6. Introduction to Seismology and Earthquakes

Lesson Objectives:

1) Outline and describe the internal structure of Earth.
2) Qualitatively describe and define the one-dimensional wave equation and four types of waves.
3) Qualitatively illustrate ray path diagrams and identify their influence on seismograms.
4) Summarize the theory of plate tectonics and identify key plates.
5) Explain the various types of faulting and their radiation patterns or seismic "beach balls".
6) Describe the far-field displacement response and directivity effects on ground motions.
7) Quantitatively compute various earthquake magnitude measures as well as the seismic moment. Describe the formulation for each magnitude scale.
8) Demonstrate the magnitude-frequency relationships of earthquakes and describe its impact on the released seismic energy.
9) Evaluate earthquake intensity using the Modified Mercalli Intensity (MMI) scale.
10) Paraphrase earthquake triggering in terms of predictable models and demonstrate the increased seismic activity for aftershock events.

Background Reading:

1) Read ____.

Introduction:

1) Seismology in general analyzes the ________________________ of the Earth using seismograms.
2) An _____________________________ or a ________________________ sets off a series of vibrations. These events are also called _________________________.
3) These vibrations are modified as they are transmitted through the Earth which creates a filter or a __________________________________ response.
4) Once these filtered vibrations reach a particular location, an instrument records the ground

motion. As noted in previously classes, the ________________________________ is also noted due to the filtering effect of the instrument.

5) The measured seismogram is dependent on:
    a. The ________________________ source or event.
    b. The complicated ____________________ structure which will distort the wave fronts.
    c. A filtering effect of the ____ which measures the response.

Earth's Internal Structure:

1) The internal structure of Earth can be determined using the travel time of seismic arrivals (from seismograms).
2) These travel times provide an estimation of the ______________________ structure of the interior.
3) The Earth can be divided into four regions.
4) ______________________ – this can be further subdivided into two types:
    a. _____________________________ - is relatively dense, but thin of approx. 6 km.
        i. It is basaltic in average composition.
        ii. Undergoes continued renewal on a geological scale.
        iii. The maximum age is less than 200 Ma.
    b. _____________________________ – relatively thicker than the oceanic crust.
        i. On average, the thickness is between 30-60 km
        ii. Some continental rocks as old as 4.1 Ga have been located.
5) ______________________ – a solid rocky outer shell that makes up 84% of the planet's volume and 68% of its mass.
    a. A transition zone exists between 300 and 700 km in depth where several mineralogical phase changes are believed to occur. This includes the 410 and 660 km seismic discontinuities.
    b. As the mantle continues in depth, sometimes called the lower mantle from 700 km to the core-mantle boundary, the velocity structure increases.

6) ______________________ – is liquid.

   a. P wave velocity drops.

   b. S wave velocity is ______________________________________.

7) ______________________ – At a radius of approximately 1121 km, the core becomes solid.

   a. It is believe to be mainly compromised of iron.

8) A diagram of the Earth's internal structure is illustrated in Figure 1.

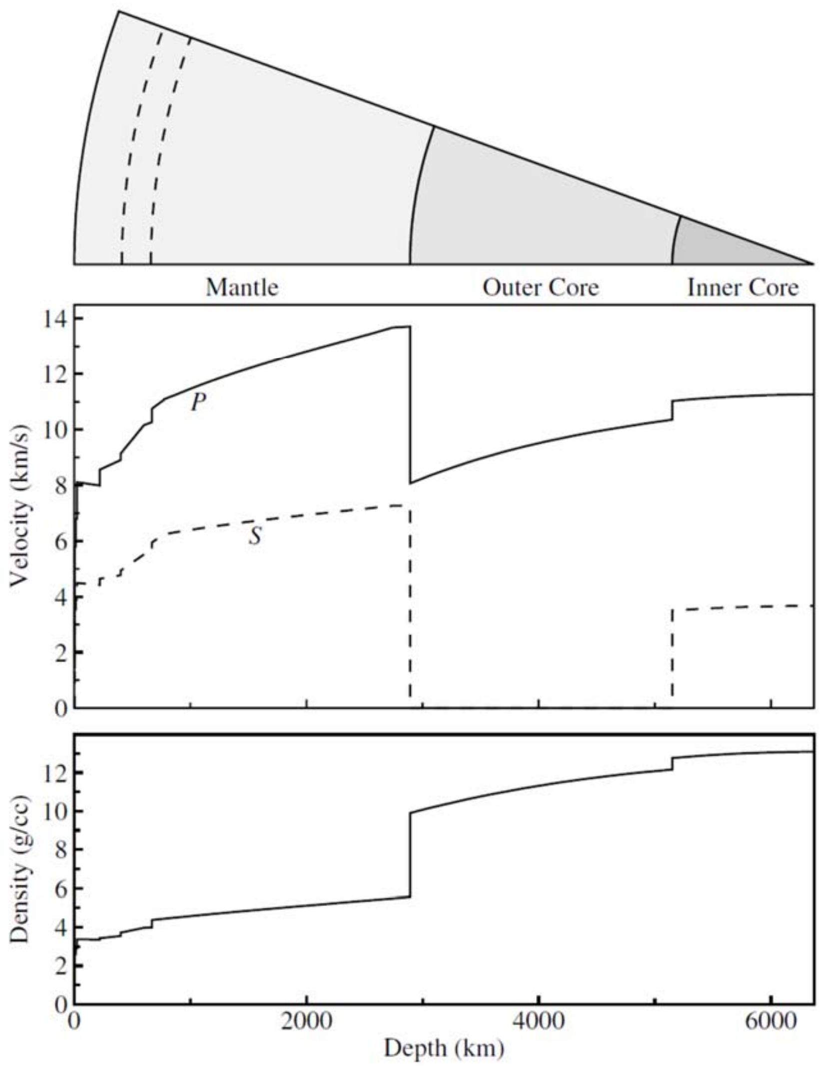


Figure 1. The internal structure of Earth with P and S wave velocity structures identified. Values are obtained from the Preliminary Reference Earth Model (PREM)[1].

[1] Figure obtained from: Shearer, P. M. (2009). *Introduction to seismology*. 2nd Edition. Cambridge University Press.

Wave Equation and Classifications:

1) The propagated waves through the earth are a function of the ________________________ ____________________________ of the internal Earth structure.
2) Therefore, for simplicity let's examine how the wave propagates in a one-dimensional spring.
3) A schematic of a spring in an undeformed and deformed (stretched) position is illustrated below:
4) The spring has an unstretched length of _______ and a deformed length of _______. A dimensionless strain _______ can be expressed as:
5) Within uniform stretching (in tension), the strain is independent of position along the length of the spring. Therefore _____ does not vary with ______. Therefore:
6) Also for a one-dimensional spring, ______ will be a function of ____ and ____. Therefore one needs to determine the force that is required to stretch the spring is proportional to ___:
7) Above ____ depends only on the material properties of the spring. This is noted to be in accordance with a one-dimensional linear stress-strain relationship or ________________.

8) For a uniformly stretched spring, _____ is independent on position within the spring because ______ is not a function of position.
9) Now let's examine if we apply forces to the spring such that the spring is not uniformly distributed. Sketch:

10) Let's define _____ as the mass per unit length of the spring. Therefore the mass of spring element is ____________________.
11) The net forces on the element can be found using ______________________________ as:

12) The acceleration is the second time derivative of the displacement, therefore:

13) For a spring with a constant elastic properties, one can write:

14) Note that the strain is small, therefore using __________________________ one can write:

15) In summary, one can write:

16) This equation above is noted as the ____ and considered the propagation of a disturbance through an elastic medium. A few notes:

   a. _____ has units of force or _________________.
   b. _____ has units of ___________________.
   c. Therefore ___________ has units of ___________________________ or squared velocity, ___________.

17) This can be written using the speed of propagation _____ as:

18) In three-dimensions this is a bit more complicated, however the disturbance that propagates through the medium in the propagation direction has a speed that is difference from the speed of propagation in an orthogonal direction. This is descriptive of various types of waves.

Wave Classifications:

19) There four general types of waves as illustrated in Figure 2 (body waves) and Figure 3 (surface waves).

20) ____:

   a. Also known as a Plane or P wave.
   b. This is includes the ______________________ and ______________________ of the material.
   c. Invokes both a volume change and shearing (change in shape) in the material.
   d. The velocity can be expressed as:

21) ____:

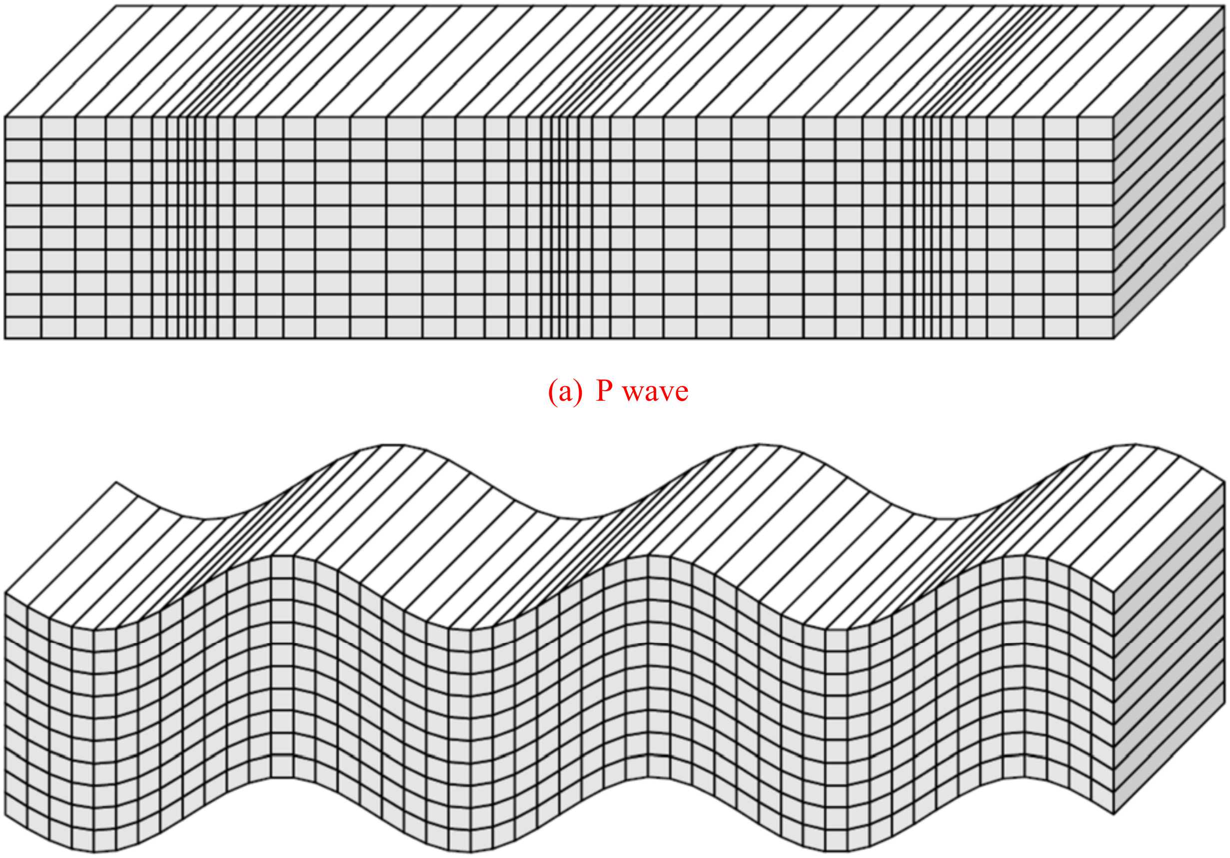
a. Also known as an S wave.
b. ________________________________ with no volume change.
c. Cannot be transmitted through a fluid.
d. The velocity can be expressed as:

22) ____:

a. A surface wave that is ____ in nature.
b. Amplitude decays strongly with depth.
c. The velocity can be expressed as:

23) ____:

a. A surface wave that contains both ____ _____________________________.
b. Amplitude decays strongly with depth.
c. The velocity can be expressed as:

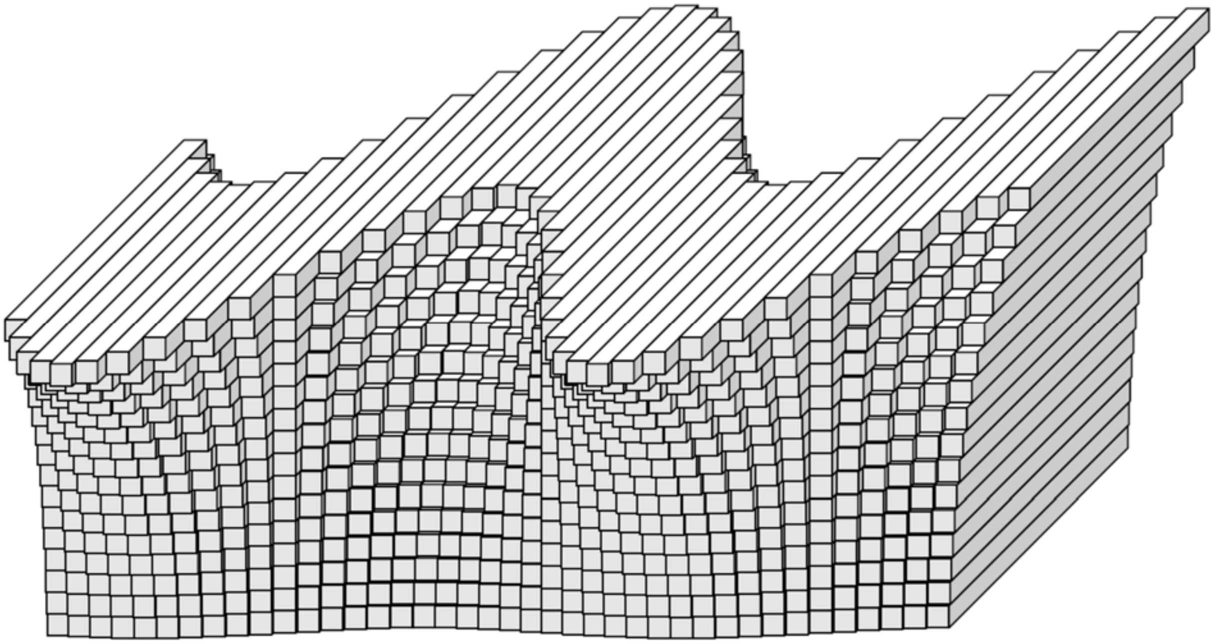


(a) P wave

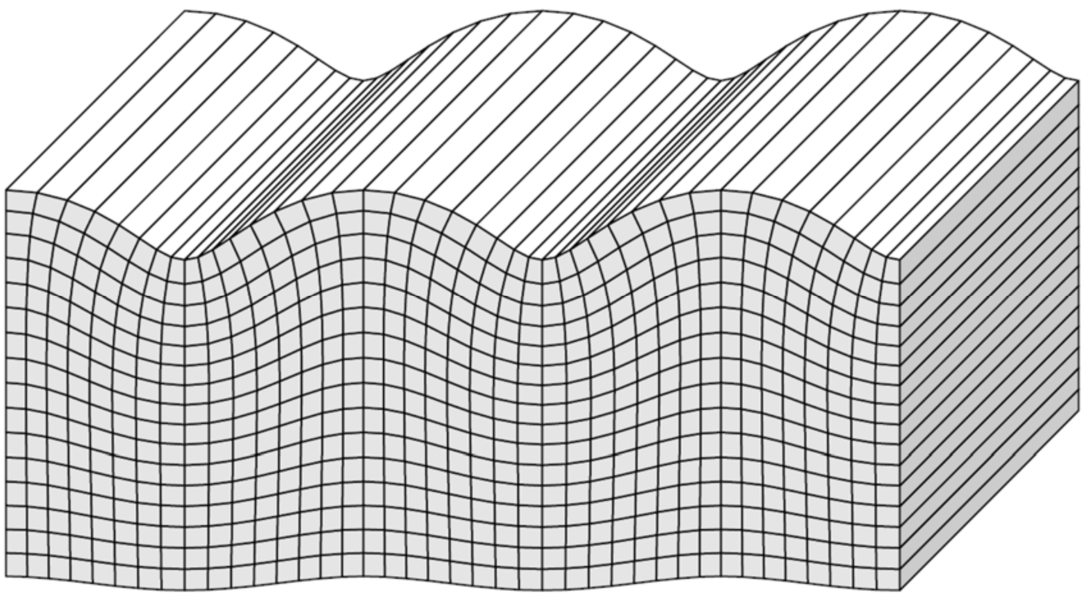
(b) S wave.

Figure 2. Harmonic P and S waves. Strains are excessively exaggerated computed to the actual seismic strains in Earth[2].

[2] Figure obtained from: Shearer, P. M. (2009). *Introduction to seismology*. 2nd Edition. Cambridge University Press.



(a) Love wave



(b) Rayleigh Wave

Figure 3. Surface waves[3].

[3] Figure obtained from: Shearer, P. M. (2009). *Introduction to seismology*. 2nd Edition. Cambridge University Press.

Velocity Structure and Ray Paths:

1) As a wave propagates through Earth, the local ___________ profiles influence the ray path.
2) In basic formulation, let's consider a ray travelling in a flat Earth which is ______________ ___________________________ and ____________________________ in depth.
3) Seismic ray theory is analogous to geometrical optics. As a ray of light passes between one medium of refractive index ____ to a medium of refractive index ____, Snell's Law gives:
4) For seismic waves, this can be written as:
5) Using a newly defined variables of slowness and ray parameter, this can be rewritten as:
6) Ray theory is useful for determining travel time curves which is indicative of the internal structure of the wave medium as well as the understanding the complications within the seismograms.
7) For various velocity structures, let's examine the results by exciting various rays with the same ray parameter, but at different take-off angles.

8) ________________________ with depth – illustrated in Figure 4.

   a. Ray paths: the rays sample progressively deeper in Earth.

   b. Travel time curves: arrive at progressive larger distances.

   c. Common and dominate nature of Earth's structure.

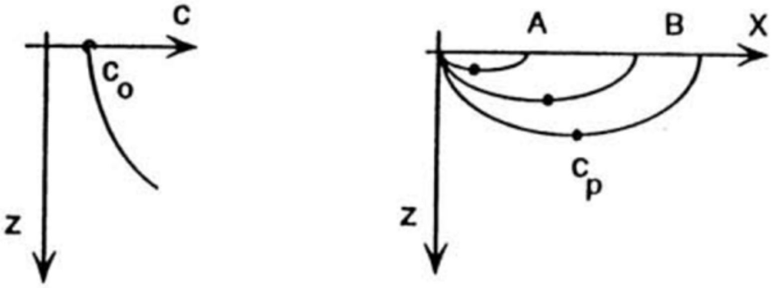


Figure 4. Wave speed increases with depth.

9) Presence of a ________________________________ – illustrated in Figure 5.

   a. Ray paths: the rays will still sample progressively deeper regions, but the pattern is more complex.

   b. When the ray parameter enters the low velocity zone (LVZ), the ray parameter decreases further. The waves turn towards the vertical direction when the velocity decreases.

   c. This results in a shadow zone where no rays arrive.

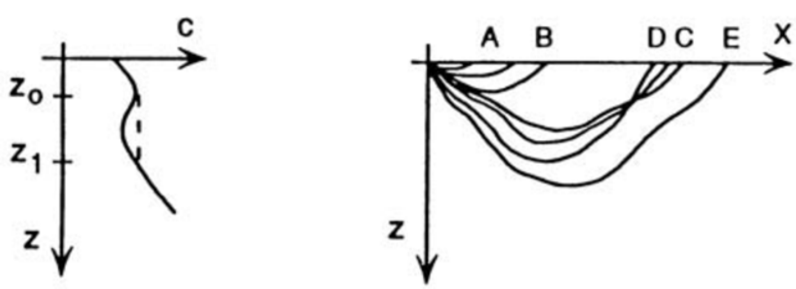


Figure 5. Wave speed encounters a low-velocity zone.

10) ____ – illustrated in Figure 6.

   a. Ray paths: when the ray parameter enters the rapid increase three arrivals exist: direct phases propagating through the medium above the interface, reflected phase, and the refracted wave that propagates in part of the medium beneath the interface.
   b. This is also called a triplication range.

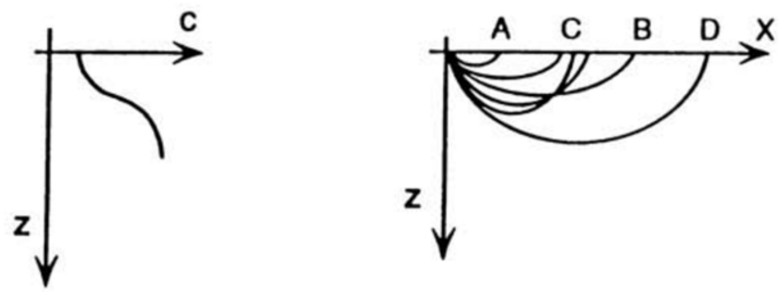


Figure 6. Wave speed encounters a sharp increase in speed with depth.

Whole Earth Phases:

1) As waves propagate throughout Earth, specific names are provided for identification.
2) The P- and S- wave segments are identified using the following nomenclature:
   a. P – P wave in the mantle
   b. K – P wave in the outer core
   c. I – P wave in the inner core
   d. S – S wave in the mantle
   e. J – S wave in the inner core
   f. c – reflection off the core–mantle boundary (CMB)
   g. i – reflection off the inner-core boundary (ICB)
3) For P and S waves in the whole earth, the above abbreviations apply and stand for successive segments of the ray path from source to receiver, such as P versus PP, PPP.
4) Example of the global body-waves are shown in Figure 7.
5) The seismograms following the 1994 Northridge (California) earthquake are shown in Figure 8 at the OBN station at Obninsk, Russia within the (GSN) Global Seismograph Network (IRIS/IDA).

a. This illustrates the different body-wave phases and their dependence on:

i. ______________________________

ii. ______________________________

iii. ______________________________.

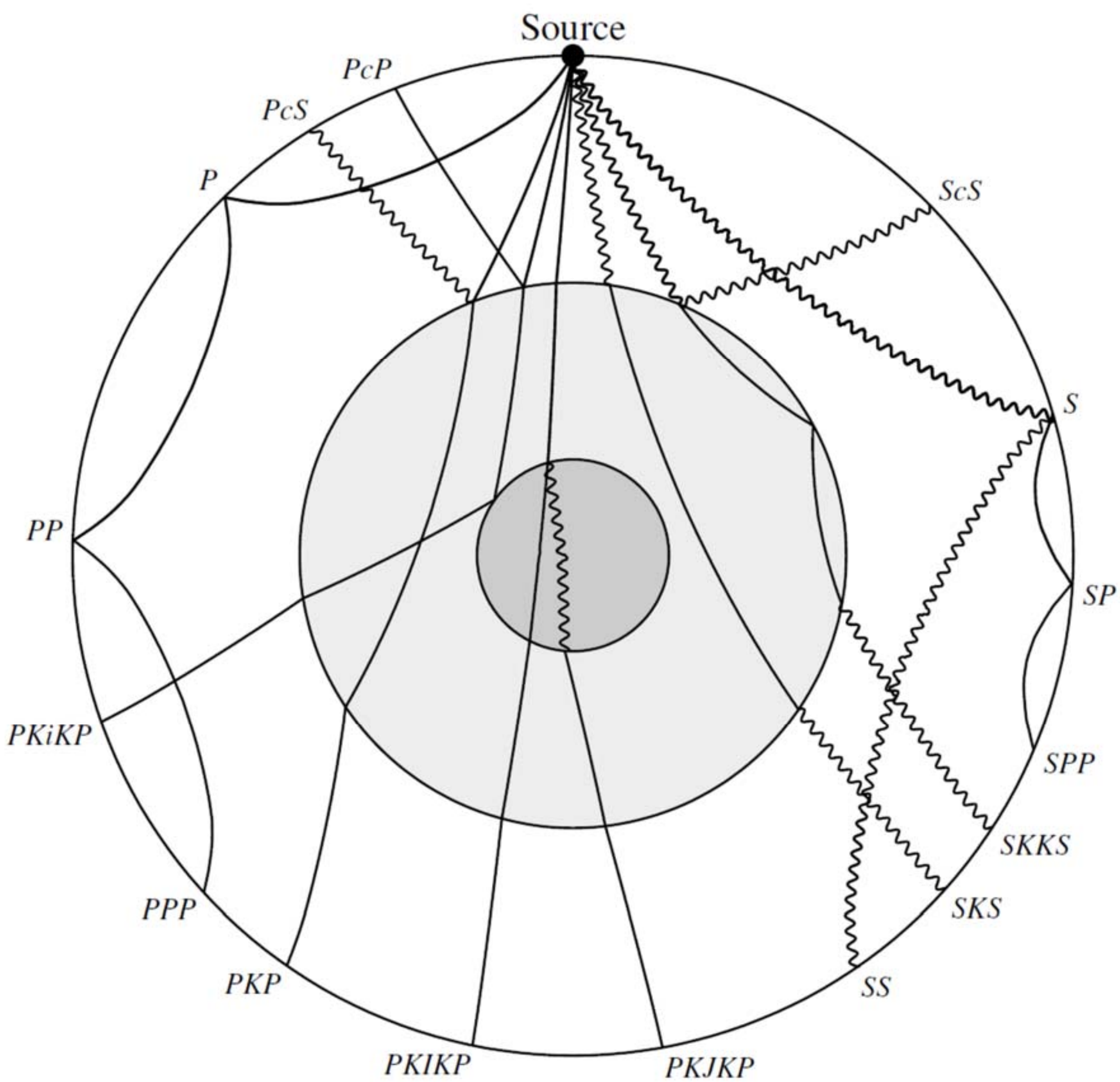


Figure 7. Global seismic ray paths. Note P waves are shown as solid lines and S waves as wavy lines. The internal structure of Earth is denoted with different shadings, namely the inner core, outer core, and the mantel[4].

[4] Figure obtained from: Shearer, P. M. (2009). *Introduction to seismology*. 2nd Edition. Cambridge University Press.

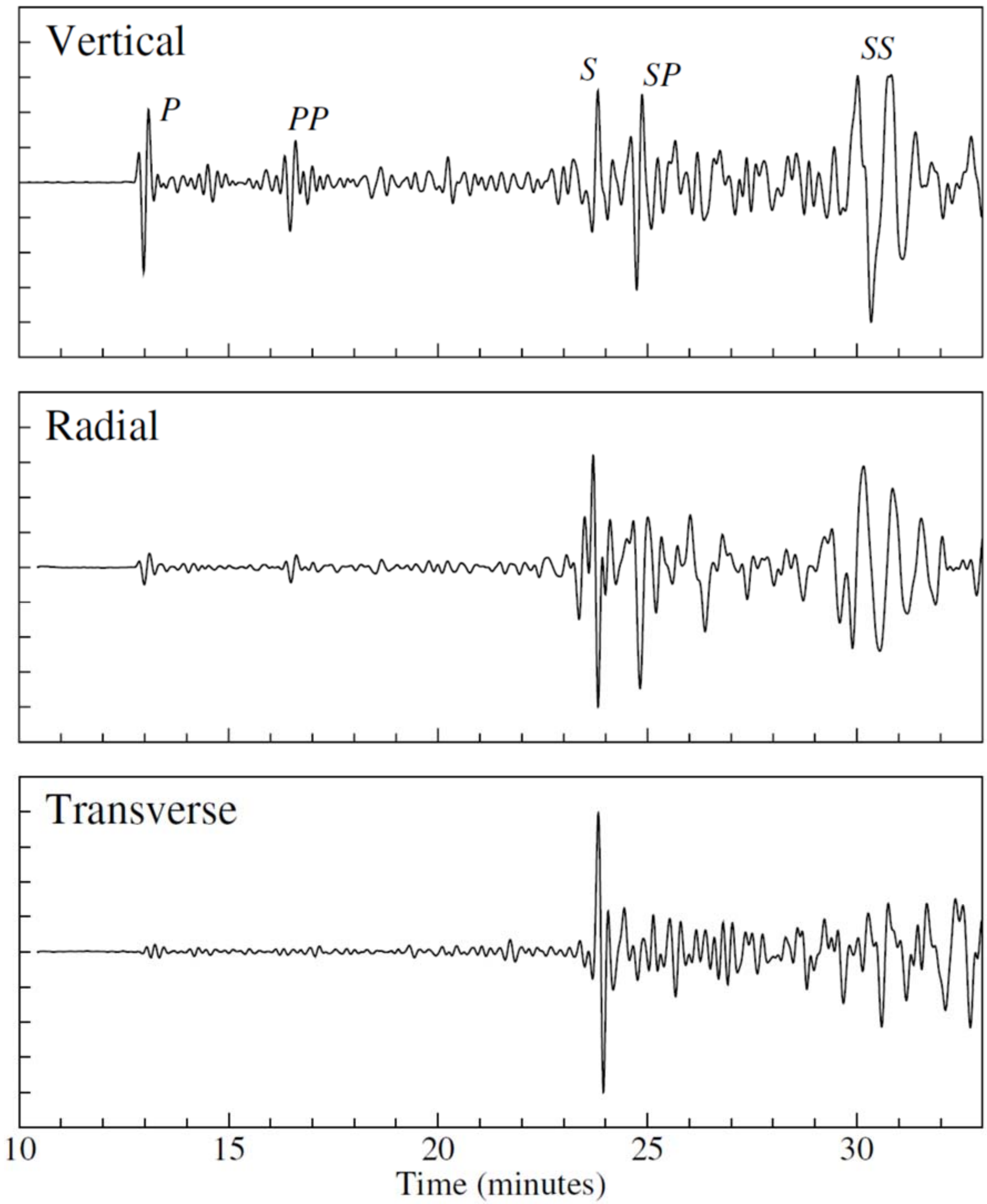


Figure 8. Vertical, radial, and transverse components of the 1994 Northridge earthquake as recorded at the IRIS/IDA station OBIN. The time scale on the x-axis is in minutes relative to the earthquake origin and the amplitude (y-axes) are arbitrarily scaled[5].

[5] Figure obtained from: Shearer, P. M. (2009). *Introduction to seismology*. 2nd Edition. Cambridge University Press.

Plate Tectonics:

1) Plate tectonics is a model in which the outer shell of Earth is divided in a number of ______ ____.
2) These plates are in motion with respect to each other. (Similar to a lava lake)
3) The relative velocities of the plates vary, generally on the order of a few millimeters per year.
4) At plate boundaries, most of the following occur:
   a. ____
   b. ____
   c. ____
5) A general map of the plate boundaries is shown in Figure 9.

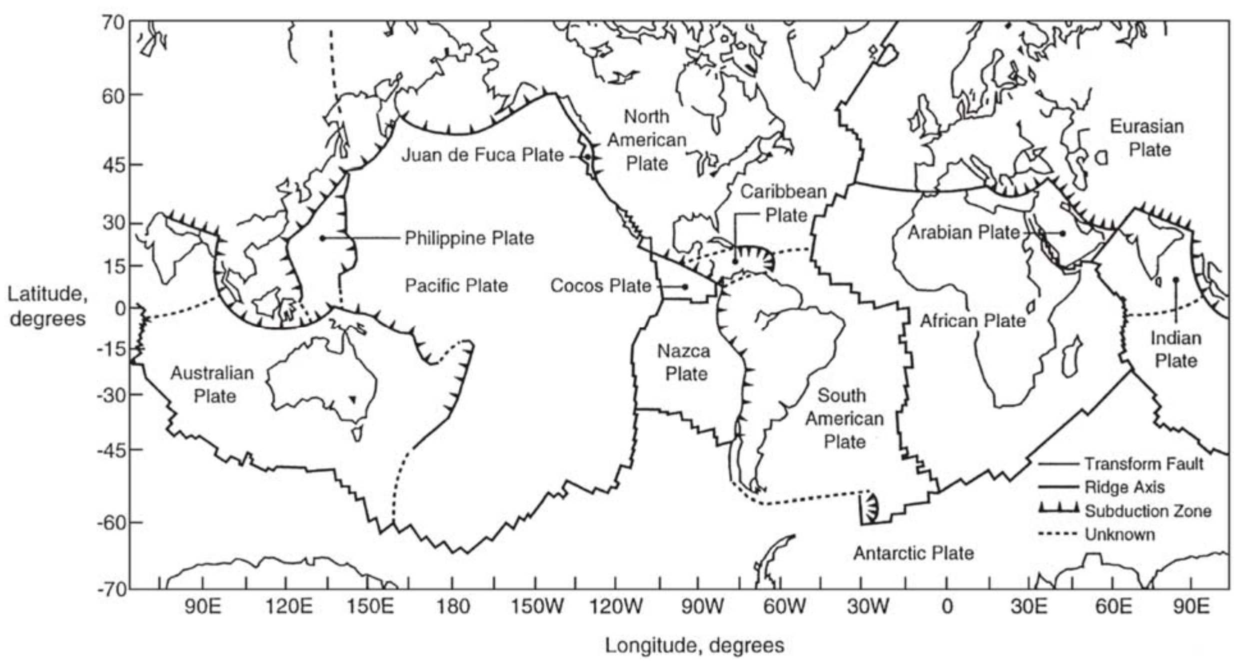


Figure 9. Distribution of major plates, spreading ridges, transform faults, and subduction zones[6].

[6] Figure obtained from: Turcotte, D. L., & Schubert, G. (2014). Geodynamics. 3rd Edition. Cambridge University Press.

6) Plates are generally cool rocks of various thickness.
7) Plates are ____________________ at ocean ridges where adjacent plates _______________ in a process known as seafloor spreading. Illustrations are shown in Figure 10 (of the entire plate) and a close-up of the spreading ridge in Figure 11.
    a. These are also known as __________________________________ plate boundaries.
    b. The hot, solid ______________________________________ ascends to fill the gap.
    c. As ______________________________ cools, it because rigid and accretes to plates.
    d. The rate of plate formation controls its spreading velocity.
8) Since there is a finite surface area of Earth, therefore plates must be consumed.

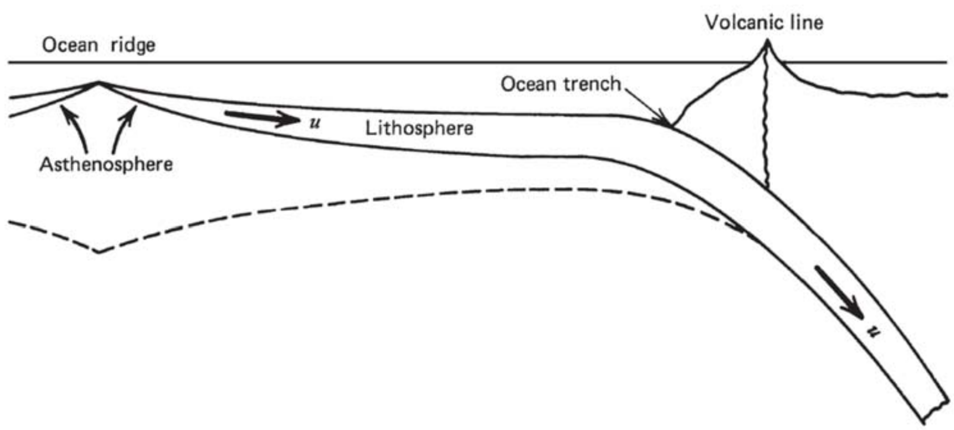


Figure 10. Accretion of the lithosphere at an ocean ridge (spreading zone) and its subduction at its collision of a continental plate[7].

[7] Figure obtained from: Turcotte, D. L., & Schubert, G. (2014). Geodynamics. 3rd Edition. Cambridge University Press.

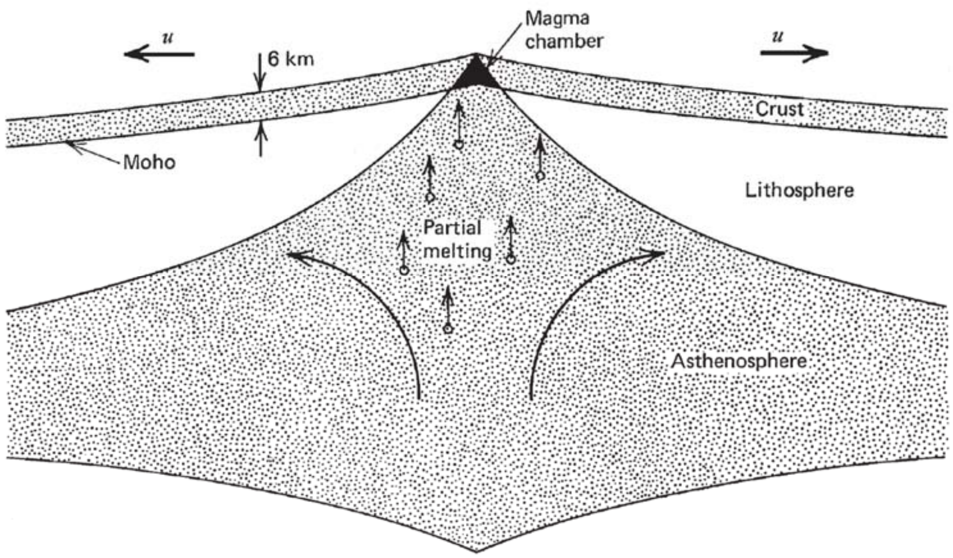


Figure 11. An accreting plate margin at an ocean ridge[8].

9) Plates bend and descend at ocean trenches in a process known as subduction (Figure 12).
   a. These are also known as ________________________________ plate boundaries.
   b. The faults at these sites are capable of the _____________ earthquakes. Including:
      i. ____
      ii. ____
      iii. ____
      iv. ____

[8] Figure obtained from: Turcotte, D. L., & Schubert, G. (2014). Geodynamics. 3rd Edition. Cambridge University Press.

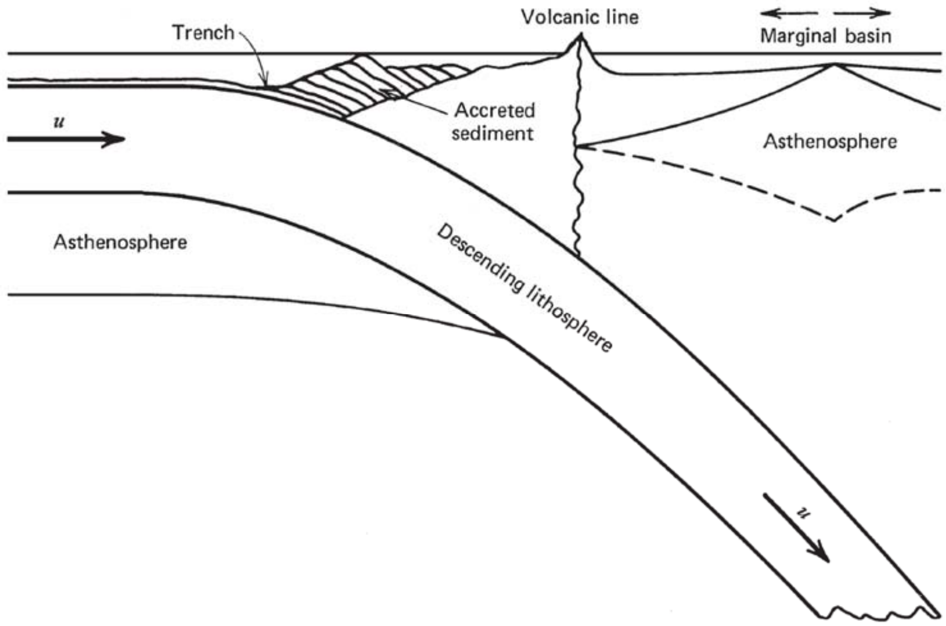


Figure 12. Subduction of the oceanic lithosphere at an ocean trench as well as the associated volcanic line due to subduction[9].

10) Near almost all ocean trenches lie a line of active ____________________________.
    a. These volcanoes generally occur about 125 km above the descending lithosphere.
    b. Some of the magmas produced that form these volcanoes are produced near the upper boundary of the descending lithosphere.
    c. These volcanoes can exist in two possible places:
        i. __________________________ – to form an island arc.
            1. _______________________________________in the North Pacific.
        ii. _____________________________ – volcanoes grow from the land surface.
            1. Western United States: Mount Baker to Mount Shasta
            2. South America – ____

11) Another type of plate boundary is a _________________________. In these cases, the rigid plates slide past each other.
    a. An ocean ridge system is not a continuous accretional margin, as illustrated in Figure 13.

[9] Figure obtained from: Turcotte, D. L., & Schubert, G. (2014). Geodynamics. 3rd Edition. Cambridge University Press.

   b. The ridge segments lie nearly perpendicular to the spreading direction, where the transform faults lie nearly parallel to the spreading direction.
   c. Not limited to just ocean ridge systems. Can also exist on continental margins.
      i. Famous example is the ______________________________________.
   d. The movement on these transform faults is _________________________, but some differential __________________________ exists because as the seafloor spreads away from a ridge crest, it also subsides.

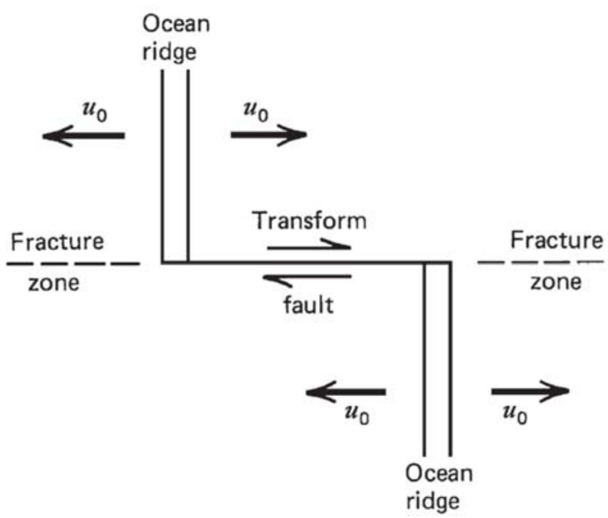


Figure 13. Segments of an ocean ridge offset by a transform or strike-slip fault[10].

12) Extension of the transform faults into the adjacent plates are known as fracture zones.
   a. Example includes the Charles Gibb Fracture Zone of the Mid-Atlantic Ridge between the Azores and Iceland. Length is over 2000 km.

13) One anomaly to areas of earthquakes and volcanism is ____________________. These are not generally related to the plate technics and may lie well within the interior of plates.
   a. Examples: ______________________________ and ____________________.
   b. Other examples are shown in Figure 14.
   c. In many cases, hotspots lie at the end of a well-defined line of volcanic ridges. Such

[10] Figure obtained from: Turcotte, D. L., & Schubert, G. (2014). Geodynamics. 3rd Edition. Cambridge University Press.

as the Hawaiian - Emperor island seamount chain that extends across the Pacific plate to the Aleutian Islands.

14) Plate boundaries can end only by the intersection of another plate boundary. This intersection is called a ______________________________________.

    a. Can include Transform-Transform-Trench (F-F-T) or Ridge-Ridge-Ridge (R-R-R).
    b. Example includes the Mendocino Triple Junction (F-F-T).

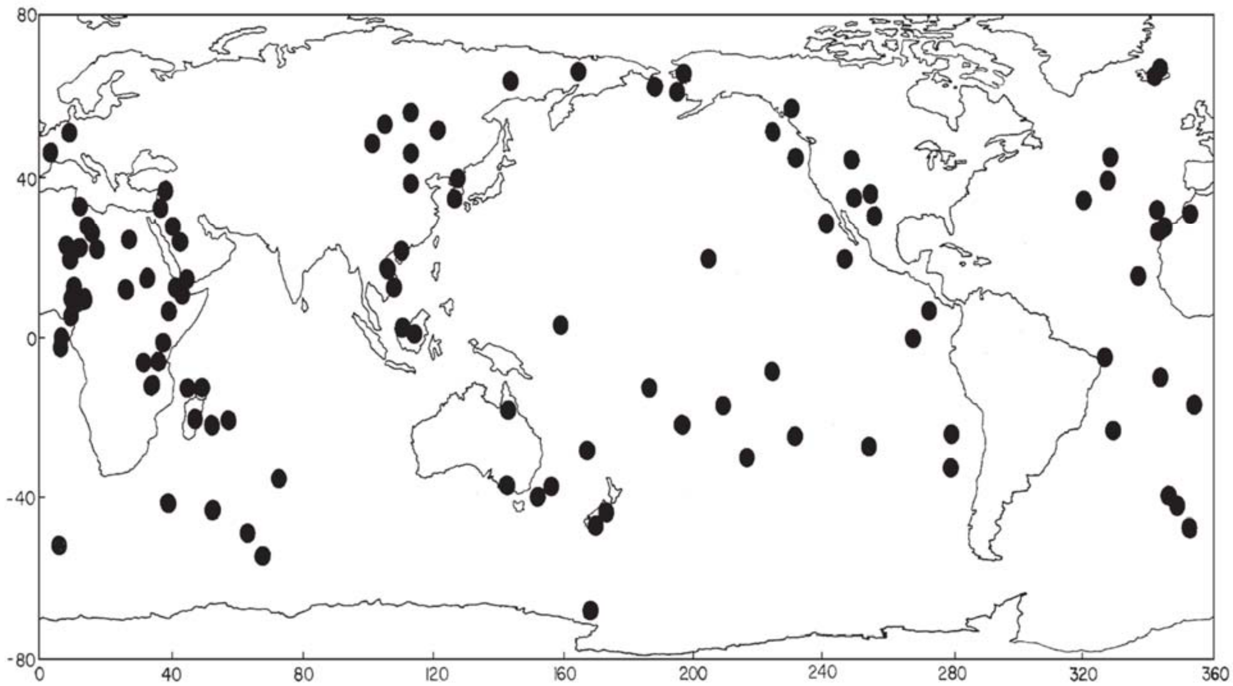


Figure 14. Distribution of surface hotspots, centers of intraplate volcanism, and anomalous plate margin volcanism[11].

Fault Mechanisms:

1) Now after discussion of the movement of the plates, let's focus on how their movements result in ______________________________________.
2) Figure 15 illustrates a global distribution of earthquakes with magnitudes larger than 5.1. Note the majority of these earthquakes occur on plate boundaries.

[11] Figure obtained from: Turcotte, D. L., & Schubert, G. (2014). Geodynamics. 3rd Edition. Cambridge University Press.

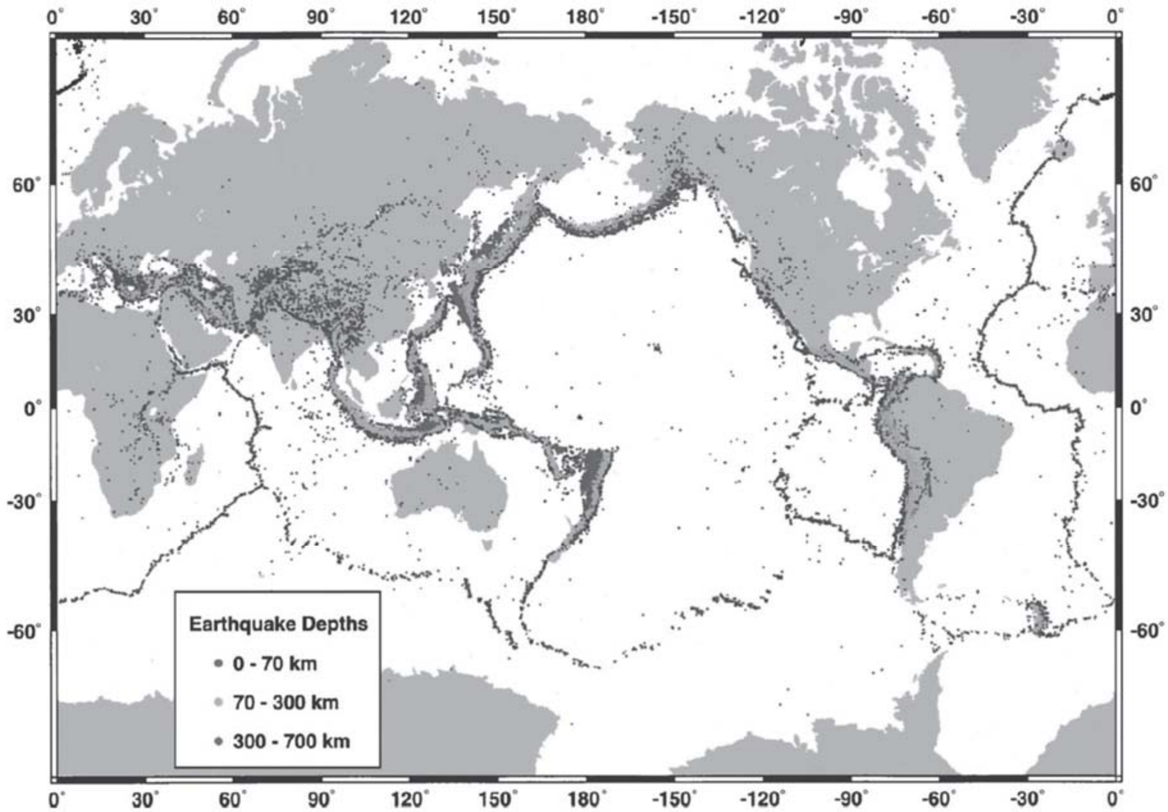


Figure 15. Distribution of earthquakes with magnitudes larger than 5.1 for 1964-1995[12].

3) Earthquakes may be represented as the movement across a ______________________________ of arbitrary orientation, as illustrated in Figure 16.
4) In this figure, some key terminology is introduced (Figure 16):
    a. _________ – azimuth of the fault from north where it intersects a horizontal surface.
    b. _______ – angle from the horizontal surface.
    c. __________________________ – the lower block (of a non-vertical fault).
    d. __________________________ – the upper block (of a non-vertical fault).
    e. _____________________ – the movement of the hanging wall relative to the foot wall.
    f. __________ – angle between the slip vector and the strike.

[12] Figure from: Engdahl, E. R., van der Hilst, R., and Buland, R. (1998). Global teleseismic earthquake relocation with improved travel times and procedures for depth determination. Bull. Seis. Soc. Am., 88, 722–43.

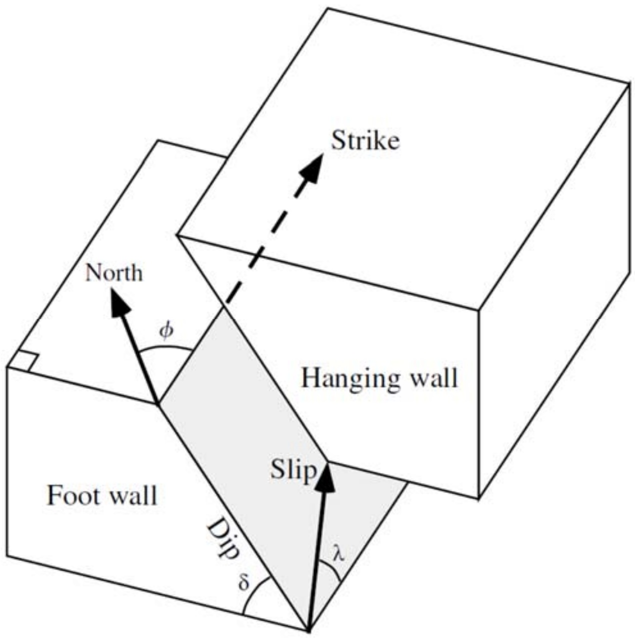


Figure 16. Planar fault of arbitrary orientation. Note this is defined by the strike and dip of the fault surface as well as the direction of the slip vector[13].

5) Types of faulting or focal mechanisms:
    a. ____________________________ – downward movement of the hanging wall.
    b. ____________________________– upward movement of the hanging wall.
        i. Reverse faulting with dip angles less than 45 degrees are also called _____ _________________________.
        ii. __________________________ – nearly horizontal thrust faults.
    c. ____________________ – horizontal movement between fault surfaces (Figure 17).
        i. Right-lateral strike slip motion – an observer standing on one side of the fault sees the adjacent block move to the right.
        ii. Left-lateral motion is the opposite.
6) To define the __________________________ for various faulting styles:
    a. Vertical fault – hanging wall is assumed to be on the right for an observer looking in the strike direction
    b. Rake is zero for a left-lateral and 180 degrees for a right-lateral fault.

[13] Figure obtained from: Shearer, P. M. (2009). *Introduction to seismology*. 2nd Edition. Cambridge University Press.

7) The seismic model of faulting or seismic event focal mechanism is determined by the:
    a. _________________ between 0 and 360 degrees
    b. _________________between 0 and 90 degrees
    c. _________________between 0 and 360 degrees
8) An __________________ on the other hand will produce an initial waveform in which the material is initially compressed in all directions. The wave front will travel away from the source and be recorded at as a compressional arrival. Note this is an ____________ source.
9) For seismograms, a compressional arrival is recorded as an _____________________ of the pen, while a dilatational arrival is recorded as a _____________________ of the pen.
10) The ________________ of the first motion at a station (the first arrival is a P-wave) is indicative of the focal mechanism.
11) For example, a strike slip fault as shown in Figure 17.

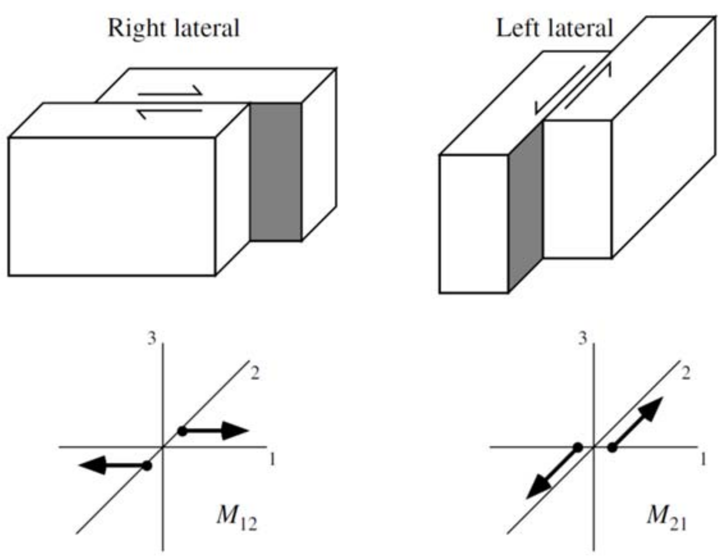


Figure 17. Right and left-lateral strike slip mechanisms and associated moment tensor representation[14].

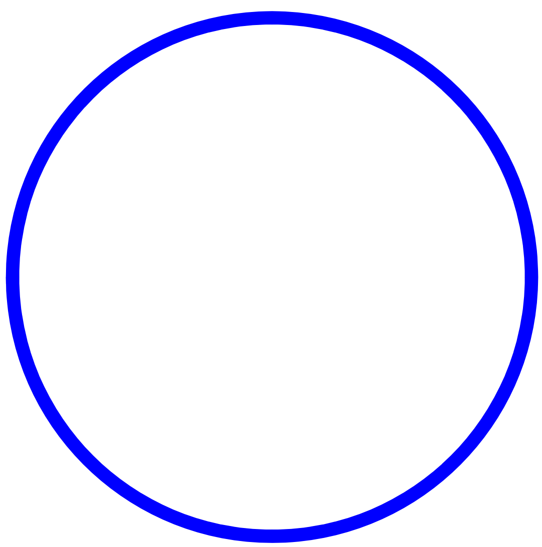
[14] Figure obtained from: Shearer, P. M. (2009). *Introduction to seismology*. 2nd Edition. Cambridge University Press.

12) A planar view of this fault can illustrate the focal mechanism and its initial arrivals at seismic stations in different quadrants.

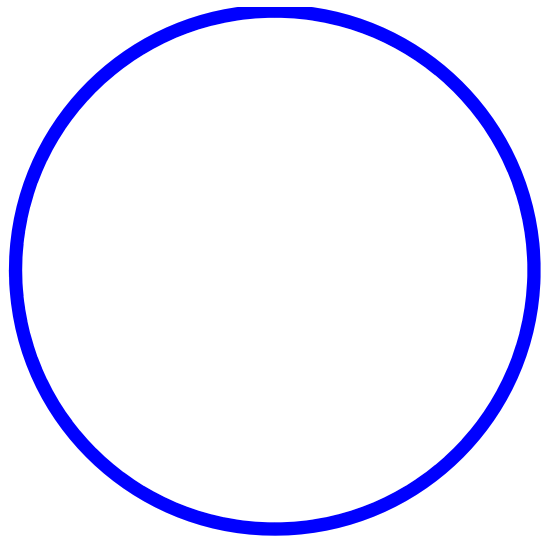
13) As noted above, the fault and auxiliary plane separate the different, observed ____________. A station in the fault or ______________________ plane will have no motion.

14) This leads to construction of ____________________________ or seismic _______________ _________________. In these scenarios, the compressional quadrants are typically shaded.

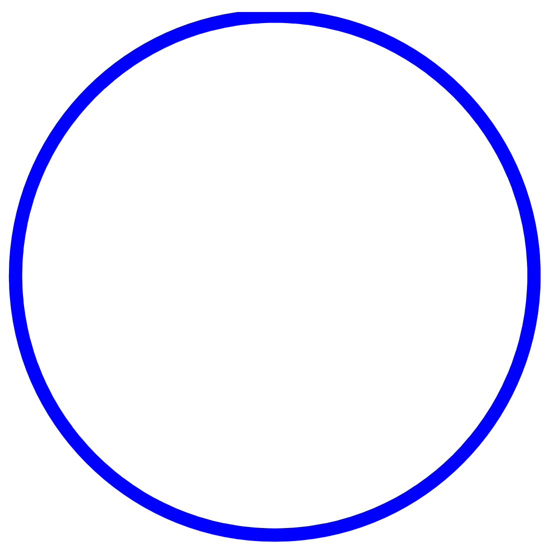
15) For strike slip faulting (also illustrated in Figure 18):



16) For normal faulting:



17) For reverse faulting:



18) After understanding of these mechanisms and resulting radiation patterns (Figure 19), these can be reviewed on the plate boundaries to understand the distribution of focal mechanisms throughout the western United States (Figure 20) and worldwide (Figure 21).

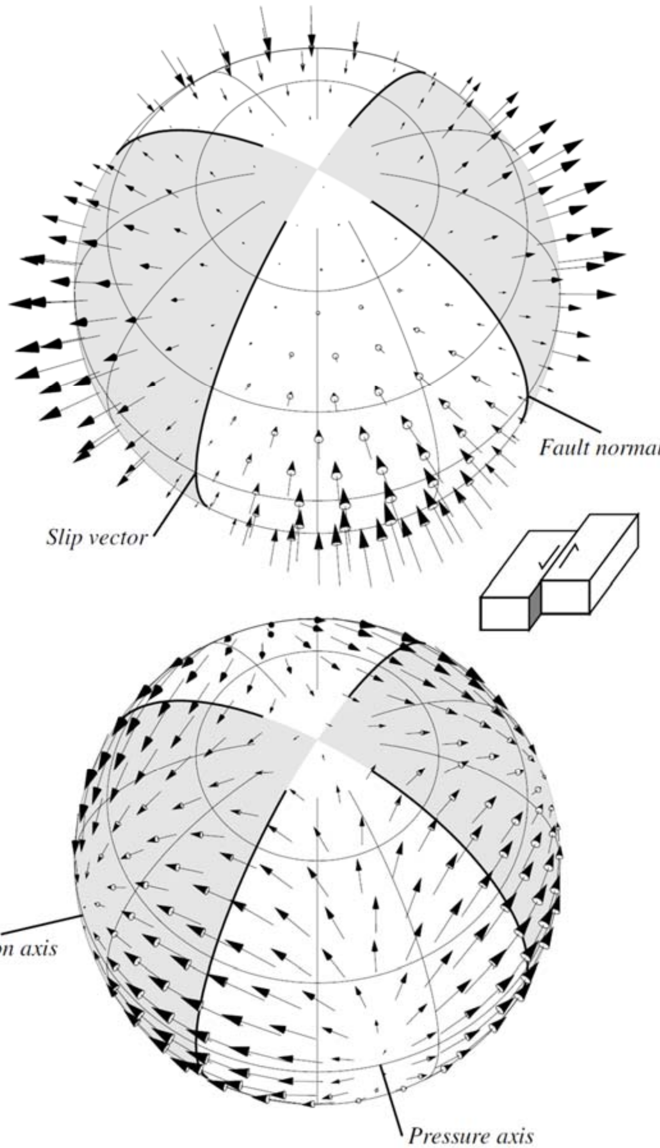


Figure 18. Far-field radiation patterns for the P-waves (top portion) and S-waves (bottom portion) for a double-couple left-lateral strike slip fault[15].

Note the primary and auxiliary fault planes are shown as thick solid lines, and the compressional quadrants are shaded. Due to the ambiguity between the primary and auxiliary planes, the position of the slip and the fault normal vectors in the top portion of the plot could be switched.

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[15] Figure obtained from: Shearer, P. M. (2009). *Introduction to seismology*. 2nd Edition. Cambridge University Press.

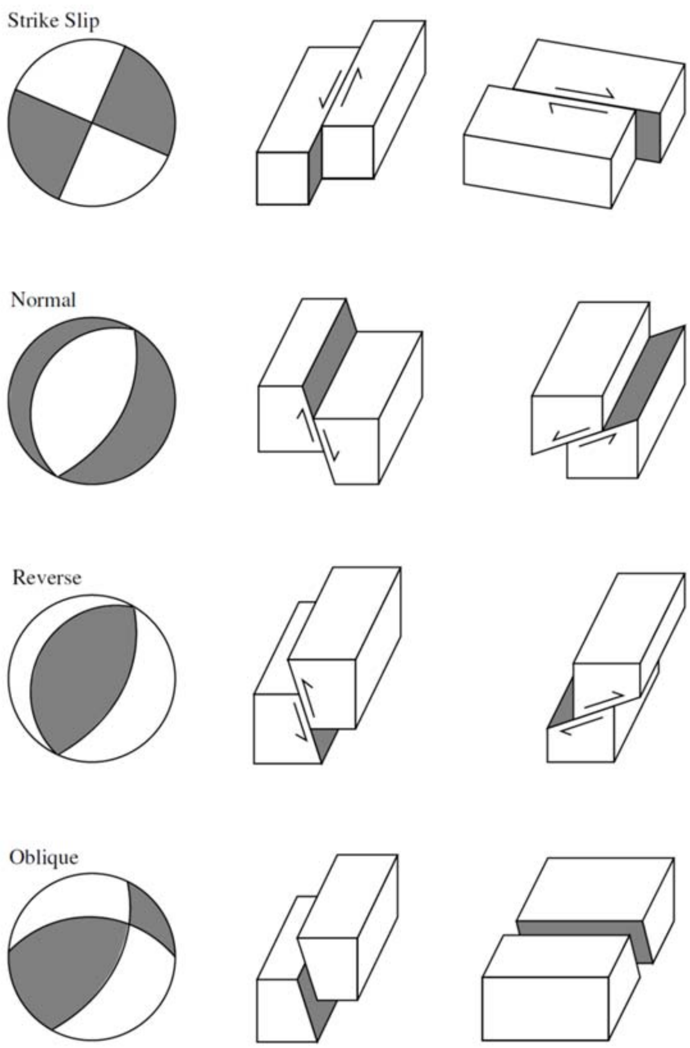

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Figure 19. Example of focal spheres or beach balls and their corresponding fault geometries. The two fault geometries (primary and auxiliary fault planes) are shown to the center and right, respectively[16].

[16] Figure obtained from: Shearer, P. M. (2009). *Introduction to seismology*. 2nd Edition. Cambridge University Press.

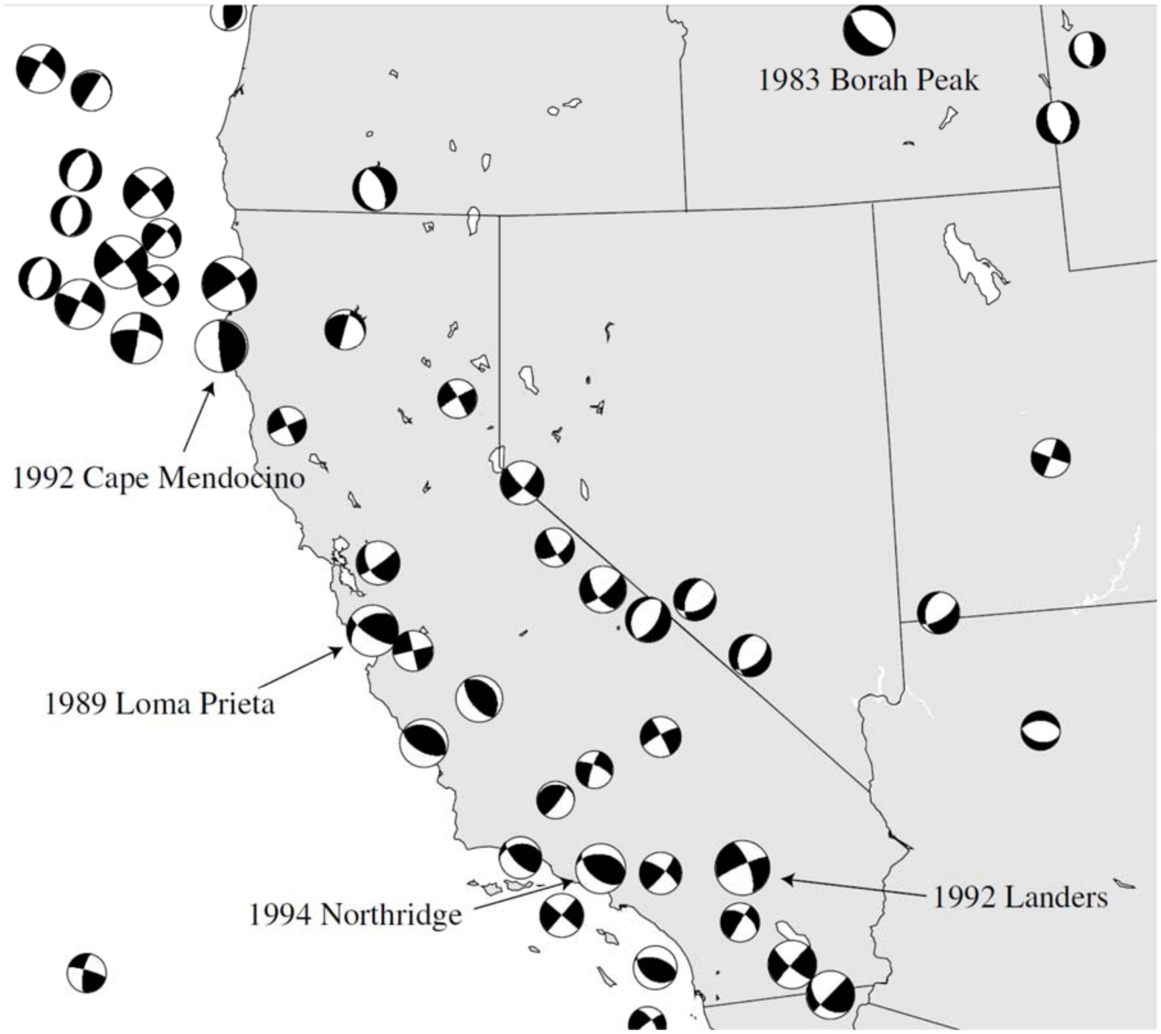


Figure 20. Focal mechanisms from the Global CMT catalogue in the western United States[17].

[17] Figure obtained from: Shearer, P. M. (2009). *Introduction to seismology*. 2nd Edition. Cambridge University Press.

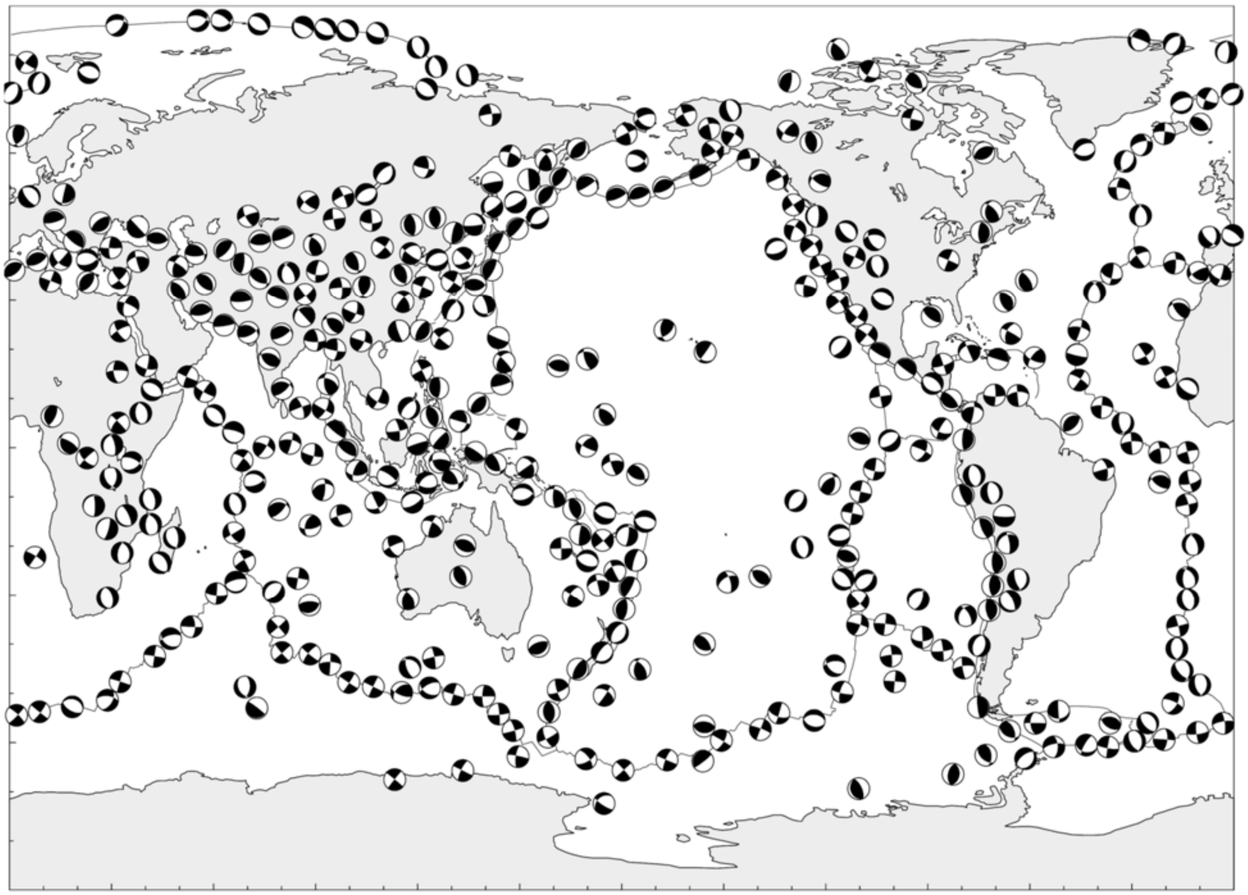
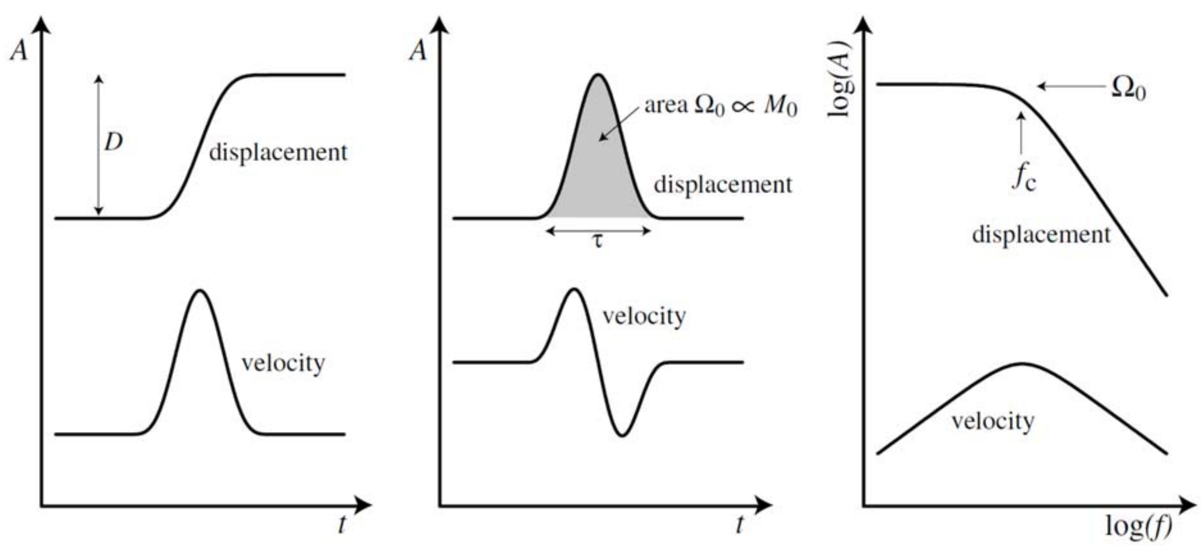


Figure 21. Select focal mechanisms throughout the world[18].

[18] Figure obtained from: Shearer, P. M. (2009). *Introduction to seismology*. 2nd Edition. Cambridge University Press.

Far-Field Pulse Shapes:

1) The resulting displacement of the crust after an earthquake is permanent. Therefore the equivalent body force representation of the displacement field must involve the change in applied forces.
2) Variations of the ____________________ in the near and far-field are shown in Figure 22.
3) In the far-field, the area underneath the pulse (____) is proportional to the scalar seismic moment (____). This area is also termed the long-period spectral level.
4) The far-field displacement spectrum will begin flat at a value of ______ and then roll off at higher frequencies with the corner frequency, _______. The corner frequency is proportional to the pulse width, ______.
5) The scalar seismic moment can be obtained from:



(a) (b) (c)

Figure 22. The displacement and velocity time series for: (a) near-field, (b) far-field, and (c) resulting far-field spectra[19].

[19] Figure obtained from: Shearer, P. M. (2009). *Introduction to seismology*. 2nd Edition. Cambridge University Press.

Directivity Effects:

1) For larger seismic events, the rupture is extended in both time and space.
2) Since the strain developed on the internal structure of the Earth is small, linear ________________________ states that a large fault can be described as a ____________ of the response of individual fault pieces.
3) Therefore by considering two directions of the response, the rupture duration _____ for P-waves in the rupture direction towards the site is:
4) On the contrary, the observed rupture time for the directly away from the site is:
5) Consequently, for direction of rupture – _______________ amplitude and ______________ durations are anticipated.
6) In contrast, _______________ amplitudes and ____________________ durations for pulses radiation in the opposite (away) direction.

Figure 23. Displacement pulses radiated as a result of directivity.

Earthquake Magnitude and Energy Release:

1) For historical reasons, the common known measure of an earthquake is magnitude. These are numerous magnitude scales as related to various largest amplitudes measured on a seismogram.

Richter Magnitude:

2) The most commonly cited magnitude in the news media is the Richter magnitude which is now called the ______________________________.
   a. This was invented in the 1930s by Charles Richter on a then standard Wood-Anderson seismogram for Southern California.
   b. This incorporates a decay rate between the logarithm of amplitude versus epicentral distance.
3) The equation can be written as:

4) This metric is not well implemented today since it developed for California and utilizes an outdated instrument.
   a. Despite this, it is common to use for engineering seismology since the dominant period of the instrument is 0.8 seconds (close to that of numerous structures).
   b. Various estimates and conversions have been derived.

Other Magnitude Scales:

5) A general magnitude scale used is the ______________ magnitude. This can be defined as:

   a. This is done on the first few cycles of the P-wave arrival on short-period vertical-component instruments.

   b. The estimates for the same event will vary between stations due to the radiation pattern, directivity, and local soil conditions by ______________________.

6) Another general seismological measure is the __________________________________ magnitude. This can be defined as:

   a. This is only applicable for ___________________ since surface wave amplitudes are greatly attenuated for deep events.

7) Note both of these aforementioned scales are designed to agree reasonable well with the local magnitude for events in California.

8) However at larger events, _____ and ______ saturate. Therefore a moment magnitude scale was developed.

Seismic Moment and Moment Magnitude:

9) The magnitude of an earthquake is related to the energy released.

10) The size of the event is given by the "moment" of the event. This can be expressed as:

11) A corresponding moment magnitude scale has been down developed based on the seismic moment.

12) Note this has been fit to provide reasonable equivalency at the surface wave magnitude at lower magnitudes and no saturation for larger events.

13) An expression for the moment magnitude is:

14) Herein the moment is measured in Newtons and meters.

15) Selected significant large earthquakes and various magnitudes is presented in Table 1 and Figure 24.

Table 1. Significant observed earthquakes[20]. Note M_0 is in 10^{20} Nm.

Table 9.1: Some big earthquakes (M_0 in 10^{20} N m)					
Date	Region	m_b	M_S	M_W	M_0
1960 May 22	Chile		8.3	9.5	2000
1964 March 28	Alaska		8.4	9.2	820
2004 Dec 26	Sumatra-Andaman	6.2	8.5	9.1	680
1957 March 9	Aleutian Islands		8.2	9.1	585
1965 Feb 4	Aleutian Islands			8.7	140
2005 March 28	Sumatra	7.2	8.4	8.6	105
1977 Aug 19	Indonesia	7.0	7.9	8.3	36
2003 Sept 25	Hokkaido, Japan	6.9	8.1	8.3	31
1994 Oct 4	Shitokan, Kuriles	7.4	8.1	8.2	30
1994 June 9	Bolivia (deep)	6.9		8.2	26
2004 Dec 23	Macquarie Ridge	6.5	7.7	8.1	16
1989 May 23	Macquarie Ridge	6.4	8.2	8.2	20
1985 Sept 19	Michoacan, Mexico	6.5	8.3	8.0	14
1906 April 18	San Francisco		8.2	7.9	10
2008 May 12	Eastern Sichuan	6.9	8.0	7.9	9
2002 Nov 3	Denali, Alaska	7.0	8.5	7.8	7
2001 Nov 14	Kokoxili, Kunlun	6.1	8.0	7.8	6
1992 June 28	Landers, California	6.2	7.6	7.5	2

[20] Table obtained from: Shearer, P. M. (2009). *Introduction to seismology*. 2nd Edition. Cambridge University Press.

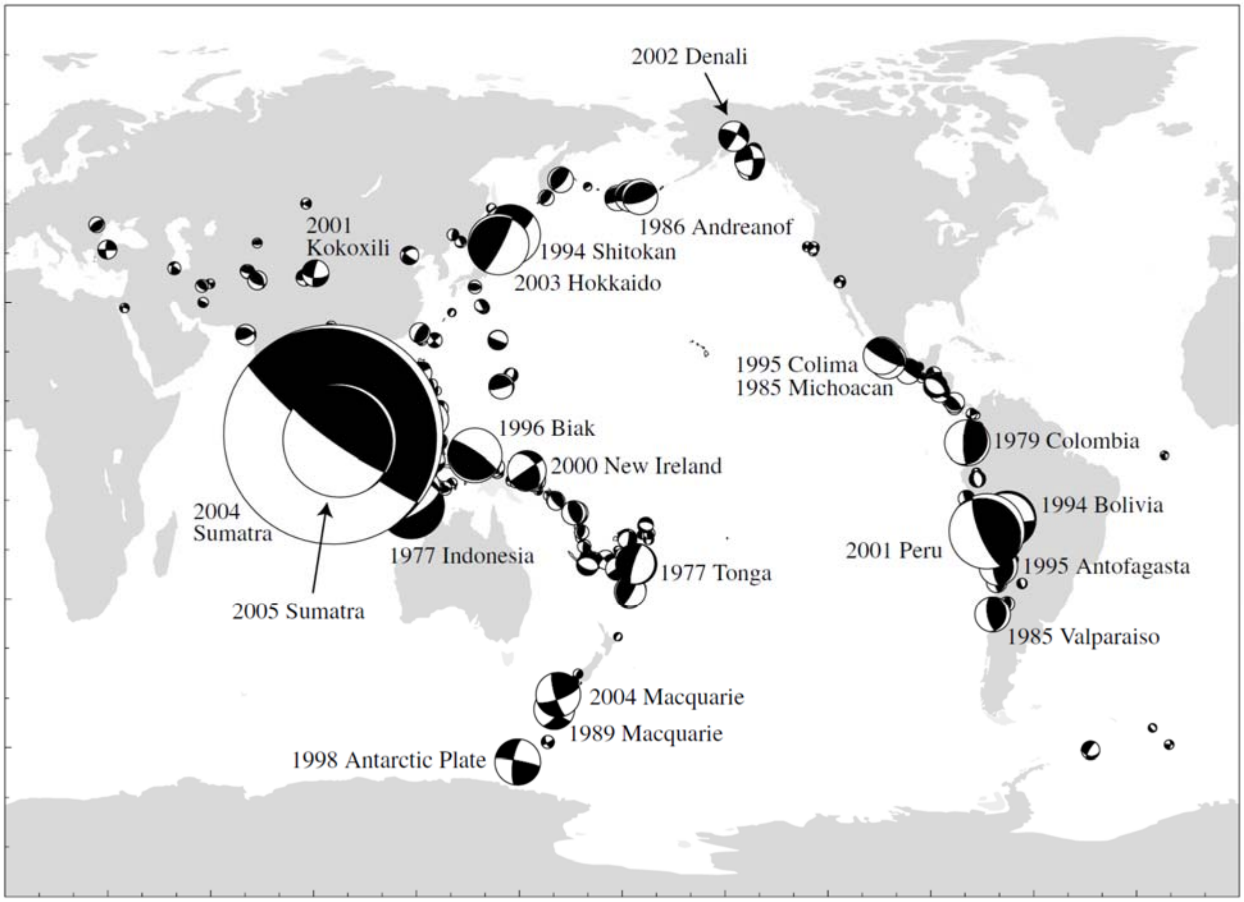


Figure 24. The focal mechanisms plotted proportional to the seismic moment[21].

Earthquake Magnitude and Frequency Relationship:

1) As one may envision, small earthquakes occur much more ______ than larger earthquakes.
2) This relationship can be quantified in magnitude-frequency relationships.
3) One empirical formula was developed by ____:

4) Where ____ is the number of events of magnitudes equal or greater than ____.
5) The parameter of ____ describes the total number of earthquakes.

[21] Figure obtained from: Shearer, P. M. (2009). *Introduction to seismology*. 2nd Edition. Cambridge University Press.

6) The parameter of ____ is the "b-value" the measures relative number of large quakes compared to smaller quakes. This value is generally between 0.8 and 1.2 for a wide variety of regions and magnitude scales. However it is often assumed to be unity.
7) When comparing the magnitudes and the energy released:
   a. The seismic moment increases by ______________ for every unit increase of M_w.
   b. The number of events only decrease by a factor of ____________ for every unit increase of M_w.
8) Therefore, the seismicity of a region is dominated by the ___________________________, rather than an accumulated sum of numerous smaller events.
9) However arbitrarily large earthquakes are not of a concern since the aforementioned equation does not have validity since there is a finite existence of Earth's faults.

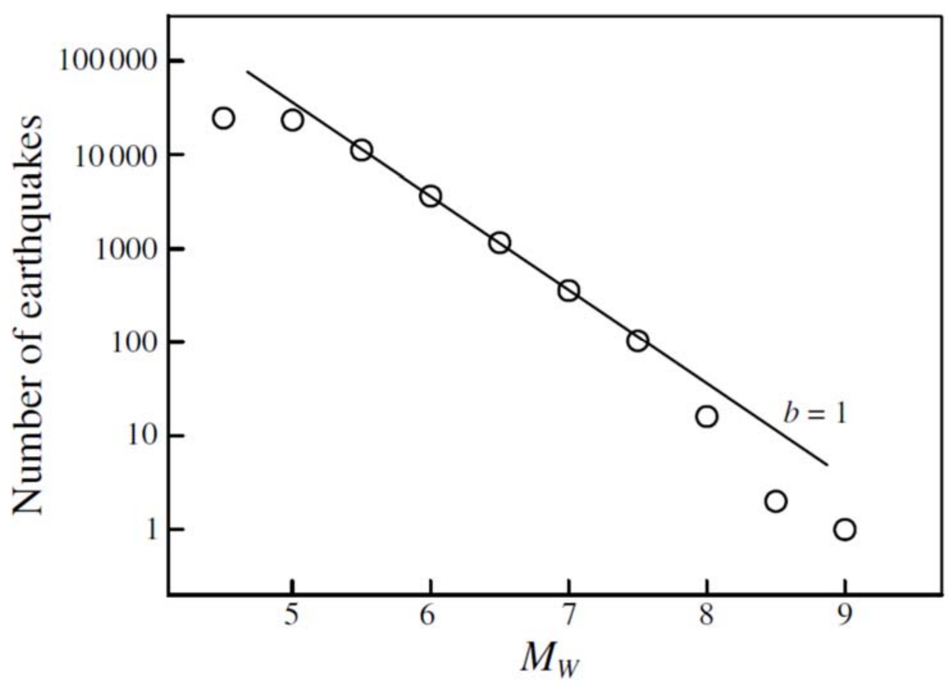


Figure 25. The number of earthquakes for the global CMT catalog from 1976 to 2005, compared to a power law decay with a b-value of unity[22].

[22] Figure obtained from: Shearer, P. M. (2009). *Introduction to seismology*. 2nd Edition. Cambridge University Press.

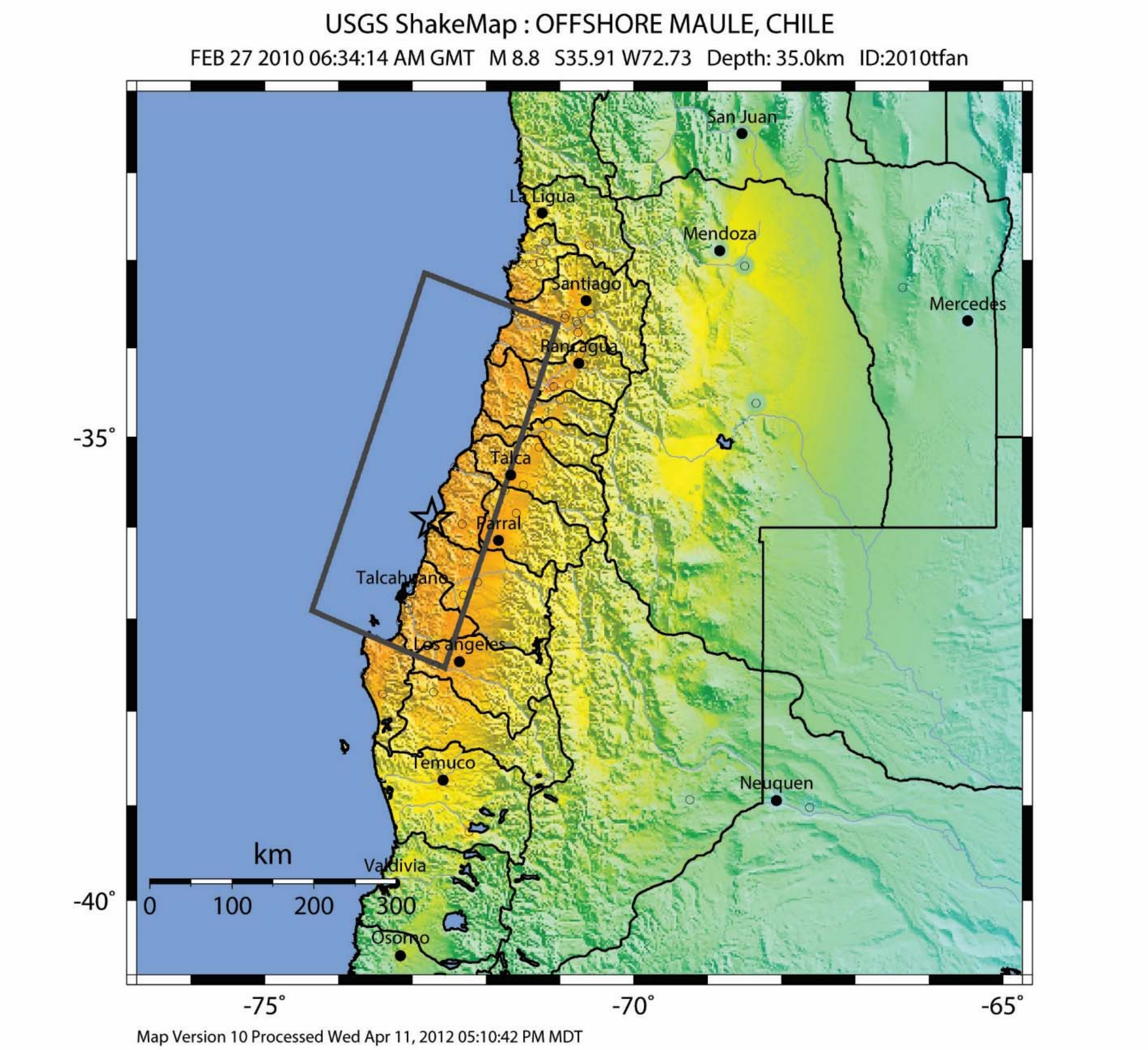
Earthquake Intensity:

1) The earthquake intensity at a particular site depends on numerous factors:
   a. ____
   b. ____
   c. ____
   d. ____
   e. ____
2) The most commonly used intensity scale is the ________________________________ as originally developed by Wood and Neumann in 1931 (Table 2).
   a. Other intensity scales exist.
   b. EMS = ________________________ macroseismic scale.
3) This scale is from I to XII and it based on _____________________ of the effects of an earthquake on the population, buildings, and ground deformations at a particular site.
4) Note this scale is __________________________ and influenced by the quality of structures at a particular area.
5) When comparing regional values of intensity, areas of equal intensity can be shown on a ______________________________.
6) An example isoseismal plot is shown for the 2010 Chile earthquake in Figure 26.

Table 2. The Modified Mercalli intensity scale[23].

Table 9.2: The modified Mercalli scale, adapted from the abridged version in Bolt (1993).	
I	Not felt except by a few under especially favorable circumstances.
II	Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.
III	Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Parked cars may rock slightly. Vibration like passing of truck. Duration can be estimated.
IV	During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed, walls make creaking noise. Parked cars rocked noticeably. (0.015–0.02 *g*)
V	Felt by nearly everyone, many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles and other tall objects sometimes noticed. (0.03–0.04 *g*)
VI	Felt by all; many frightened and run outdoors. Some heavy furniture moved, a few instances of fallen plaster or damaged chimneys. Damage slight. (0.06–0.07 *g*)
VII	Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight-to-moderate damage in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by people driving cars. (0.10–0.15 *g*)
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 frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Disturbs people driving cars. (0.25–0.30 *g*)
IX	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken. (0.5–0.55 *g*)
X	Some well-built wooden structures destroyed; with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed over banks. (> 0.6 *g*)
XI	Few, if any, masonry structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.
XII	Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air.

[23] Table obtained from: Shearer, P. M. (2009). *Introduction to seismology*. 2nd Edition. Cambridge University Press.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.1	0.5	2.4	6.7	13	24	44	83	>156
PEAK VEL.(cm/s)	<0.07	0.4	1.9	5.8	11	22	43	83	>160
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Wald, et al.; 1999

Figure 26. USGS isoseismal plot for the 2010 Mw 8.8 earthquake offshore Chile[24].

[24] Figure obtained from: http://earthquake.usgs.gov/earthquakes/shakemap/global/shake/2010tfan/

Earthquake Triggering and Aftershocks:

1) Models based on the ____ have been proposed to account for the temporal dependence on earthquakes (Figure 27).
2) The ________________________________ is the time between subsequent earthquakes.

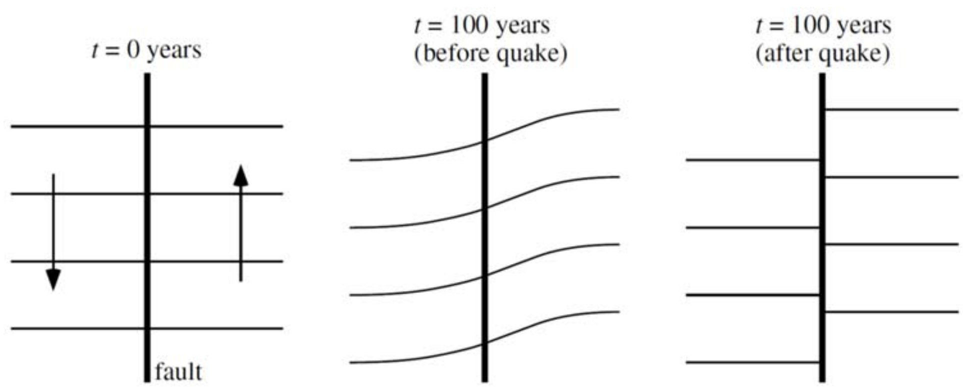


Figure 27. An elastic rebound model for earthquakes. Herein a left-lateral strike slip earthquake releases the slowly developed stress and strain that had built up along the rupture zone[25].

3) Examples of predictable models include :
   a. Completely predictable – the recurrence interval is known due to a stick-slip behavior since the static friction, dynamic friction, and the pull rate are all "known".
   b. ____________ predictable – the time of occurrence can be predicted, but the dynamic friction varies randomly between events.
   c. ____________ predictable - the amount of slip for an event at any time can be predicted, however the static friction may randomly vary between events.
4) These simplistic models assume that the individual fault segments can be treated in _________________ and a characteristic earthquake will occur at fairly regular intervals.
5) A failed example of these models was noted of the San Andreas Fault at Parkfield, California. Regular seismic events occurred at 1857, 1881, 1901, 1922, 1934, and then 1966. The prediction in 1984 was for a body-wave magnitude event of about 6 before 1993.

[25] Figure obtained from: Shearer, P. M. (2009). *Introduction to seismology*. 2nd Edition. Cambridge University Press.

a. However, this expected earthquake did not occur until 2004.
b. The erroneous assumption that the 1934 was a premature triggering of the expected 1944 earthquake.

6) Actually in reality, faults are not isolated and are representative of a very complex and interconnected series of faults.

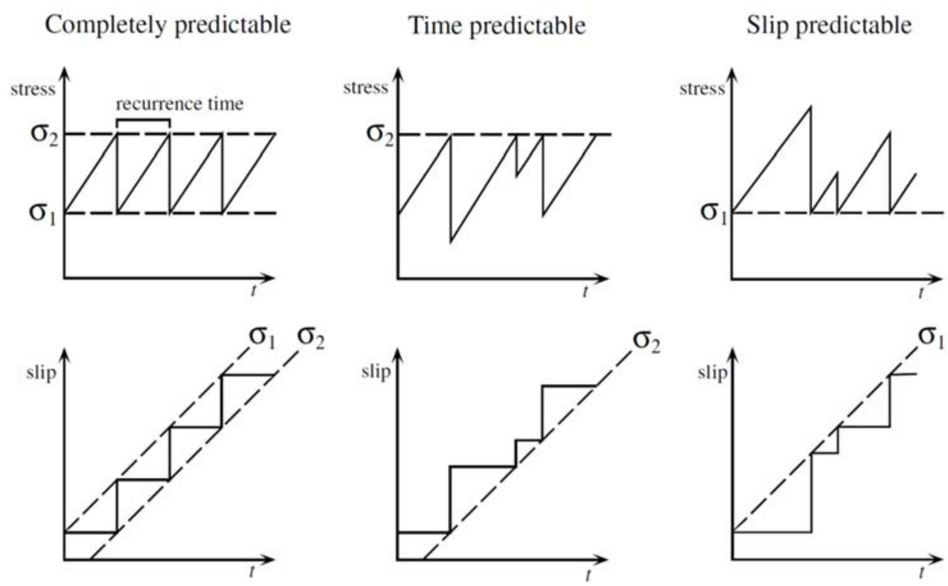


Figure 28. Simplistic models of recurring earthquakes models[26].

7) On type of non-random earthquakes is the existence of ______________________________ after large earthquakes.
8) It is noted that the exact timing of individual events is still very random, an increased rate of seismic activity is observed that is both temporally and spatially correlated with the mainshock.
9) The seismicity rates with time following a power-law relationship as developed by Omori (1984). Omori's law can be written as:

[26] Figure obtained from: Shearer, P. M. (2009). *Introduction to seismology*. 2nd Edition. Cambridge University Press.

10) Earthquakes are through to trigger such aftershocks due to the dynamic stress changes at large distances. It can be argued as well as to the influence of near-field aftershocks.
11) Omori's law does not describe the ______________________________ of the aftershocks or their spatial distribution.
12) The magnitude distribution can be assessed by analyzing the Gutenberg-Richter magnitude-frequency law.

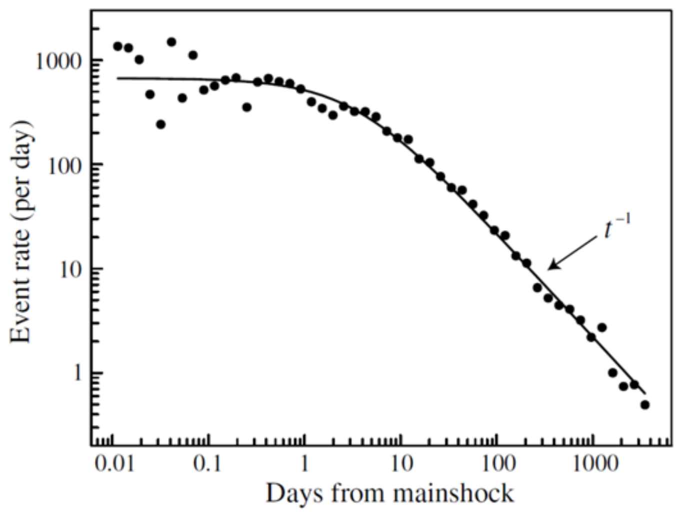


Figure 29. Aftershock rate for the 1994 Northridge California earthquake as a function of time[27]. The line illustrates Omori's law for K = 2230, c = 3.3 days, and p =1.

[27] Figure obtained from: Shearer, P. M. (2009). *Introduction to seismology*. 2nd Edition. Cambridge University Press.