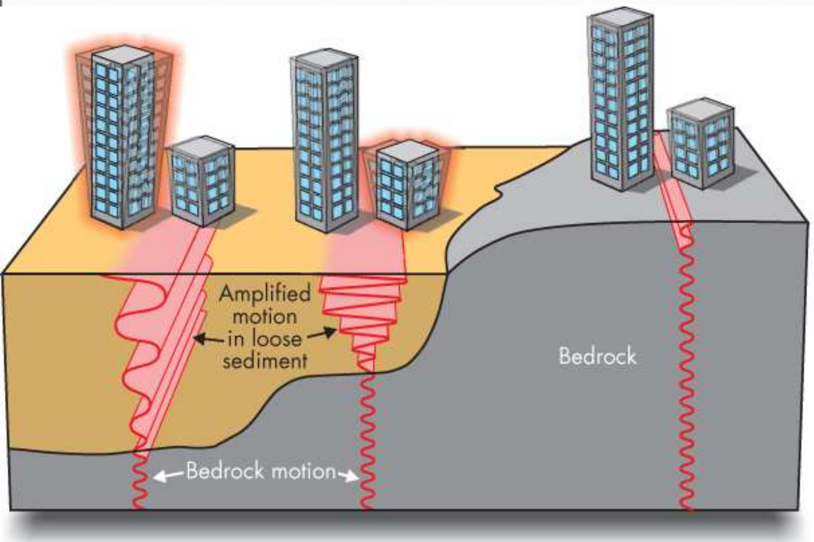


Local Soil and Rock Conditions

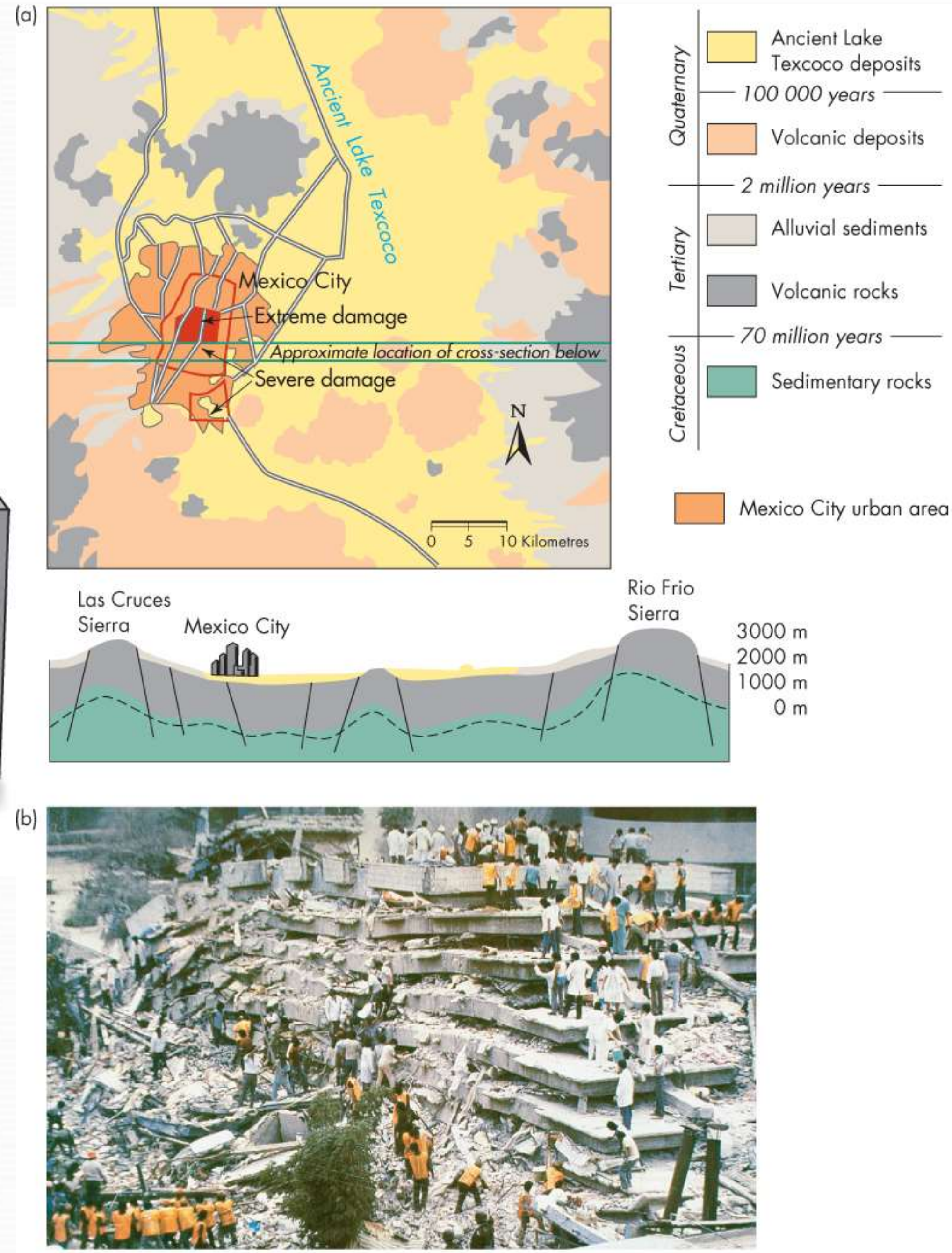
- Local geology influences the amount of ground motion
  - Dense rocks (e.g. bedrock) transmit earthquake energy quickly
  - Seismic waves slow down in heterogeneous rocks , unconsolidated sediment and sediment with high water content

- **Amplification** occurs when energy is transferred from P waves and S waves to surface waves

- More damage can occur in areas farther away from the epicentre depending on local ground conditions



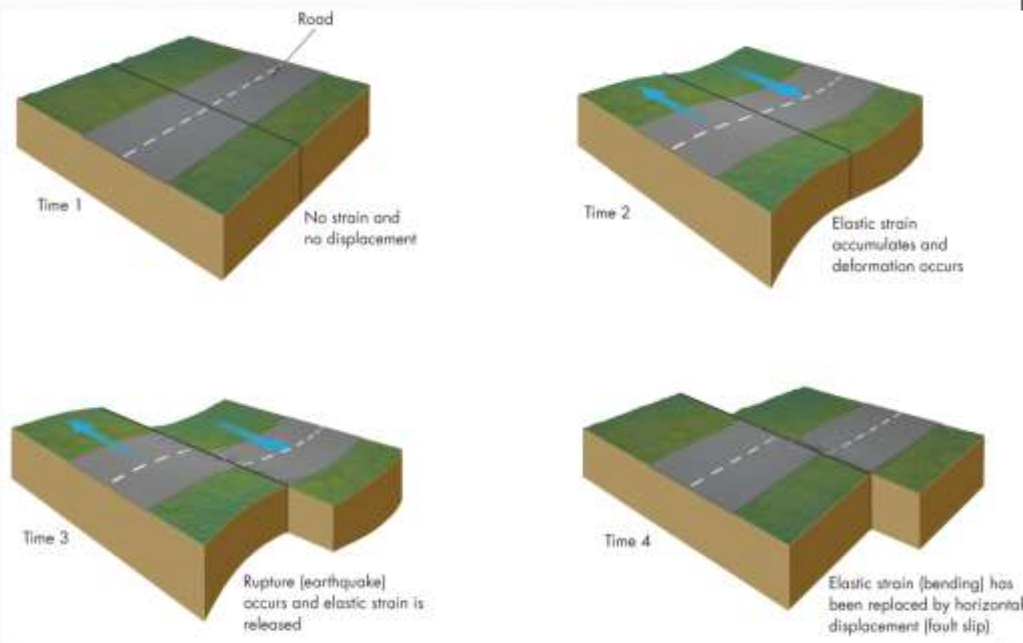
Amplified
motion
in loose
sediment
Bedrock
Bedrock motion



(a)
Ancient Lake Texcoco
Mexico City
Extreme damage
Approximate location of cross-section below
Severe damage
N
0 5 10 Kilometres
Quaternary
Ancient Lake Texcoco deposits
100 000 years
Volcanic deposits
2 million years
Tertiary
Alluvial sediments
Volcanic rocks
70 million years
Cretaceous
Sedimentary rocks
Mexico City urban area
Las Cruces Sierra
Mexico City
Rio Frio Sierra
3000 m
2000 m
1000 m
0 m
(b)

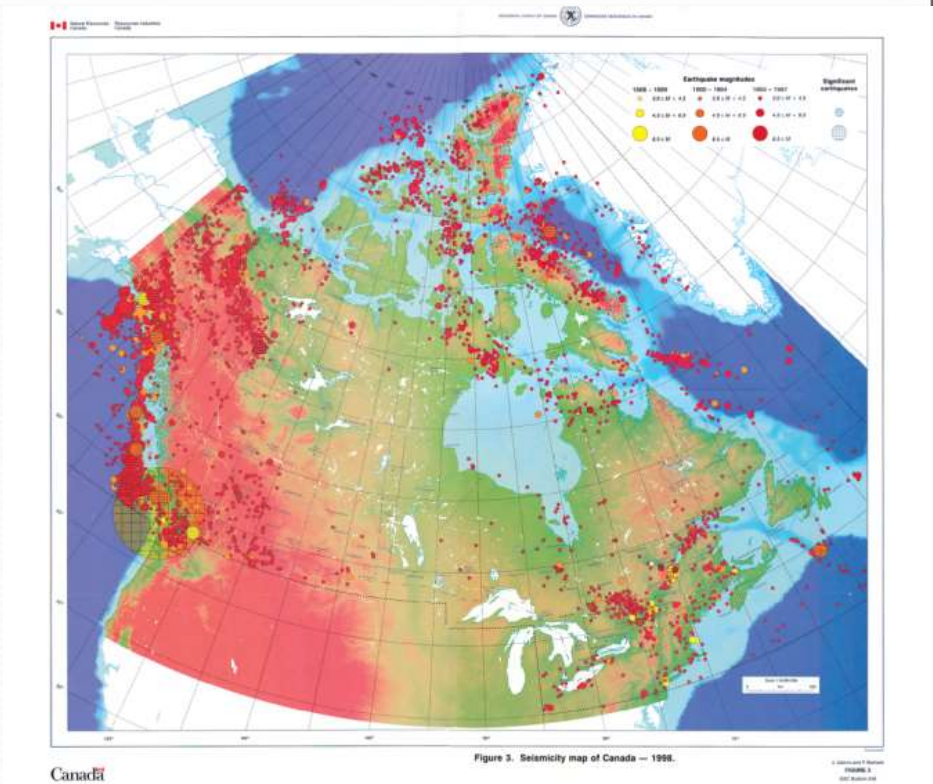
The Earthquake Cycle

- Inactive period where builds in the fault
- Period of small earthquakes where the stress begins to release, causing strain
- **Foreshocks** occur prior to a major release of stress
  - This stage does not always occur
- **Mainshock**
  - when the fault releases the majority of the stress
- **Aftershocks**
  - releases of stress after a major earthquake

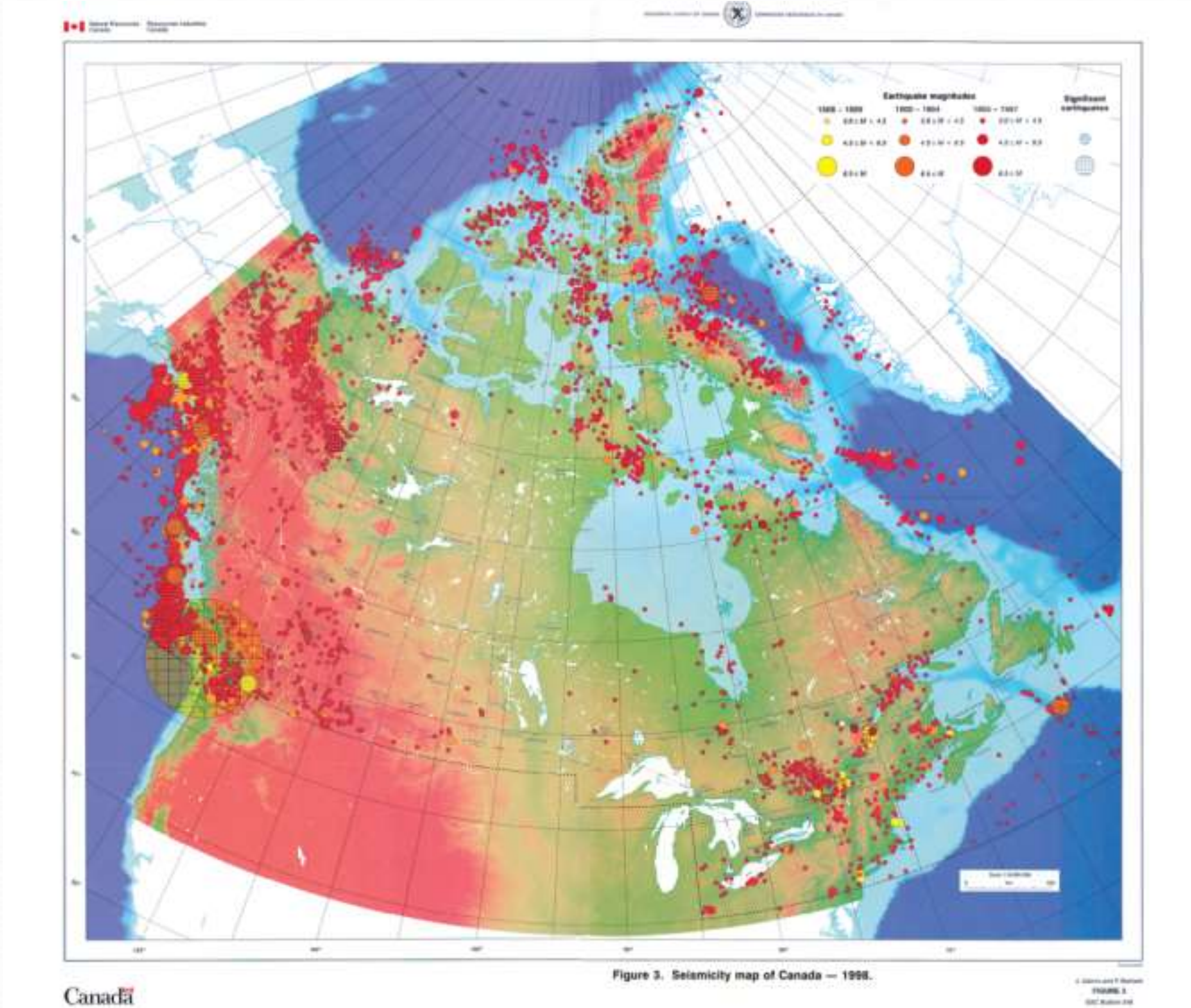


Geographic Regions at Risk from Earthquakes

- Earthquakes are not randomly distributed
- Most occur along plate boundaries
  - “Pacific Ring of Fire”: Japan, Western U.S./Canada, Indonesia, New Zealand
  - Himalayan Mountains
  - Middle East
- However, not all areas at risk are near plate boundaries



▲ **FIGURE 3.18 EARTHQUAKES IN CANADA** A map showing epicentres of historic earthquakes in Canada (**M** ≥ 2.5). *(Reproduced or adapted with the permission of Natural Resources Canada, courtesy of the Geological Survey of Canada (Bulletin 548))*



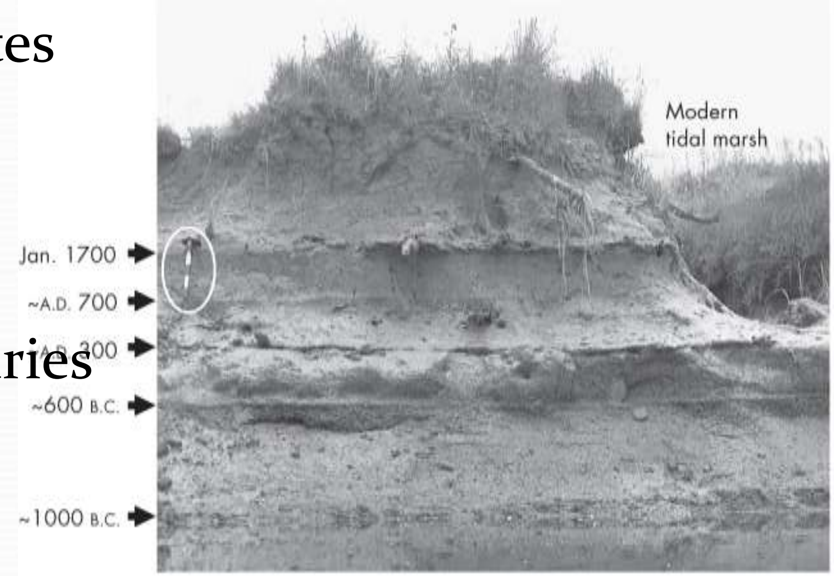
▲ **FIGURE 3.18 EARTHQUAKES IN CANADA** A map showing epicentres of historic earthquakes in Canada (**M** ≥ 2.5). *(Reproduced or adapted with the permission of Natural Resources Canada, courtesy of the Geological Survey of Canada (Bulletin 548))*

Plate Boundary Earthquakes

- **Strike-slip earthquakes**
  - Occur on transform faults
  - Ex: San Andreas and Queen Charlotte faults

- **Thrust earthquakes**
  - Faults separating converging plates
  - Ex: Cascadia subduction zone

- **Normal fault earthquakes**
  - Occur on diverging plate boundaries
  - Ex: Mid-Atlantic Ridge



Intraplate Earthquakes

- Earthquakes that occur within plates
  - Ex: New Madrid seismic zone in Missouri
  - Ex: Southern Quebec and eastern Ontario

- Intraplate earthquakes are often smaller than plate boundary earthquakes.
  - However, they can cause considerable damage due to the lack of preparedness and because they can travel greater distances through dense continental bedrock

Effects of Earthquakes and Linkages

- Shaking
  - Causes damage to buildings, bridges, dams, tunnels, pipelines, etc
  - Measured as ground acceleration
  - Buildings are damaged due to resonance
- Ground Rupture
  - Displacement along the fault causes cracks in the surface and **fault scarps**

Effect of Earthquakes and Linkages, cont.

- Liquefaction
  - Water-saturated loose sediment turns from solid to liquid, causing buildings and land to subside

- Land-level changes

- Landslides

Effect of Earthquakes and Linkages, cont.

- Fires
  - Ground shaking and surface rupture can sever electrical power and gas lines

- Disease
  - A loss of sanitation and housing, contaminated water supplies, and disruption of public health services all contribute

Natural Service Functions of Earthquakes

- Water, oil, and natural gas may be rerouted due to faults
  - Faults can channel groundwater to the surface at **springs**
- New mineral resources may be exposed
  - Some minerals are preferentially deposited in **veins**
- Scenic landscapes may form
  - Ex: Rocky Mountains

Human Interaction with Earthquakes

- The weight from water reservoirs may create new faults or lubricate old ones
- Liquid waste disposals deep in the Earth can create pressure on faults
- Pumping of oil and gas and hydraulic fracturing can both cause small earthquakes
- Nuclear explosions can cause the release of stress along existing faults

Minimizing the Earthquake Hazard

- Earthquake Hazard Reduction Programs
  - Five major goals:
    - Operate national seismograph networks
    - Develop an understanding of earthquake sources
    - Determine earthquake potential
    - Predict effects of earthquakes on buildings and other structures
    - Communicate research in order to educate individuals, communities, and governments

Estimating Seismic Risk

- Hazard maps show earthquake risk
- May show epicentres of historic earthquakes
- Complex maps show probabilities and ground acceleration

◄ FIGURE 3.33 EARTHQUAKE HAZARD MAP OF THE SEATTLE AREA The map shows areas that are susceptible to liquefaction and ground motion amplification, and the zone of possible ground rupture and displacement associated with the Seattle fault. Major infrastructure is also shown. (U.S. Geological Survey)

Short-Term Prediction

- Forecast - specifies the probability of an earthquake occurring

- Prediction - specifies when and where an earthquake will occur

- Precursors
  - Pattern and frequency of earthquakes
  - Land-level change
  - Seismic gaps along faults
  - Physical and chemical changes in Earth’s crust

▲ **FIGURE 3.31 TRANS-ALASKA OIL PIPELINE SURVIVES A LARGE EARTHQUAKE** The Alyeska pipeline was designed to withstand several metres of horizontal displacement where it crosses the Denali fault. The design was put to the test in November 2002 when it shifted horizontally 4.3 m during the **M** 7.9 Denali earthquake. Slider beams, Teflon shoes, and built-in bends of the pipeline accommodated the earthquake rupture and demonstrated the importance of geologic investigations for seismic hazard assessments. *(Alyeska Pipeline Service Company)*

Short-Term Prediction, cont.

- Pattern and frequency of earthquakes
  - Foreshocks and **microearthquakes**
- Land-level change
  - Uplift or subsidence
- Seismic gaps
  - Areas that have not seen recent earthquakes
- Physical and chemical changes
  - Changes in **electrical resistivity** and groundwater levels

Status of Earthquake Prediction and Forecasting

- Some success with earthquake predictions
- Predictions need to be scientifically reviewed
- Difficulty in predicting or forecasting earthquakes
- Research projects like SAFOD help gain better understanding of earthquakes and potentially better predictions

- **Earthquake warning systems**
  - Current warning systems provide 15 seconds to 1 minute of warning

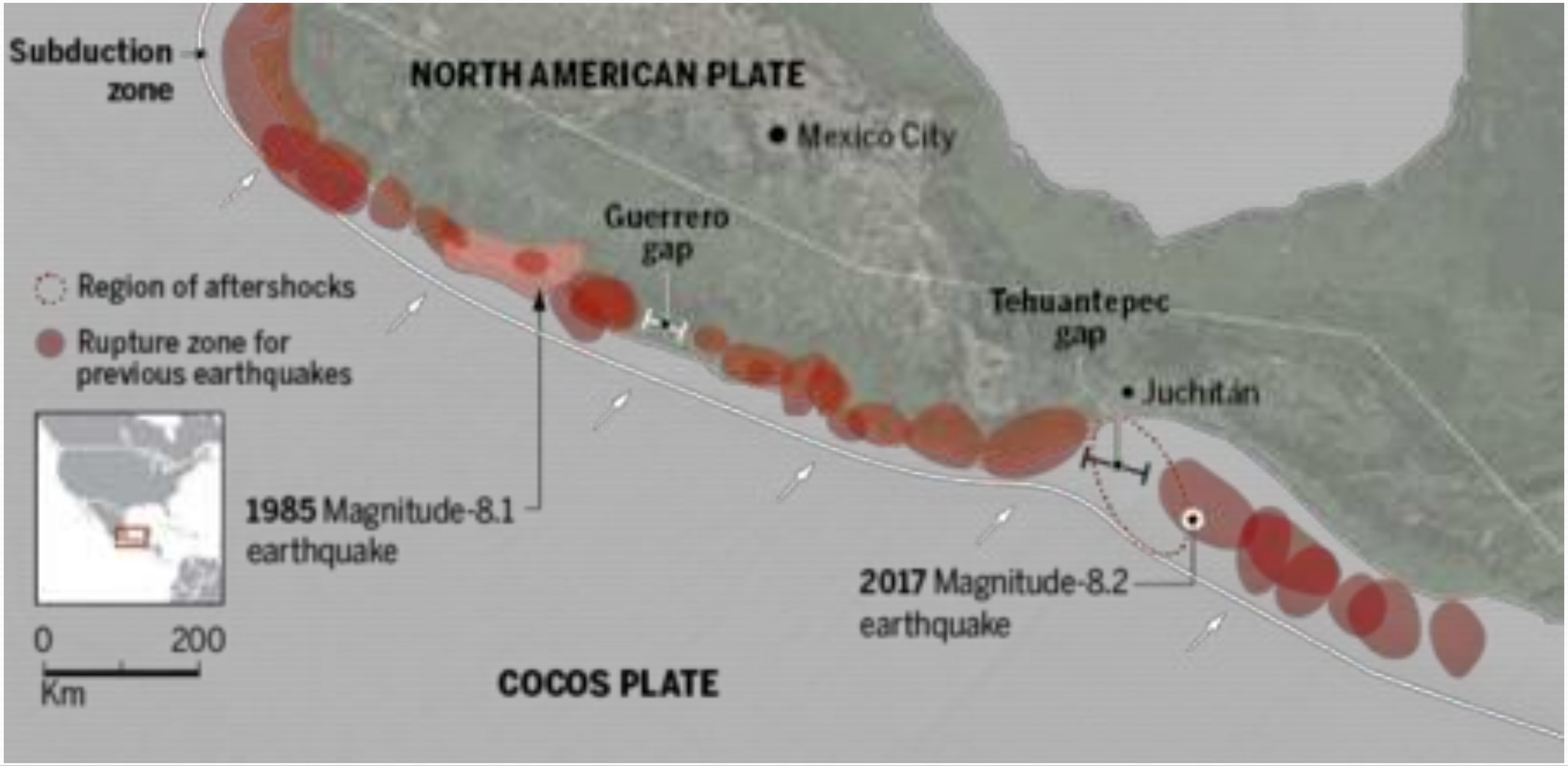
Perceptions of and Adjustment to the Earthquake Hazard

- Perception
  - One community's experience does not stimulate other communities to improve their preparedness

- Community Adjustments
  - Critical facilities must be located in earthquake safe locations
  - Requires detailed maps of ground response to seismic shaking
  - Buildings must be designed to withstand vibrations
  - Retrofitting old buildings may be necessary
  - People must be prepared through education
  - Insurance must be made available

Personal Adjustments before, during, and after an Earthquake

- Before the shaking starts
  - Make sure that your home is structurally sound
  - Secure large objects
  - Turn off gas, water and electricity
  - Make a personal plan of how to react to a earthquake
- During the shaking
  - Do not panic!
  - Move away from windows, protect your head and face
- When the shaking stops
  - Leave the building
  - Check for damage and injuries


Subduction zone
NORTH AMERICAN PLATE
Mexico City
Guerrero gap
Region of aftershocks
Rupture zone for previous earthquakes
Tehuantepec gap
Juchitán
1985 Magnitude-8.1 earthquake
2017 Magnitude-8.2 earthquake
0
200
Km
COCOS PLATE