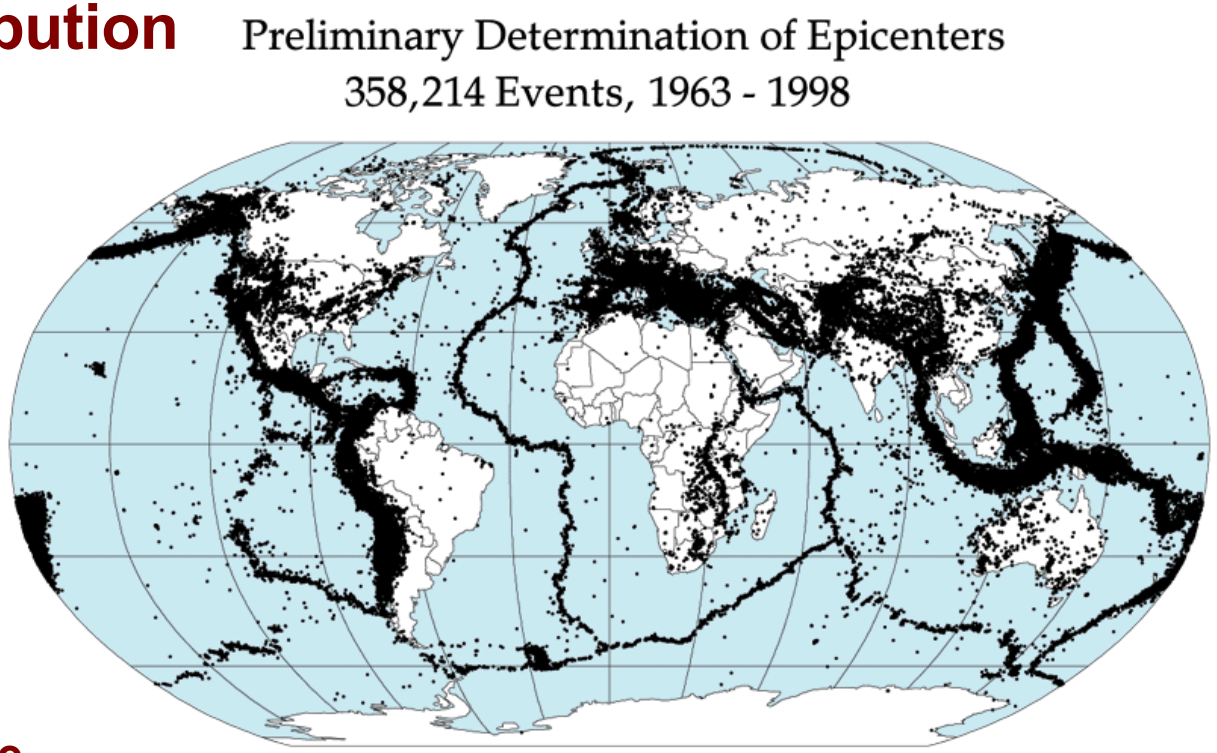
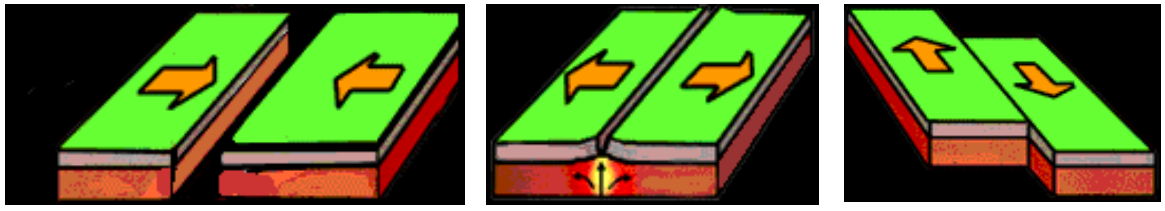
Physics of Earthquakes

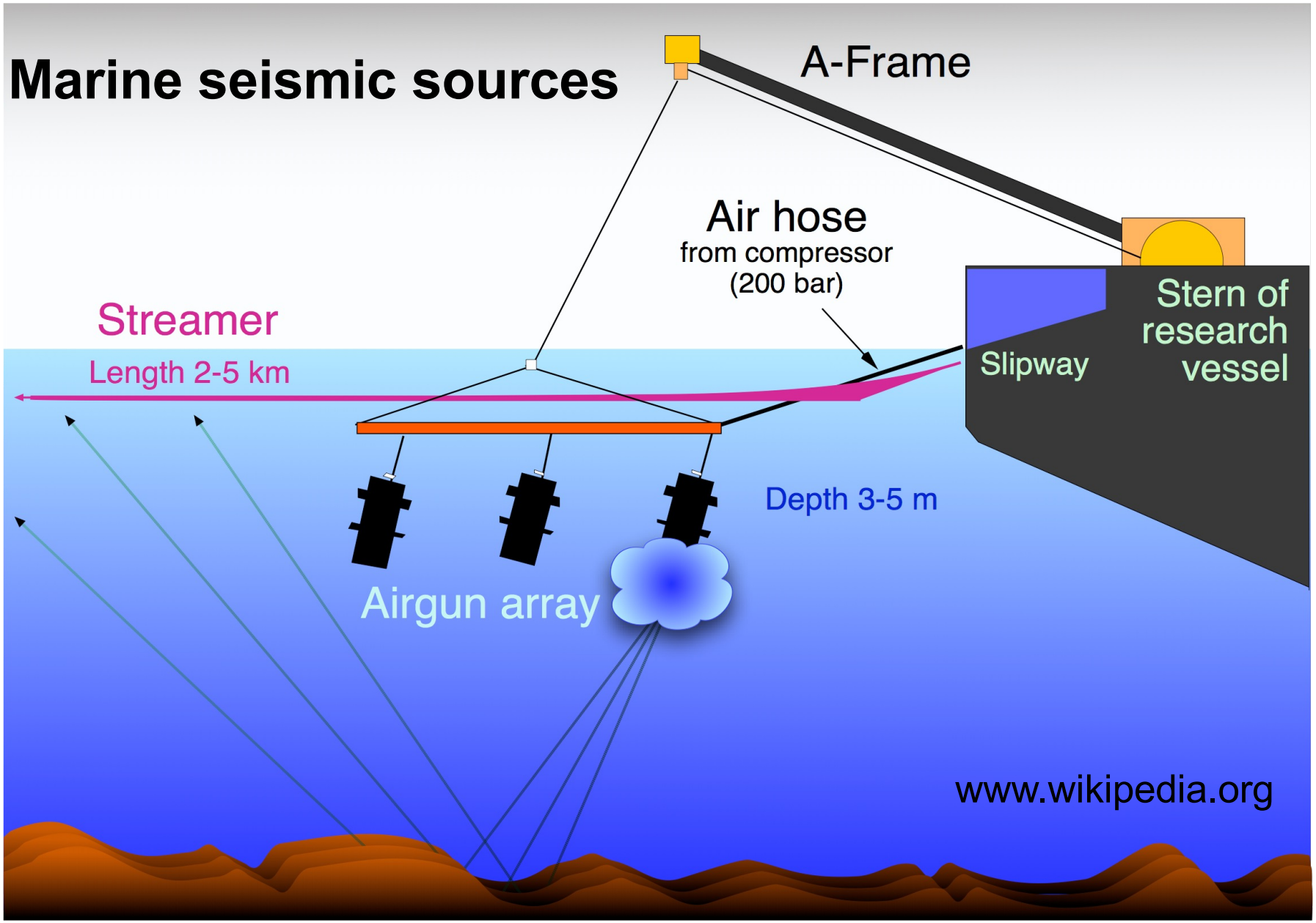
Earthquake Distribution

- concentrated at plate boundaries – **interplate earthquakes**
- narrow zones along MOR's and oceanic transform faults
- wider region at convergent margins continental plate boundaries – **plate boundary zone** or **diffuse plate boundary**
- also have **intraplate earthquakes**





(http://en.wikipedia.org/wiki/Earthquake)



Air gun arrays: 1. use multiple airguns to minimize reverberation (related to bubbles)
2. Recover all frequencies (10s of MPa pressure).

Sparkers, Pingers, Boomers

- high frequency, electrically produced source

- order of increasing strength (pingers, sparkers, boomers, airguns).

sample ‘squid’ sparker



ACD Technology

PROS:

- well-defined, repeatable, inexpensiv

CONS:

- high frequency (10-100,000 Hz) → rapid attenuation

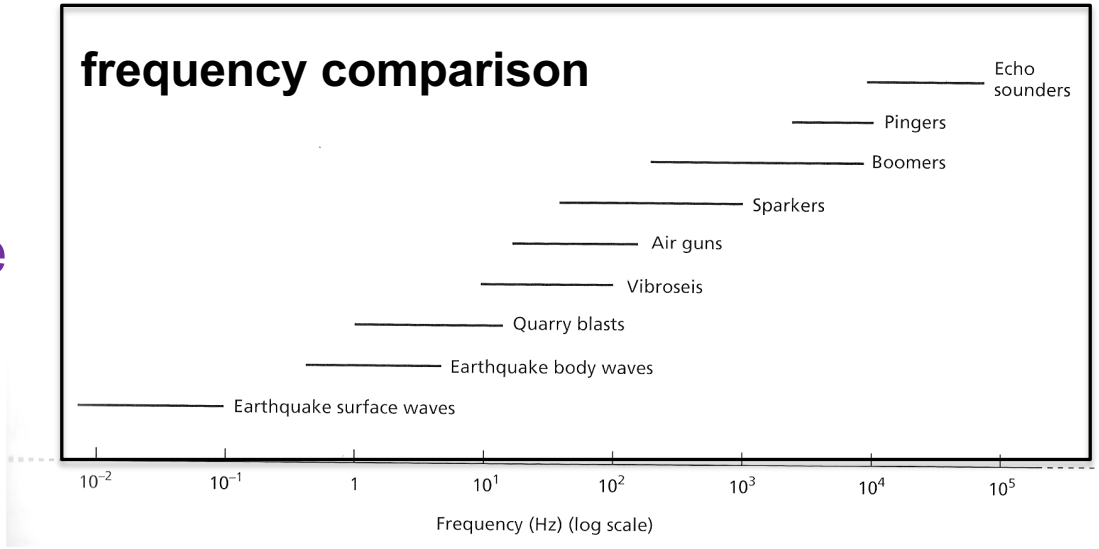
- good for shallow seafloor mapping / surveying

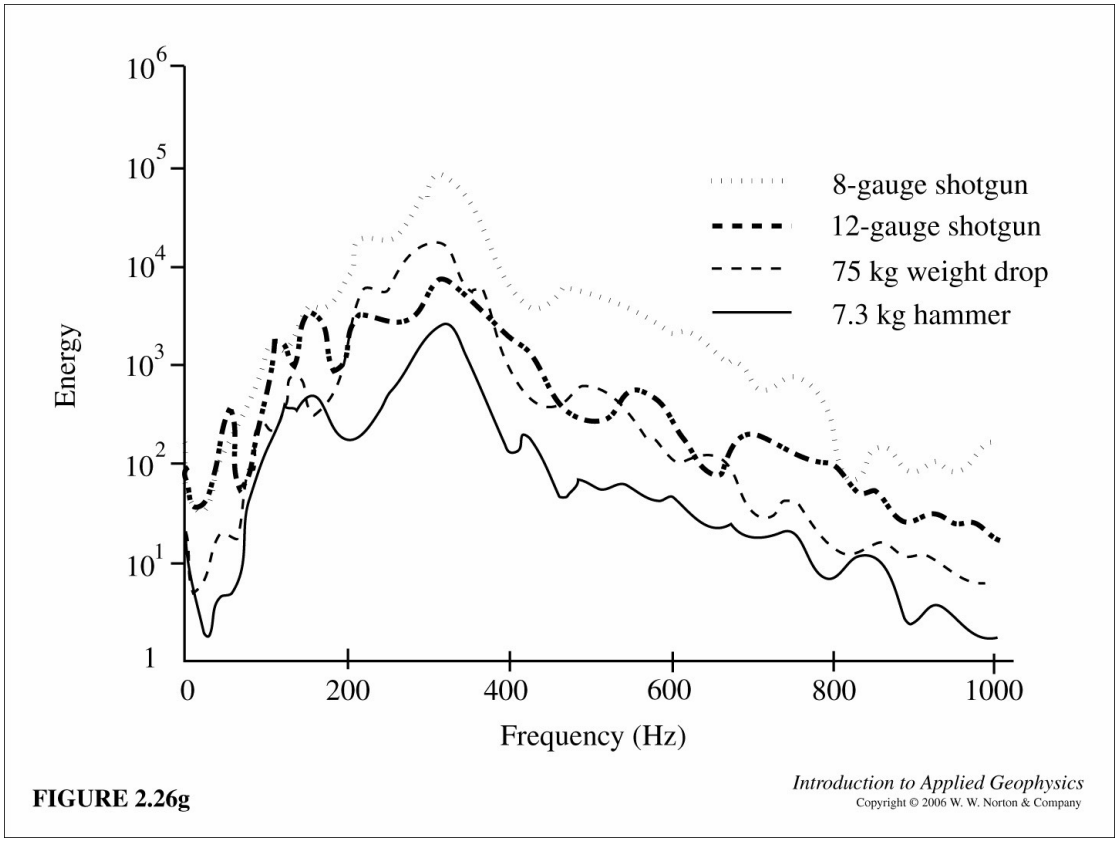
(upper ~1m of seafloor)

Seismic Sources

Seismic sources cover wide frequency range

(Kearey et al., 2002)





Above: frequency ranges of seismic sources. Earthquakes are mainly sensitive to frequencies between 0.1 to 10 Hz, while marine seismic sources are strong at frequencies higher than 15 Hz.

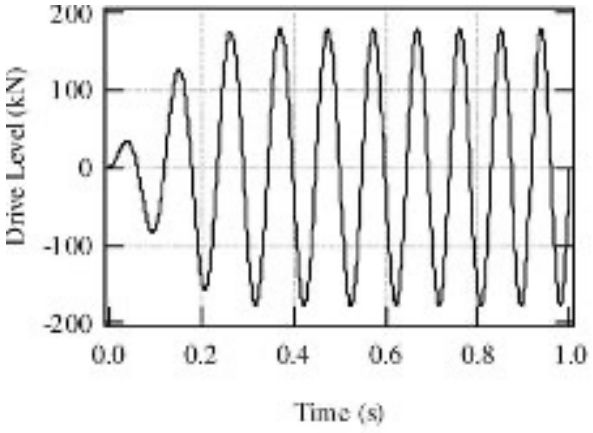
Left figure: 8-Gauge shotgun has strong amplitudes at a wide range of frequencies, which make it a very good source of seismic wave generation.



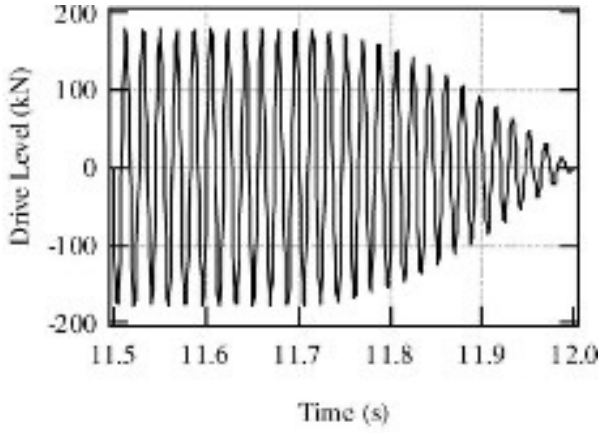
*** Vibroseis trucks, also known as ‘dancing elephants’,**

*** Generates signals from a range of frequencies. Commonly used in oil/gas surveys.**

Vibroseismic signals



a) beginning of sweep

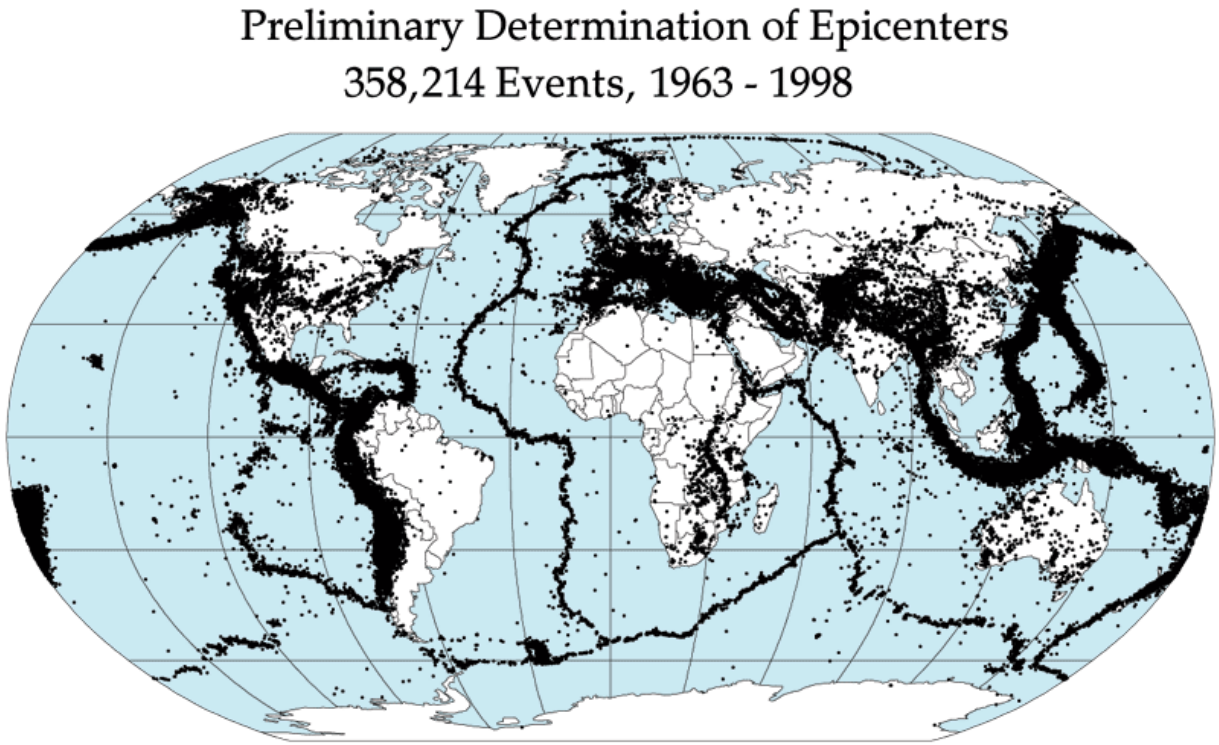


b) end of sweep

From https://www.researchgate.net/figure/Typical-Vibroseis-Sweep-8-56-Hz-12-s-upsweep-03-s-taper_fig2_228077784

Importance of earthquakes

- delineate plate boundaries
- fault slip can be used to determine relative plate motions
- source of seismic waves that illuminate the internal structure of the Earth
- societal hazard (shaking and possible tsunamis)



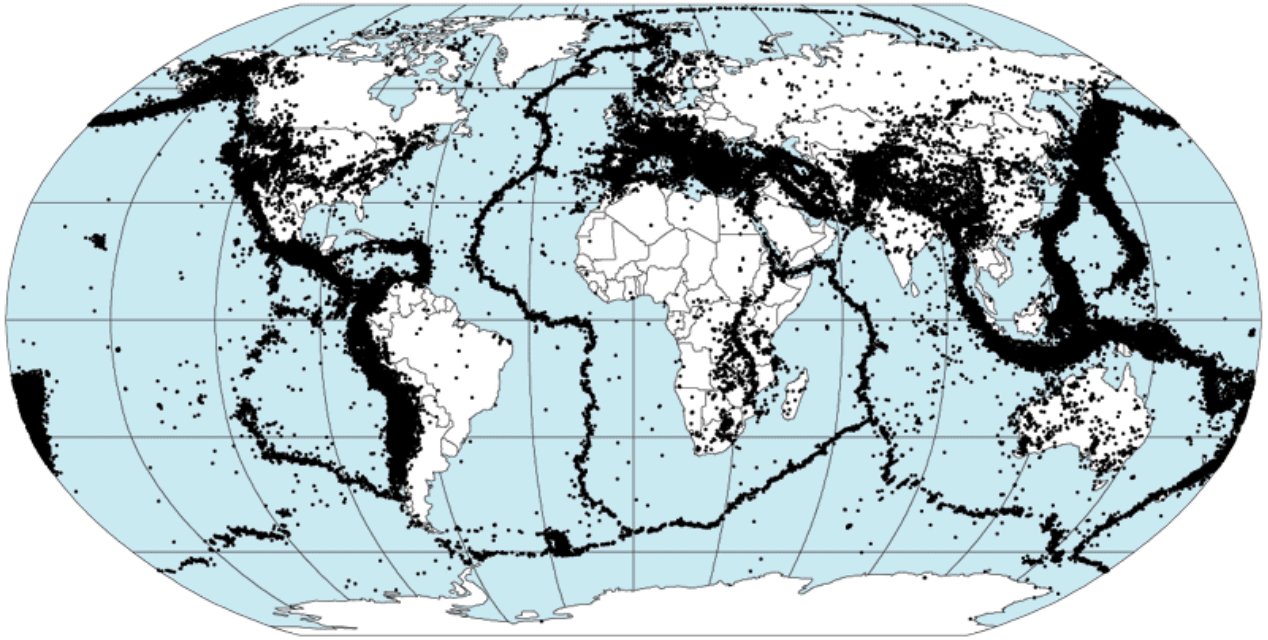
(http://en.wikipedia.org/wiki/Earthquake)

Locating Earthquakes

Hypocenter (focus) – location at which earthquake rupture begins
– rupture has finite size – location is usually the point where rupture started **(latitude, longitude, depth)**

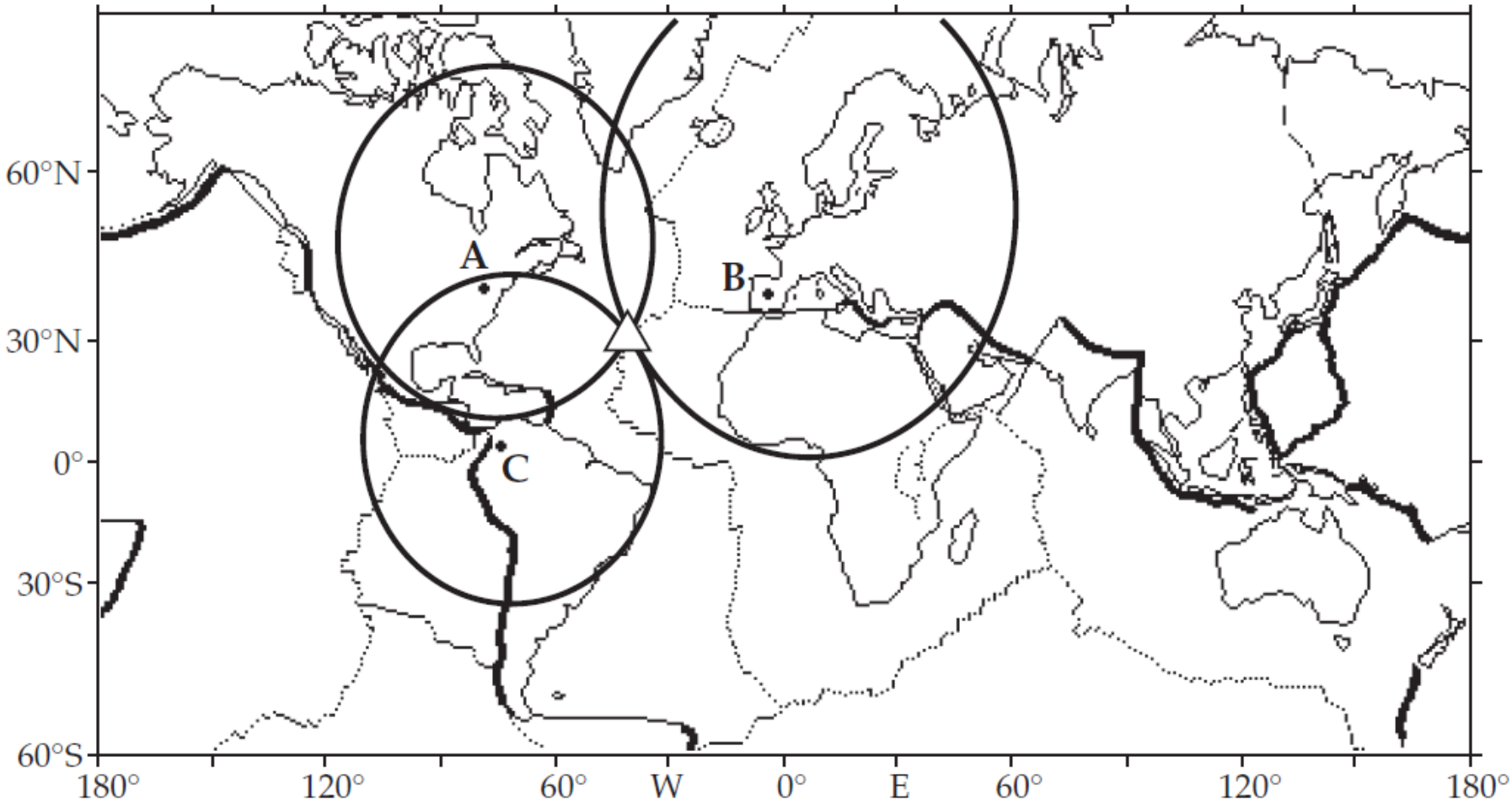
Epicenter – point on the Earth's surface directly above the hypocenter
(latitude, longitude)

Preliminary Determination of Epicenters
358,214 Events, 1963 - 1998



Location of the epicenter of an earthquake

triangulation

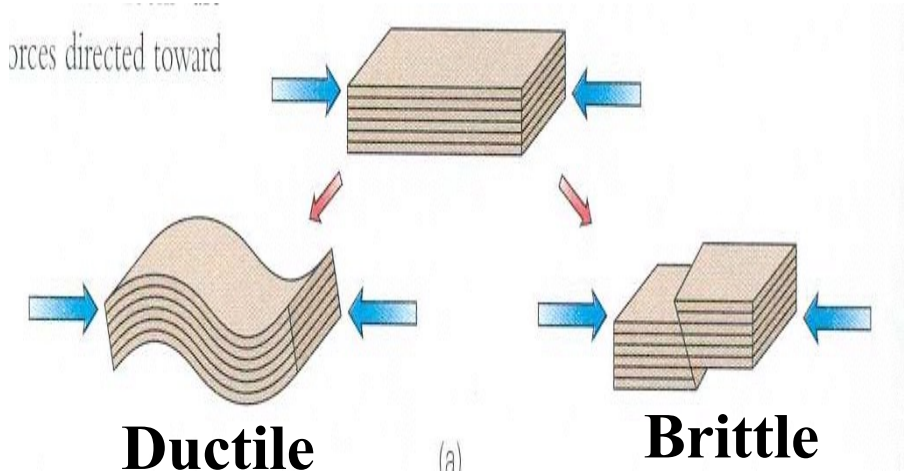


Lowrie, 2007

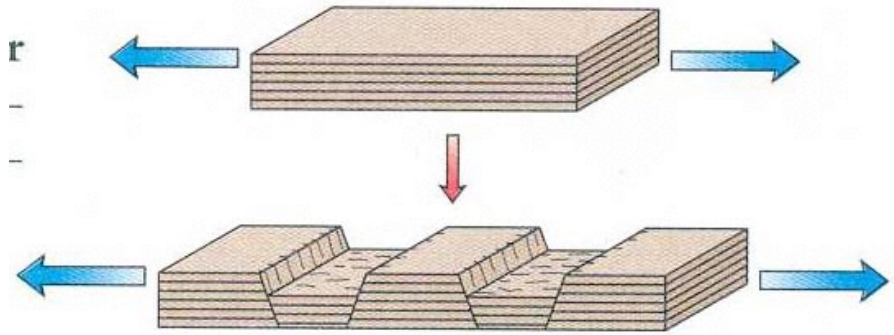
Triangulation is used to determine the hypocenter location. 3 stations are technically sufficient in finding a mutually agreeable location to 3 distant stations

Seismic Sources

Compressional stress induces shortening and/or *reverse faulting (e.g., subduction zones at depths < 100 km, many land earthquakes)*

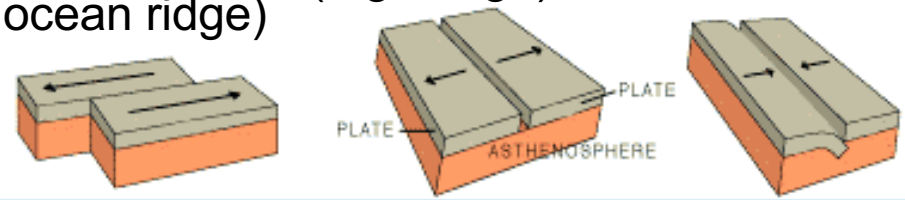


Extensional stress induces normal faulting (e.g., subduction zones at mid depths, many land earthquakes)



Transforms
(near ocean ridge)

Extensions
(e.g., ridge)



Convergence
(subduction boundaries

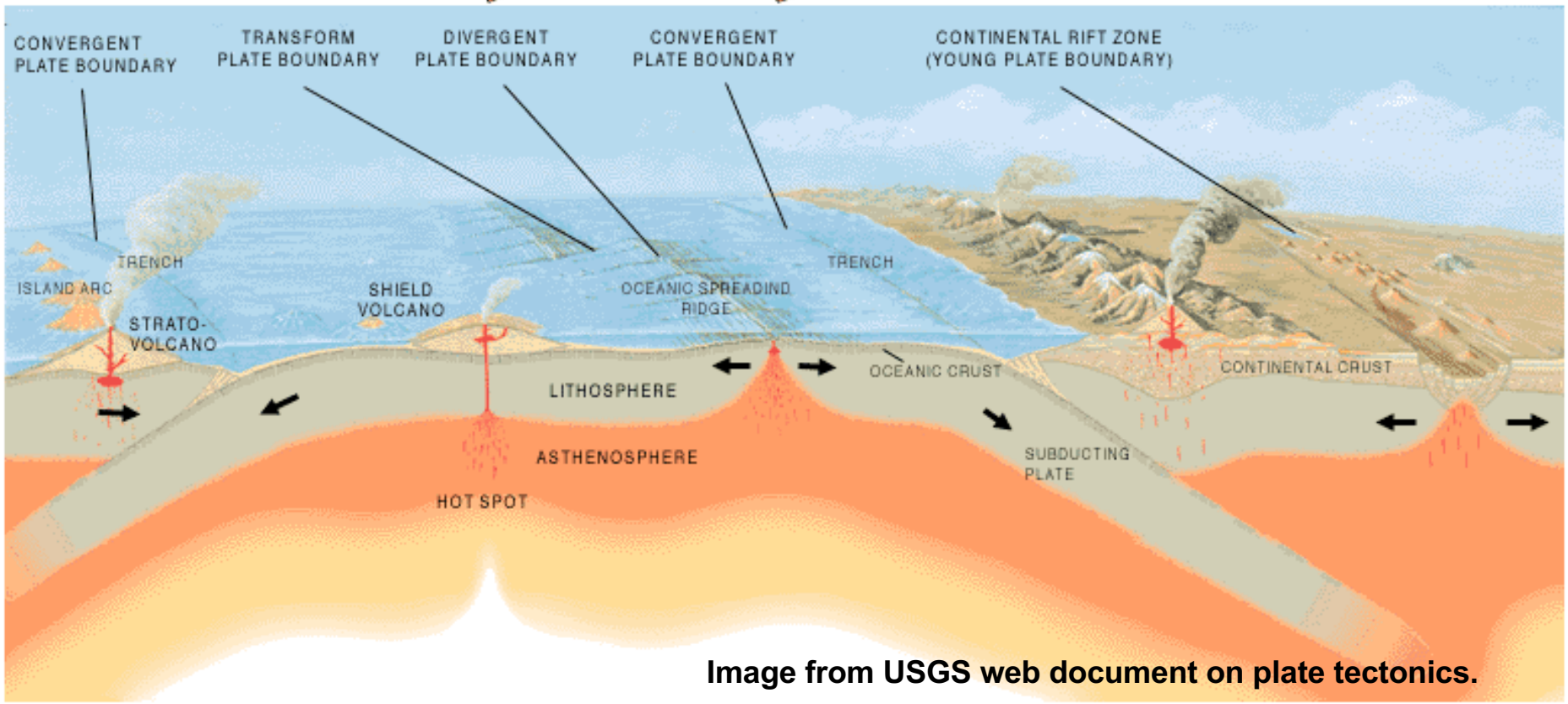
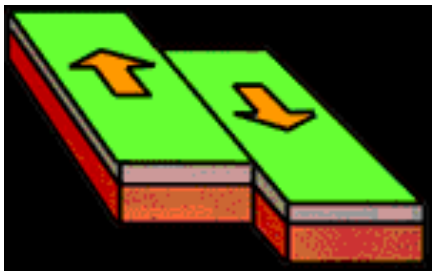


Image from USGS web document on plate tectonics.

'Dewatering': At ~100-200 km depths, ocean sediments dewater within subducting plate due to high pressure → water lowers melting temperature of surrounding rocks → melt rises quickly and melts more → melt/partial melt comes out of Arc volcanos

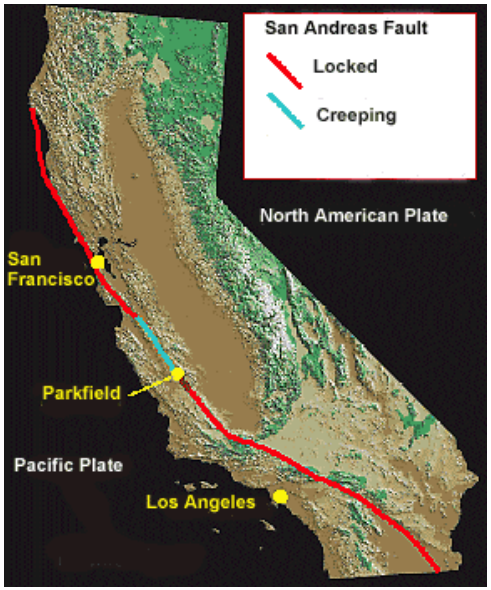


Conservative Plate Margins

(strike-slip faults)

San Andreas Fault

- plate boundary between North American and Pacific Plates
- developed in the last 20 Ma as mid-ocean ridges collided with the subduction zone along western North America
- actually a series of sub-parallel faults

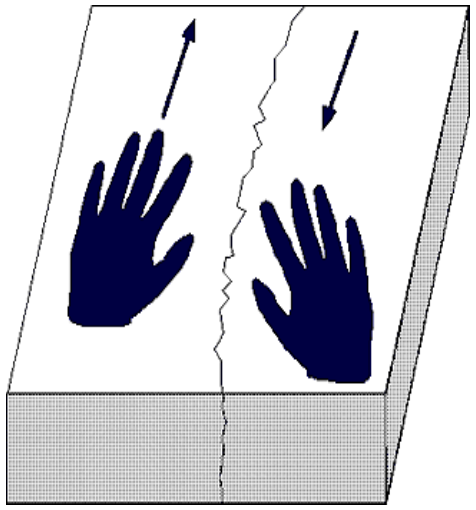




(http://geomaps.wr.usgs.gov/socal/geology/geologic_history/san_andreas_history.html)

transform faulting: horizontal sliding plates or blocks, near-vertical dip angle

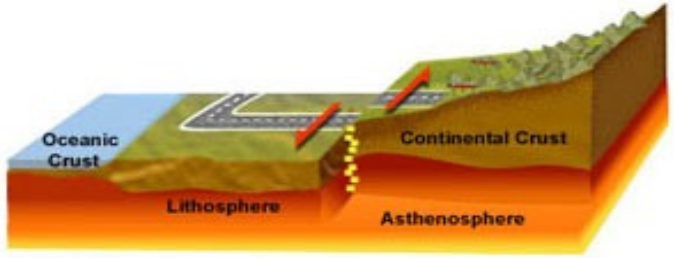
Simple illustration



Part of San Andreas Fault

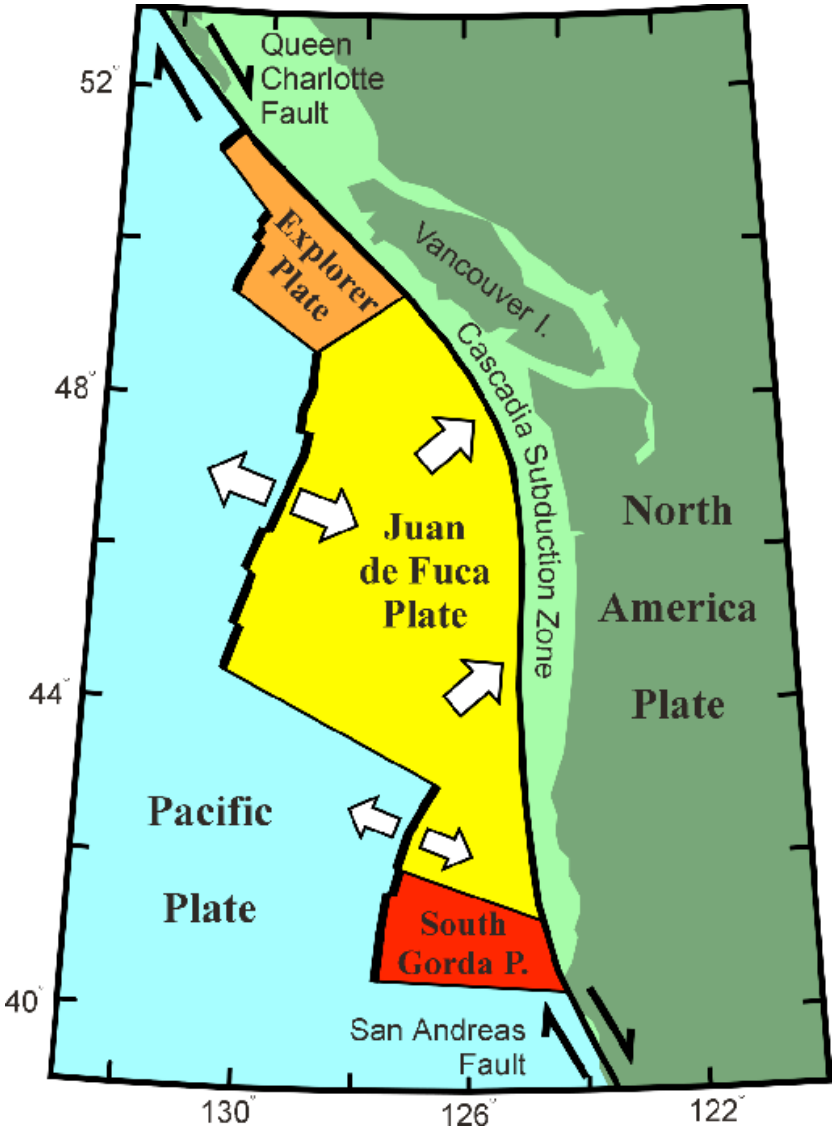


Note: lots of faults are actually "buried" (no fault line on the Earth's surface.

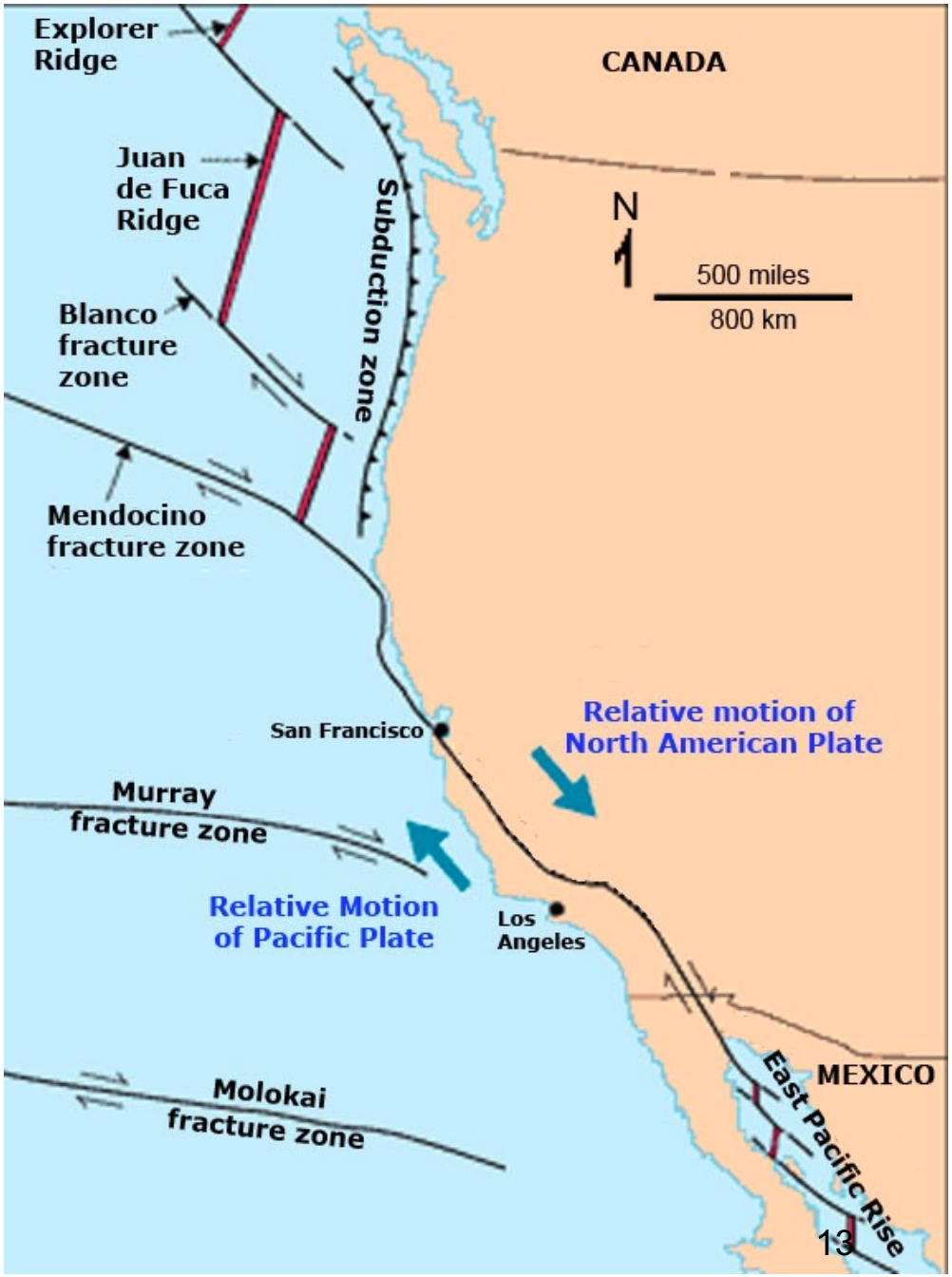


These land 'transform' earthquakes are called 'strike-slip faults'

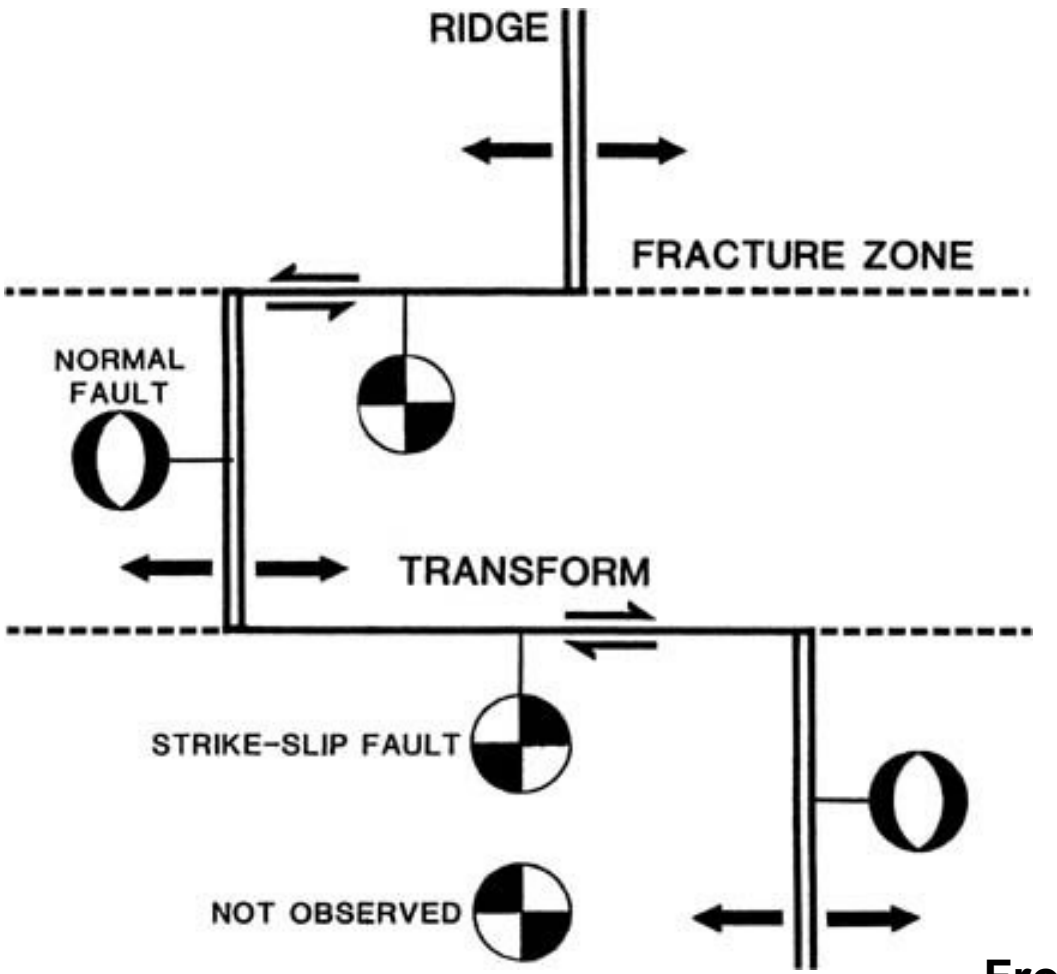
Ocean transform faults



Fracture zones are often failed transform faults



Mechanics of Ocean Transform Faults



From Stein & Woods

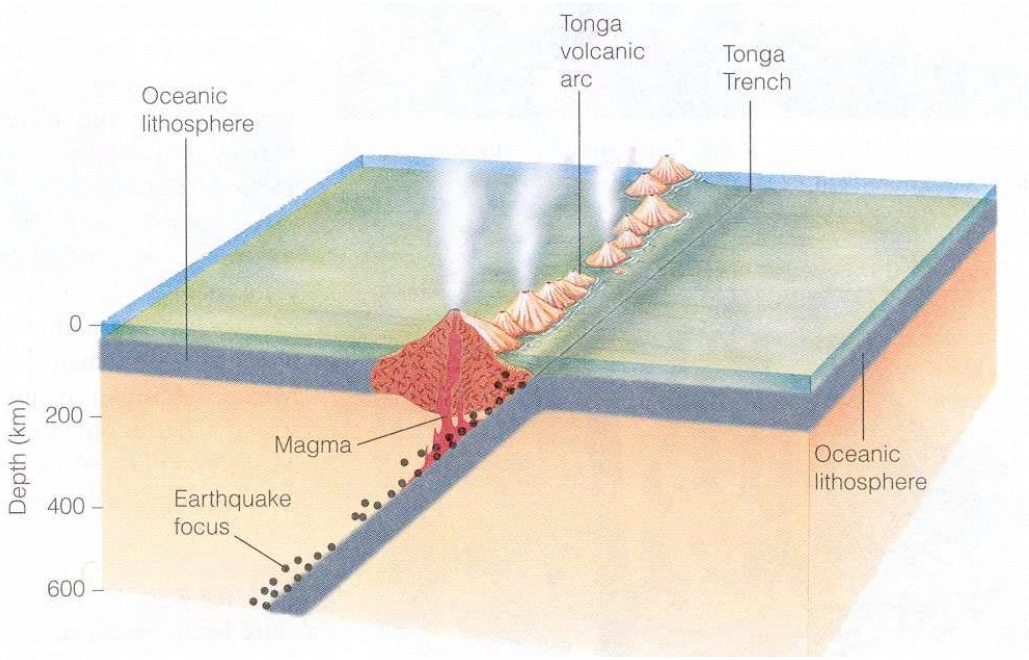
Key: Plates diverge at offset ridge segments, which causes horizontal sliding motion along fraction zones (old, failed/abandoned ridges)

Subduction Earthquakes

Fig 1: Earthquakes can be caused by both compressional and extensional forces near subduction boundaries.

Shallow (< 60 km):
compressive forces between two colliding plates, results in reverse or thrust (<30 deg dip angle reverse) faulting earthquakes.

Intermediate (100-300 km):
After overcoming the initial compressive stage, slab drops due to its weight, cause 'stretching' (also known as 'down dip tension' at intermediate depths.



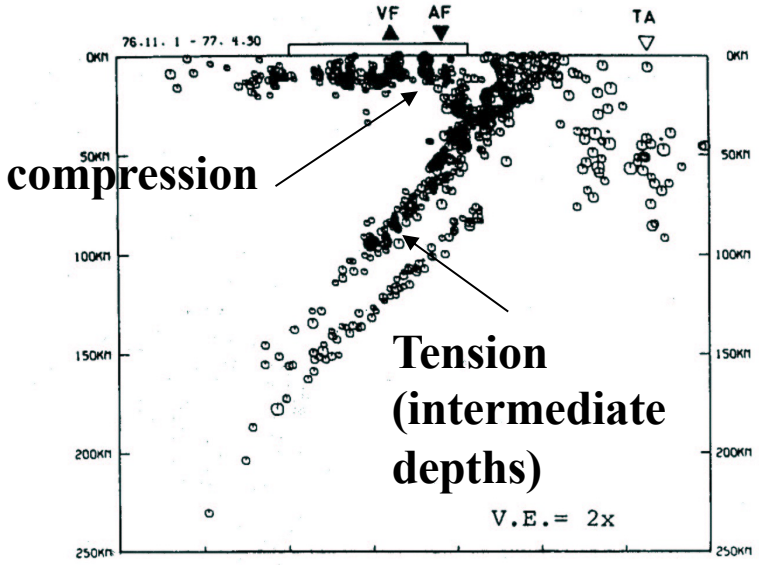


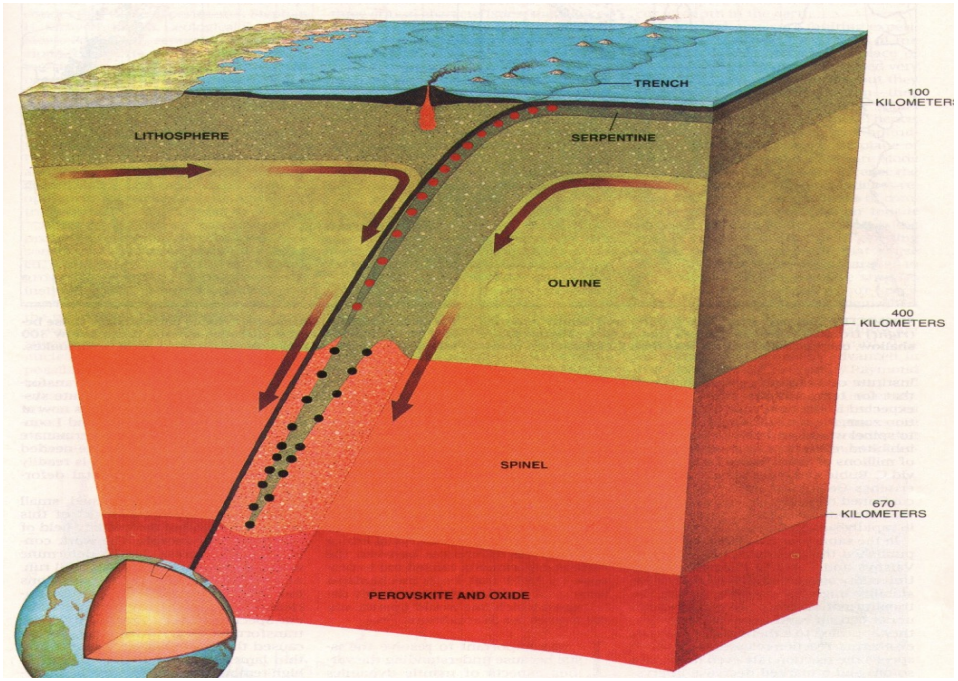
Figure 4.16. The Wadati-Benioff zone under northern Honshu, Japan, showing two parallel planes of earthquake foci. VF indicates the volcanic front, at the centre of the land area. Reproduced by permission from Hasegawa (1989). For a colour plot with greater detail see Hasegawa et al. (1991).

Fig 2: double seismic zone from 1. surface contact of the slab, 2. base of the crust within subducting slab.

Deep Earthquakes

Deepest known earthquakes: Near Tonga region, down to ~680 km, at the base of upper mantle.

<u>Why not below 680</u>*:* change of mineralogy and overwhelming pressure prevents the existence of faults



***Phase change hypothesis*: Sudden phase change of olivine can cause a major drop of volume. Therefore "collapse" of space could induce earthquakes. This is not well understood. The faulting types could be normal or reverse/thrust (eometimes even transforms)**

Summary: Depth distribution of earthquakes

- mostly < 33 km, except at convergent margins (subduction zones)

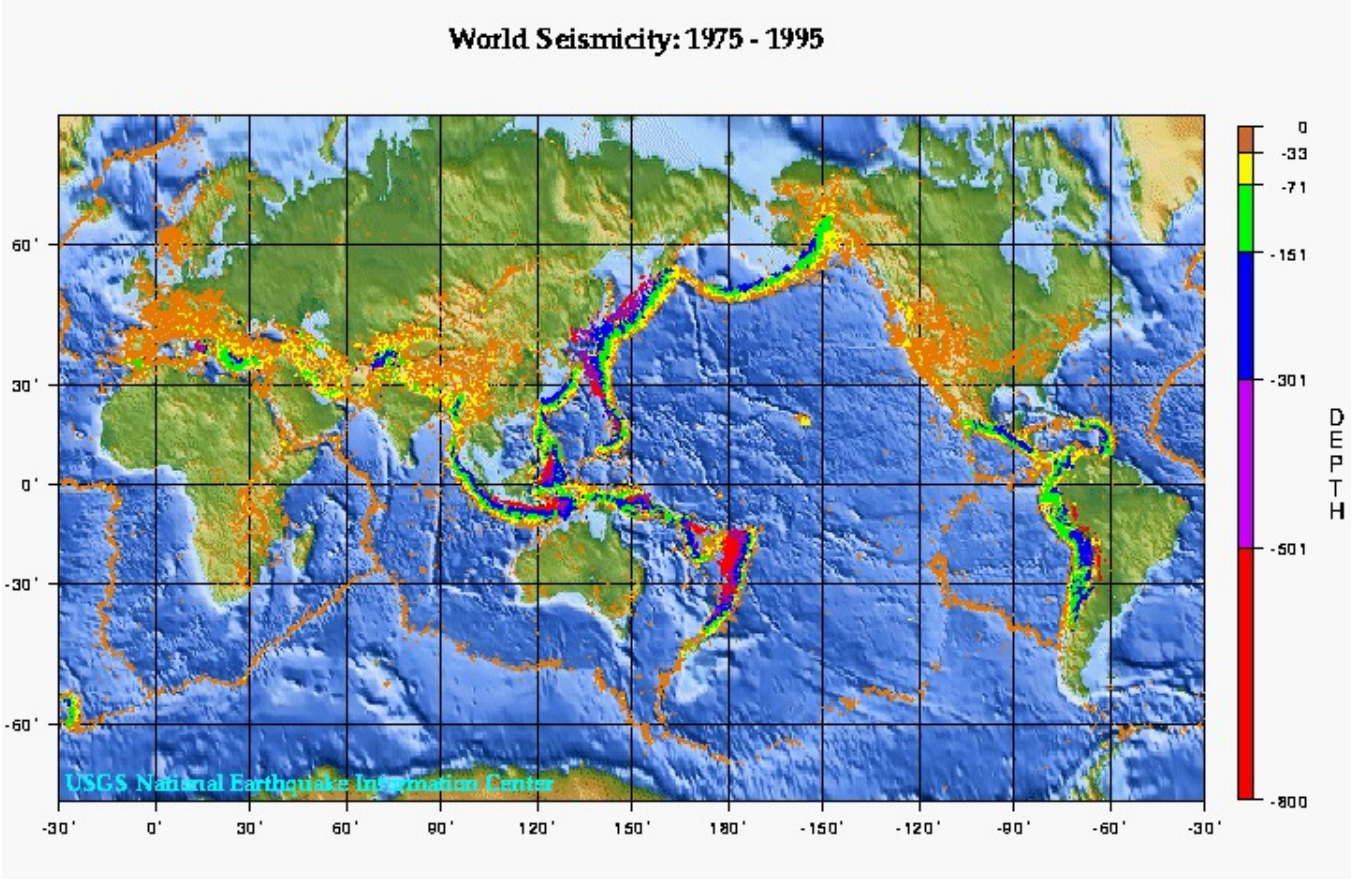
- earthquakes = brittle failure

- brittle behaviour at temperatures < 250 to 400° C for most rocks

- at higher T, rocks deform through ductile creep (flow)

- temperature increases with depth in the Earth (avg. 10-20° C per km)

- for typical continental crust, the brittle-ductile transition occurs at depths of 15-35 km

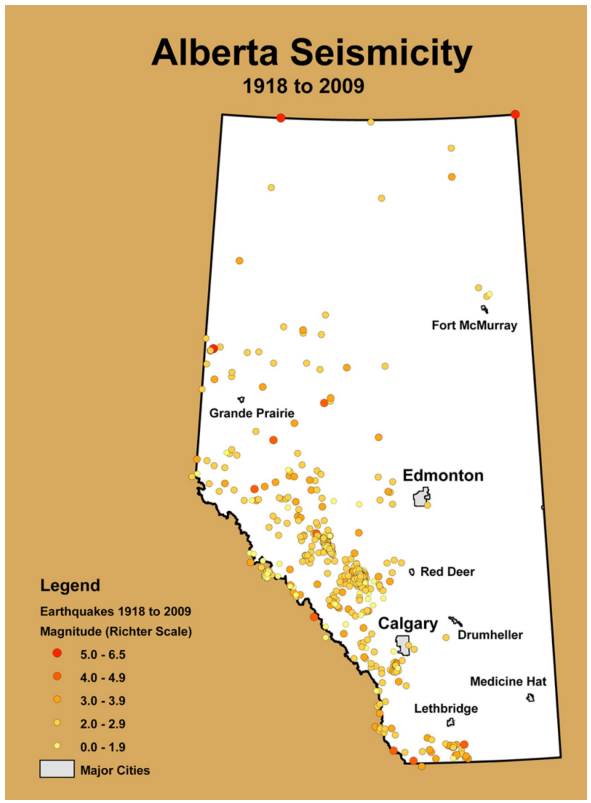


(http://earthquake.usgs.gov/regional/world/seismicity/)

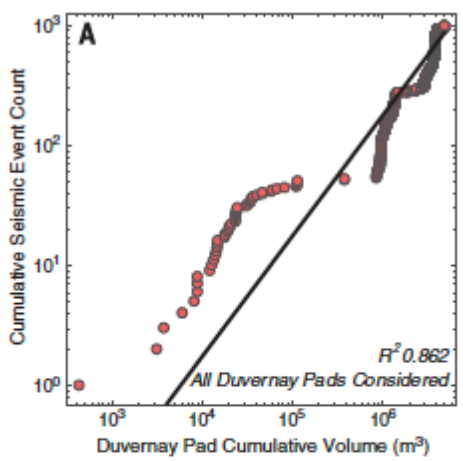
Second type: Intraplate Earthquakes

(earthquakes that do not occur near plate boundaries)

These earthquakes are fairly rare, and their causes are not very well understood. They could occasionally reach damaging magnitudes. Example:



Schultz et al., 2017, Science



INDUCED SEISMICITY

Hydraulic fracturing volume is associated with induced earthquake productivity in the Duvernay play

R. Schultz,[1]* G. Atkinson,[2] D. W. Eaton,[3] Y. J. Gu,[4] H. Kao[5]

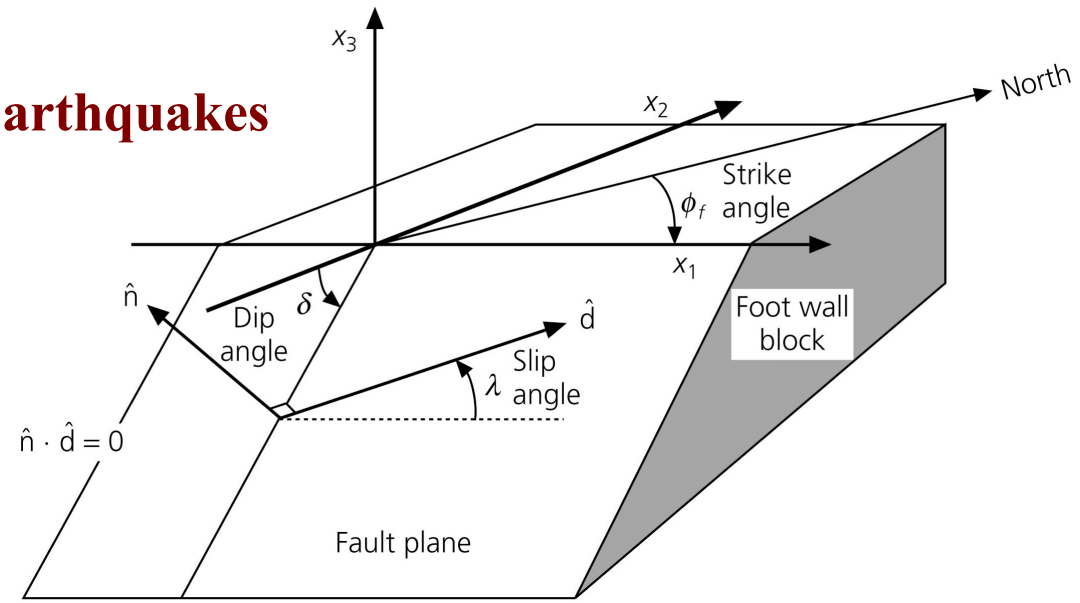
A sharp increase in the frequency of earthquakes near Fox Creek, Alberta, began in December 2013 in response to hydraulic fracturing. Using a hydraulic fracturing database, we explore relationships between injection parameters and seismicity response. We show that induced earthquakes are associated with completions that used larger injection volumes (10^4 to 10^5 cubic meters) and that seismic productivity scales linearly with injection volume. Injection pressure and rate have an insignificant association with seismic response. Further findings suggest that geological factors play a prominent role in seismic productivity, as evidenced by spatial correlations. Together, volume and geological factors account for ~96% of the variability in the induced earthquake rate near Fox Creek. This result is quantified by a seismogenic index–modified frequency-magnitude distribution, providing a framework to forecast induced seismicity.

Fig. 3. Number of earthquakes above the detection threshold (M_L 1.3) versus cumulative injection volume. (**A**) Volumes from all HF operations within the Kaybob Duvernay play (red circles) are compared with the best fit of the data points (black line). (**B**) Analogous to (A), except only seismogenic HF pads are considered. Both panels are during a period where the detection threshold remains constant (July 2014 to February 2016). Well flow-back was not considered in computing volumes. In both panels, the goodness-of-fit of the data to the expected line is displayed with the R^2 (coefficient of determination) values.

Induced earthquakes due to oil/gas industry? Lubrication of faults?

Ultimately, there is a stress build-up and a catastrophic stress release!

Quantifying Earthquakes



Fault geometry in earthquake studies

***Foot wall*: What is shown here**

***Hanging wall*: the block that is sliding against this block.**

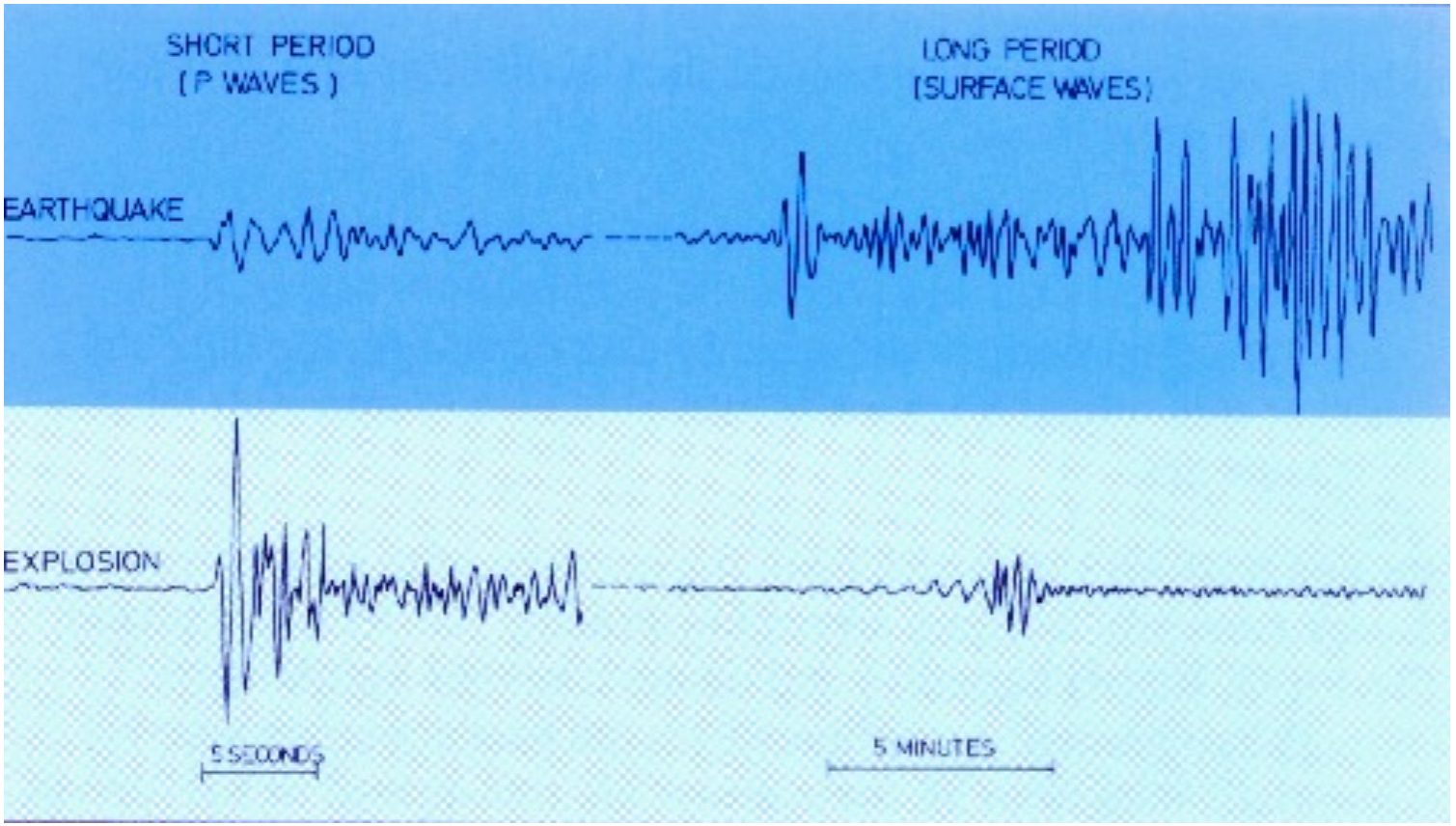
Three angles that uniquely describes a fault:

Strike (ϕ) : angle of fault on earth's surface with respect to North (0-360)

dip (δ) : fault dip angle measured with -x2 direction (condition = angle must be less than 90.

Rake or Slip (λ) : the angle that hanging wall moves against this block, measured with x1 direction (0--360).

What kind of pattern might you expect for a nuclear explosion?



Note that these do not have the same appearance as the earthquake arrivals which had strong S waves and surface waves . P arrival can be just as strong or stronger for an explosion. From http://www.norsar.no/

Explosions is NOT Described by the 'strike-dip-rake' system since there is technically no 'fault plane' (this is a problem!)