The interior of the Earth

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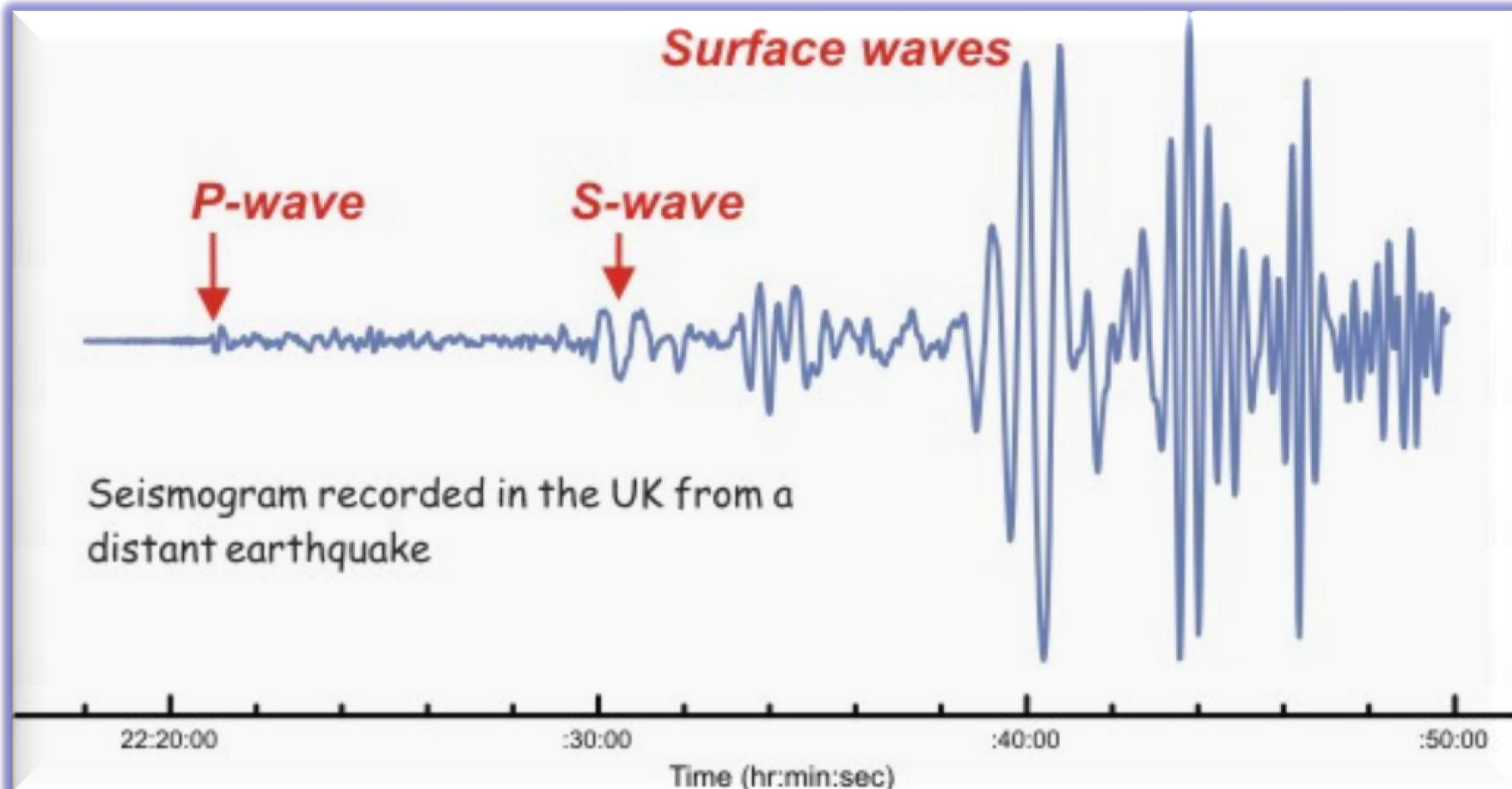
EARTHQUAKE SEISMOLOGY



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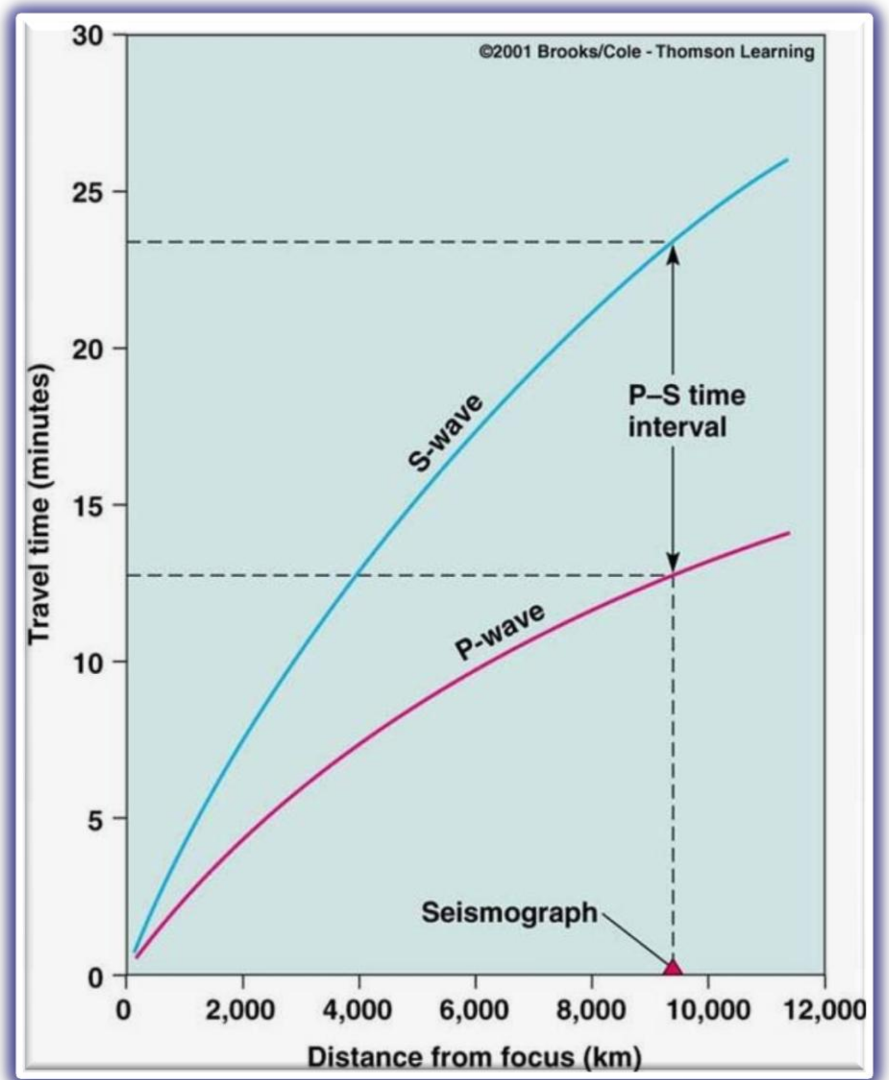
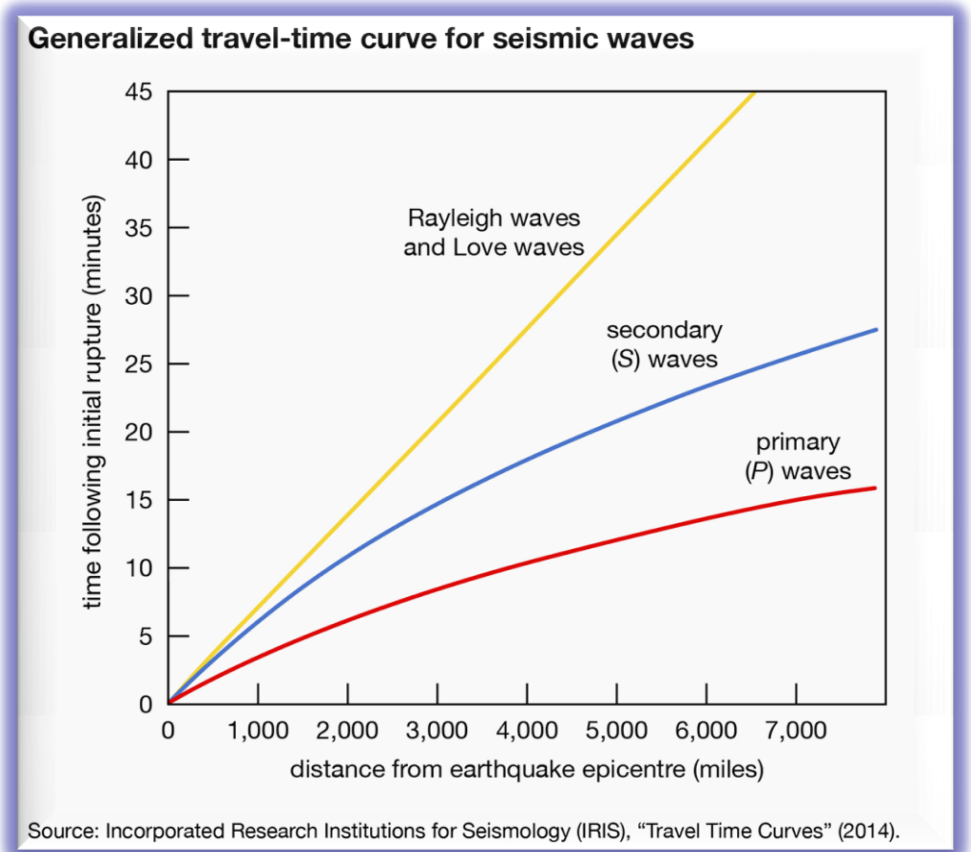




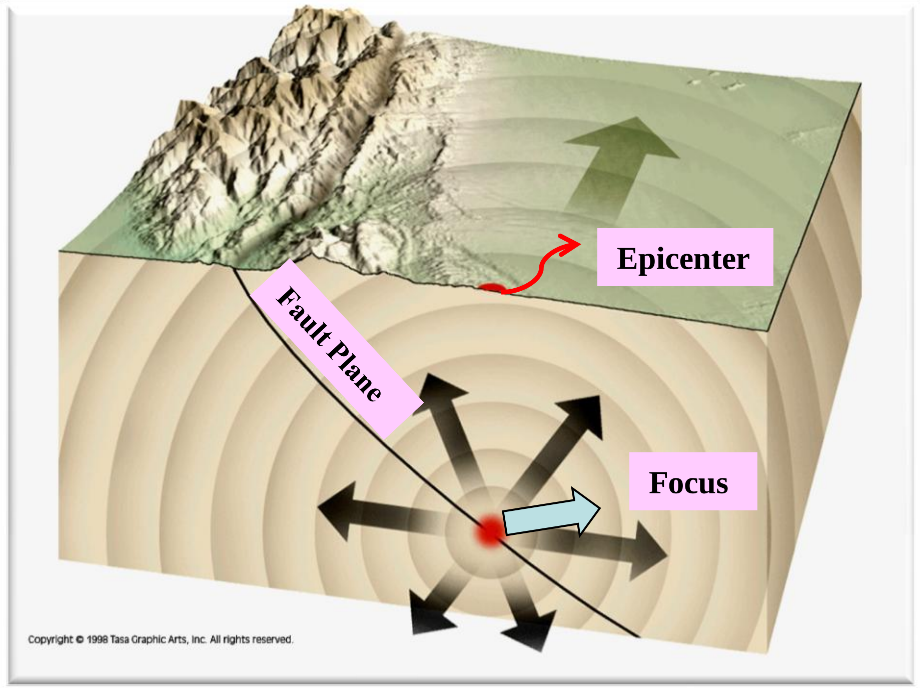
https://www.mathsisfun.com/physics/wavesseismic.html

Earthquake Focal Mechanisms or fault plane solution

- Seismic beach balls or earthquake focal mechanism are used to indicate directions of movement on regional faults and plate boundaries on regional tectonic maps (Sykes, 1967)

- Earthquake generated seismic waves , when received at various seismograph stations all-around the earth tell about the tectonic transport/stress directions, internal structure of the earth, stratigraphy and orientation of the lithospheric fault planes

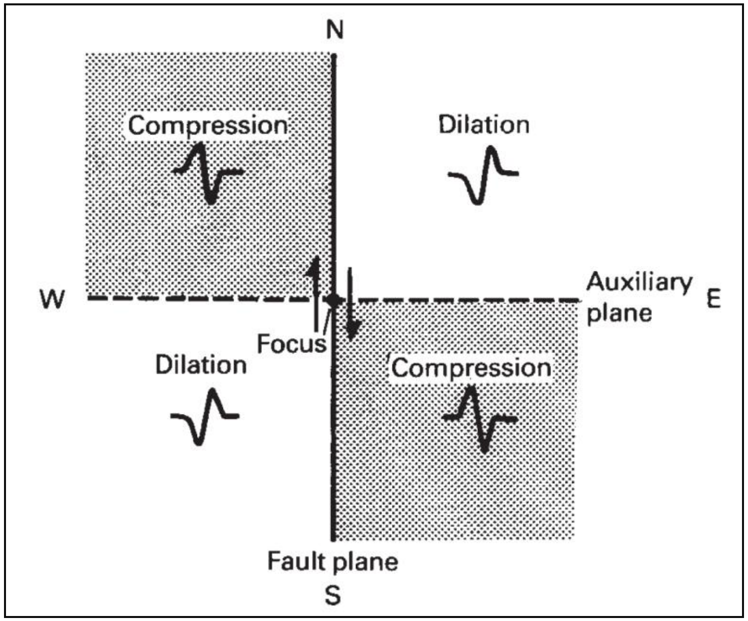
- The first P-waves measurement at cluster seismometers indicate compression Vs dilation at focus (source region) (Kearey et al., 2013).

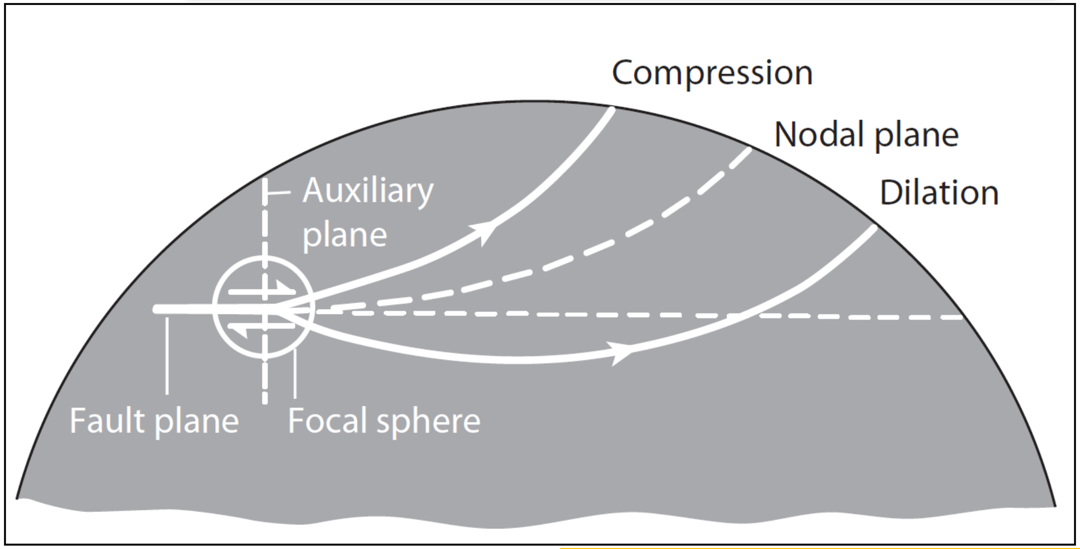


Earthquake Focal Mechanisms

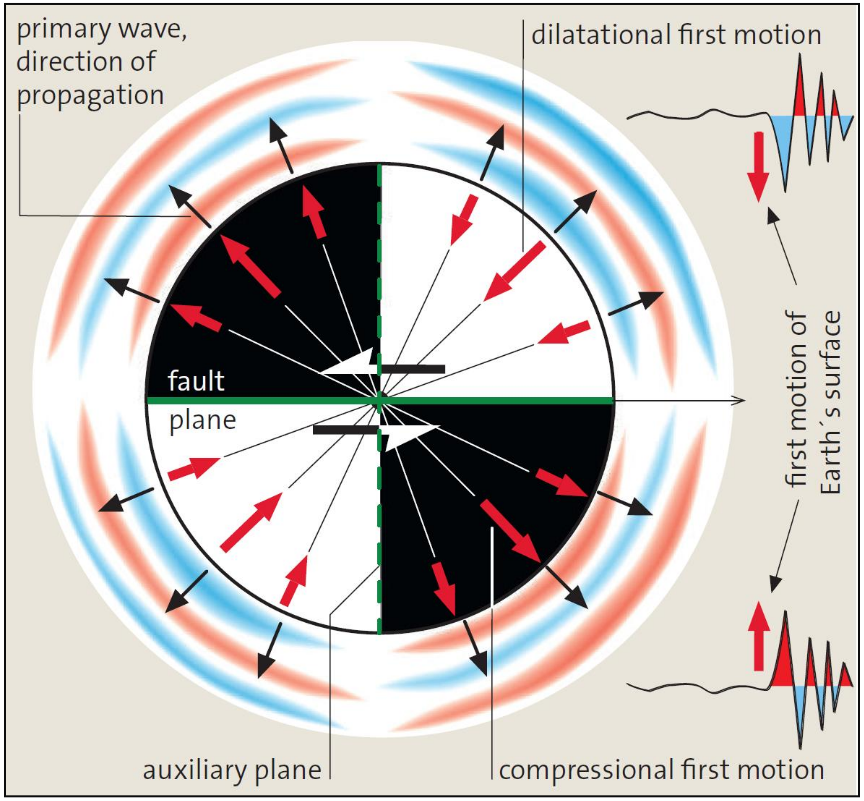
The first P waves motion at the seismometer indicates about compression and dilation at source region

Upward P waves motion means an expansion around the focus; downward P waves motion suggests a contraction in the source region

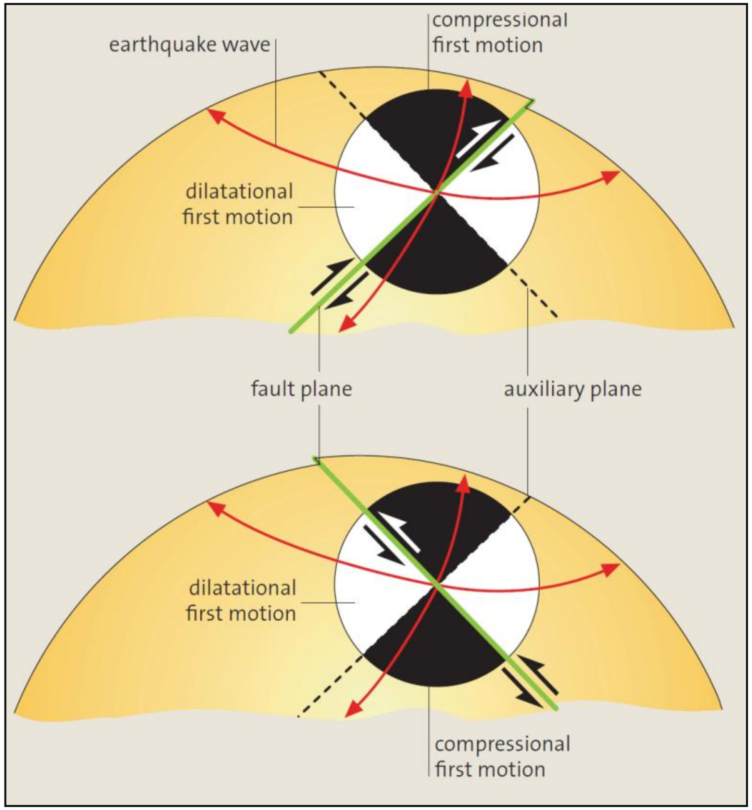




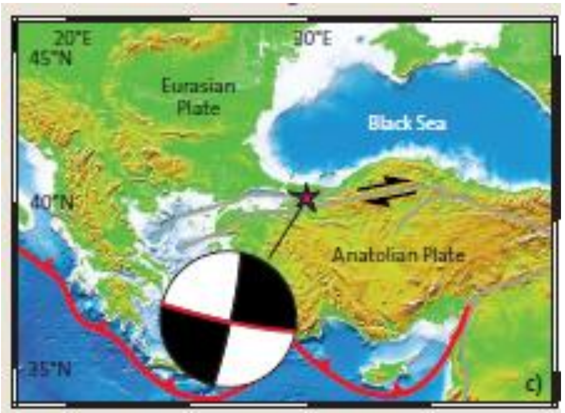
Kearey et al., 2013).



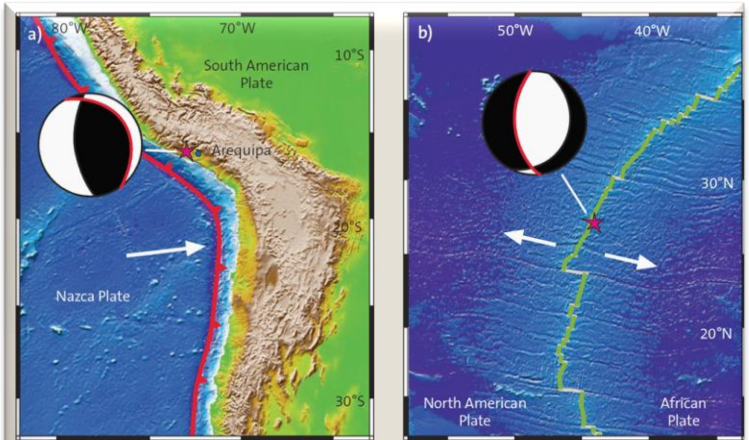
Compressional vs Dilatational first motion



Fault Plane Solutions by earthquake



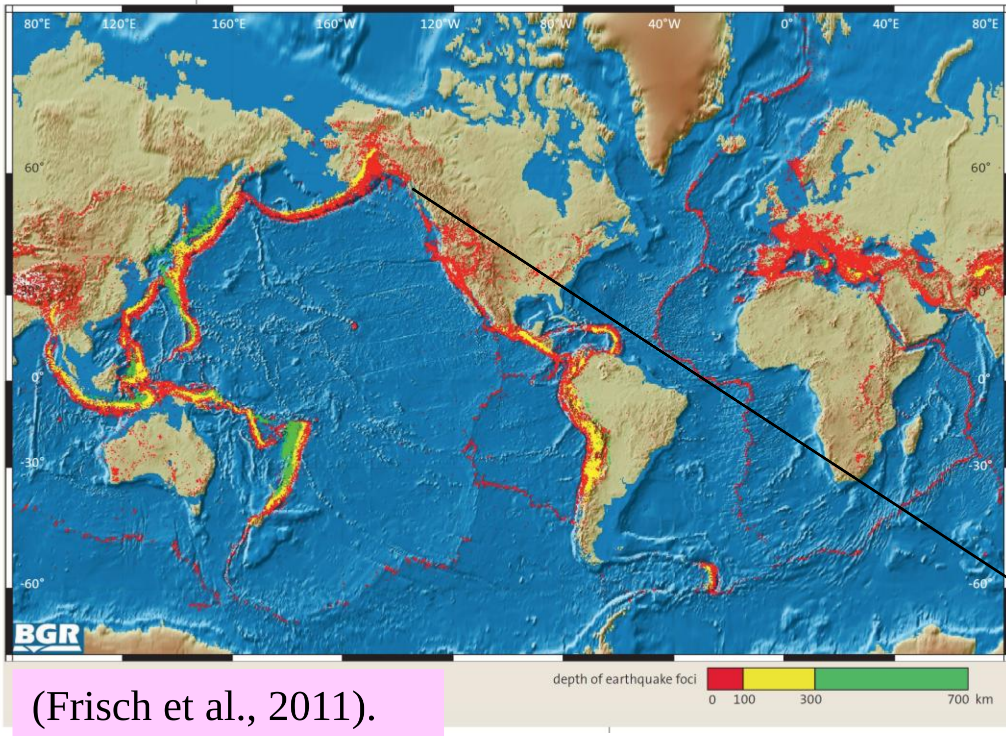
c) Izmit, Turkey. Aug. 17, 1999, magnitude 7.4



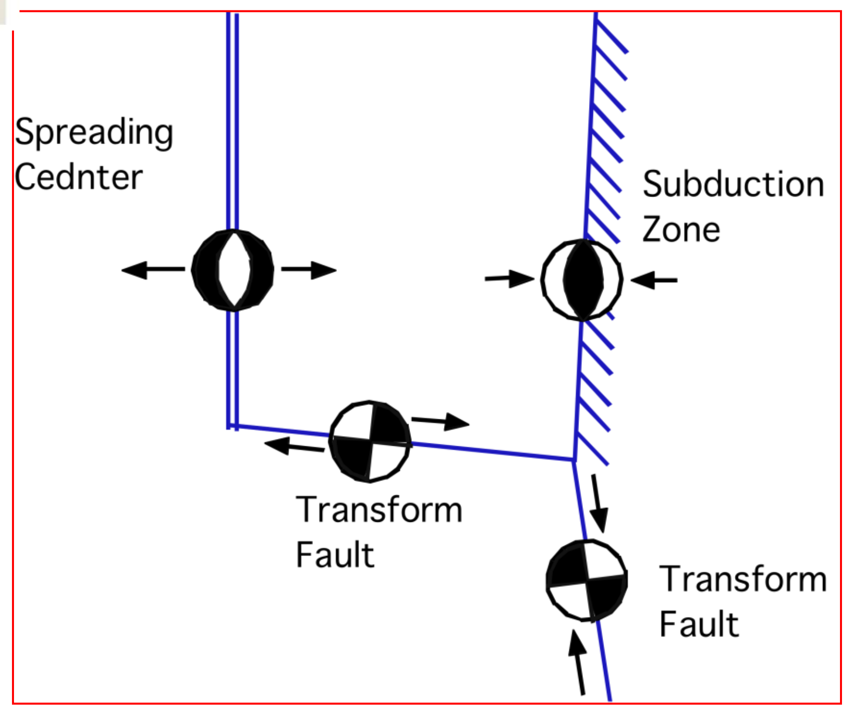
a) Arequipa, Peru. June 23, 2001, magnitude 8.1

b) Mid-Atlantic Ridge, 27.1°N, 44.3°W. Dec. 13, 2001, magnitude 5.9

(Frisch et al., 2011).



(Frisch et al., 2011).



First Motions

- Japanese seismologist in 20th Century started work on first upward or downward motion of seismic waves recorded at different seismometers

- Initially it was conceived that different earthquakes produce upward and downward spikes on seismographs. However later it was ascertained that a single earthquake could potentially acquire different spikes at different seismometers that produce from a fault rupture in the source region.

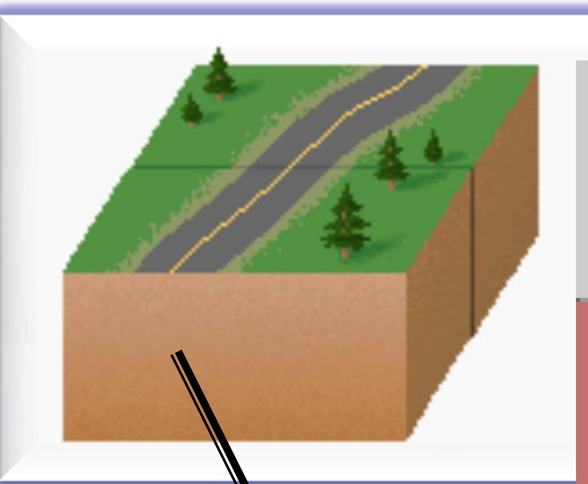
- Onward the First wave motions were used as slip indicator to segregate regions of compression and dilatation using beach ball technique

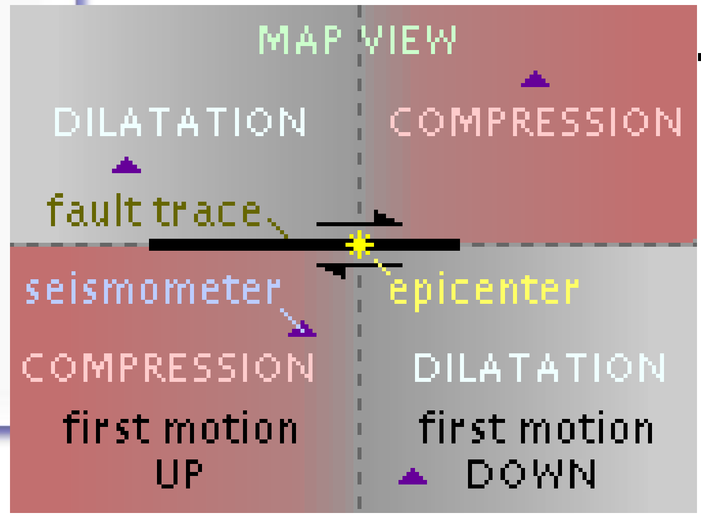
First Motions

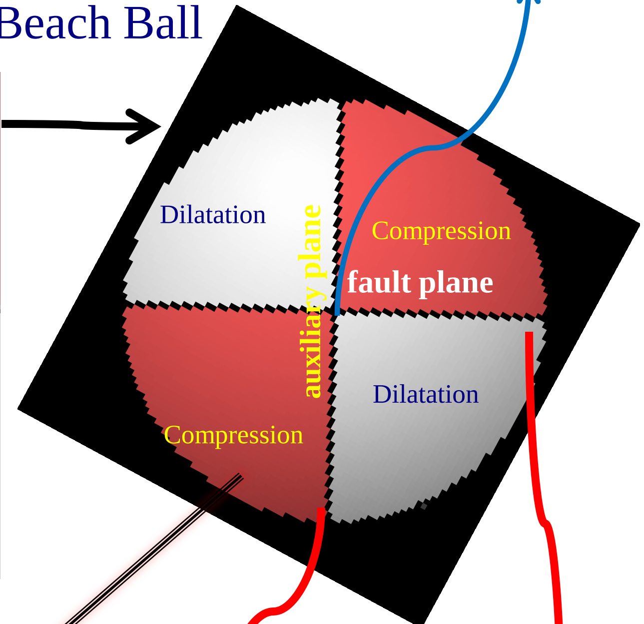
Sense of Slip at fault plane
focal mechanism

Earthquake's Hypocenter (Focus)

Beach Ball

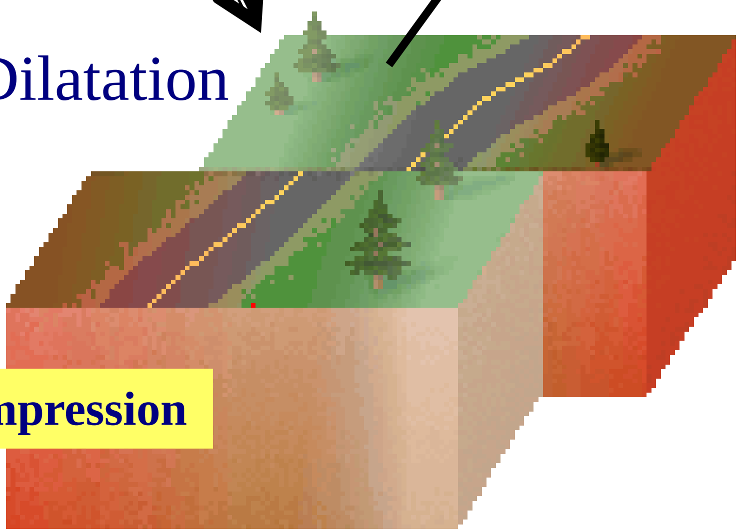






nodal planes

Dilatation



Compression

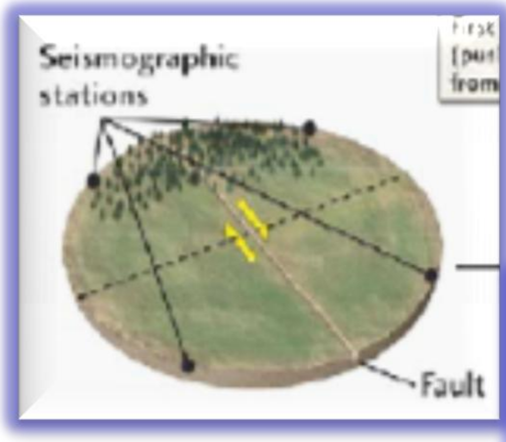
Initial rupture behavior at the Hypocenter

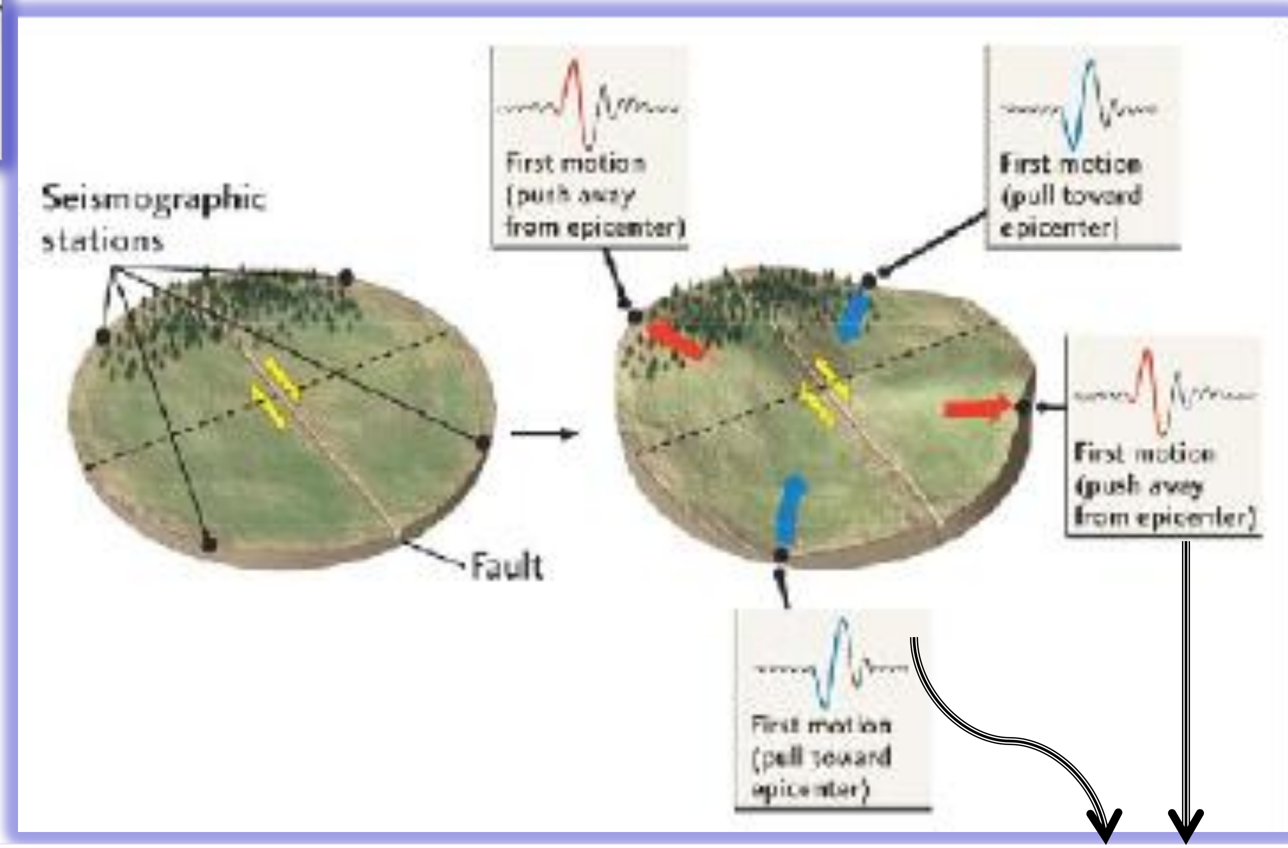
pushing you away from the source of the earthquake

Compression

https://slideplayer.com/slide/6494989/

Focal Mechanisms -- Seismological "Beach Balls"





First P-wave motions recorded at different seismometers

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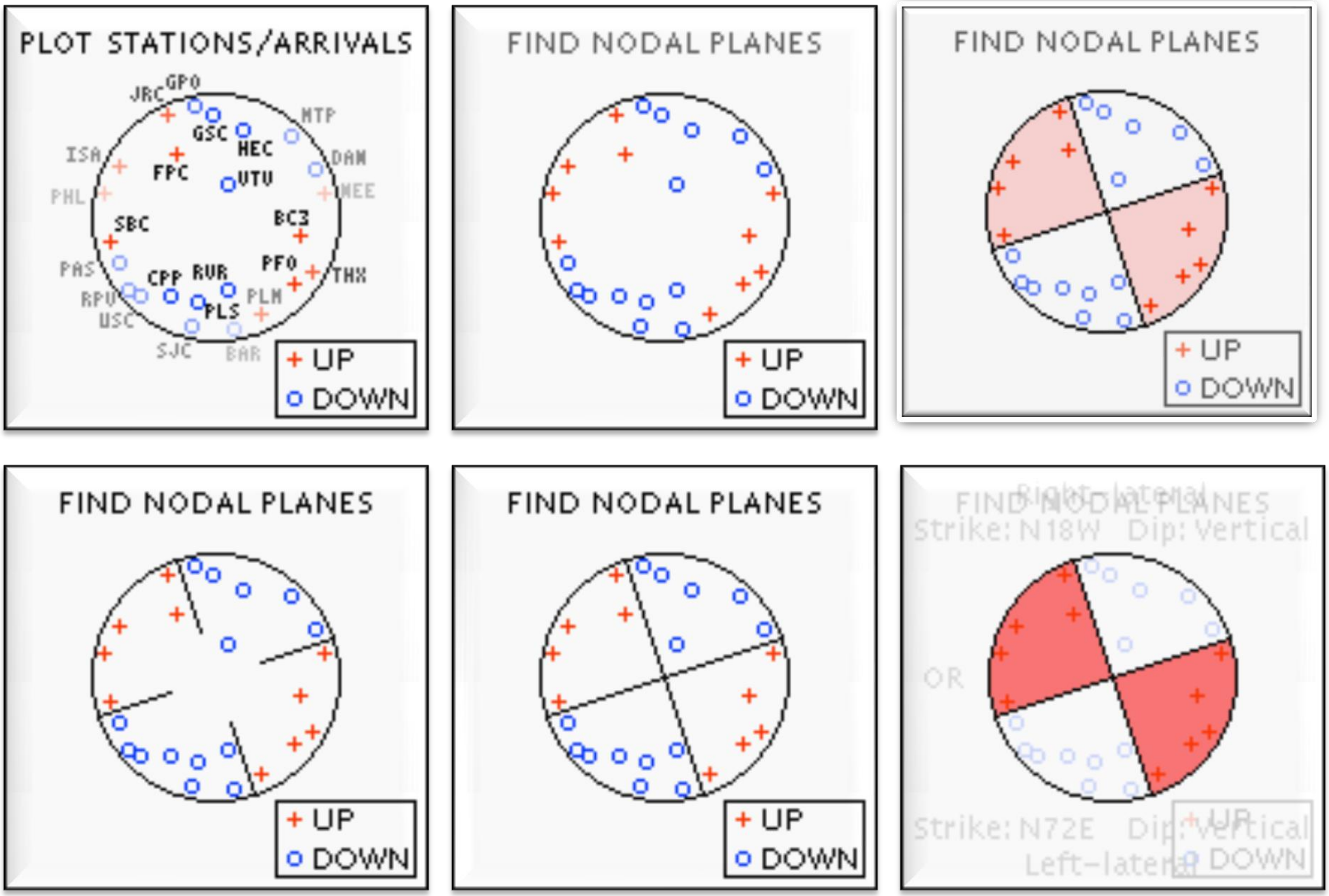
Creating Focal Mechanisms



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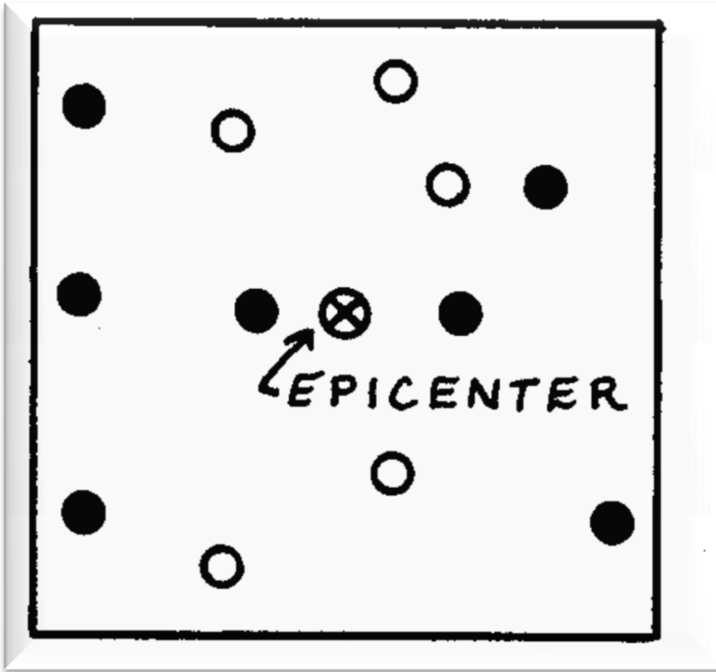
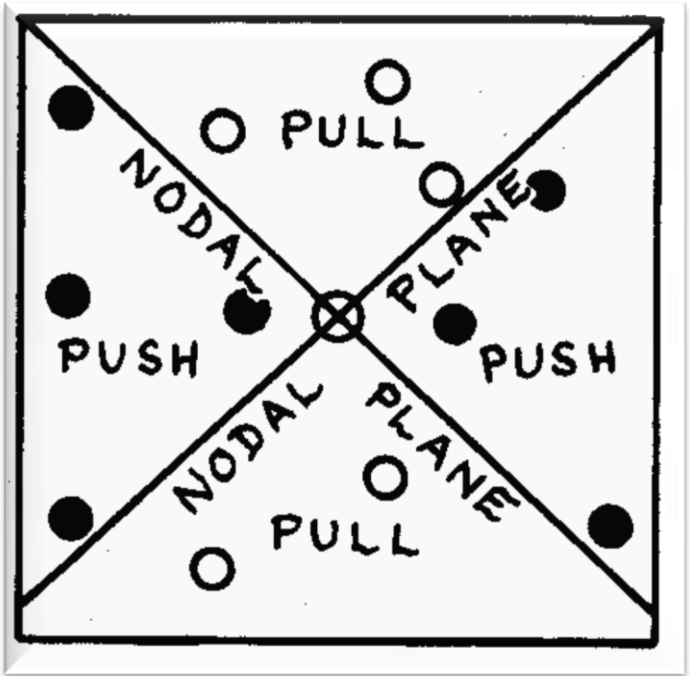
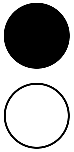
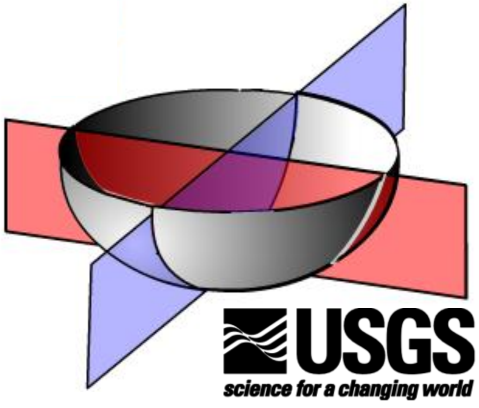
Determination of nodal planes

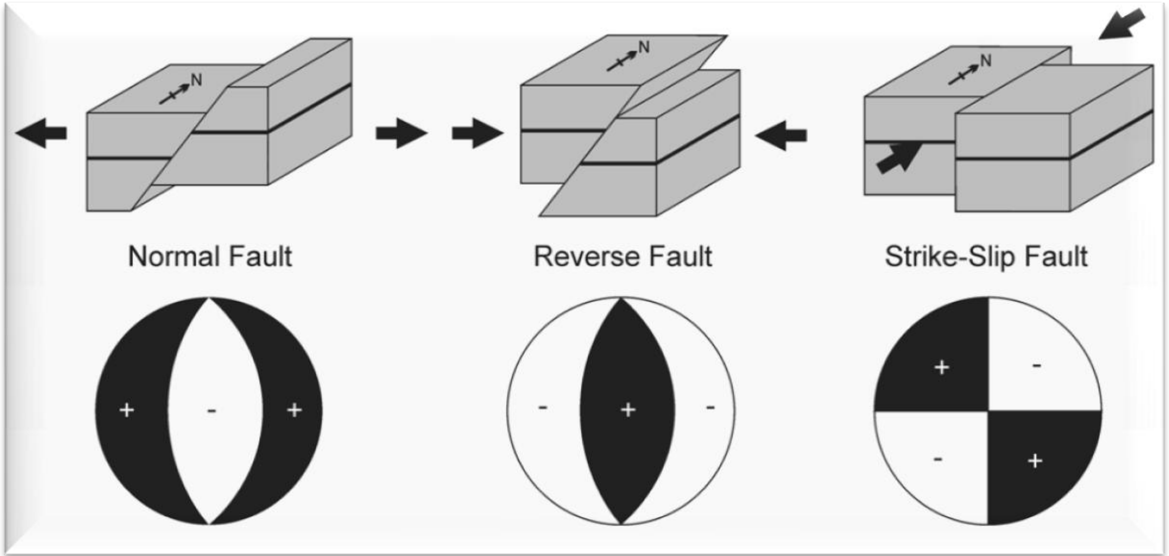




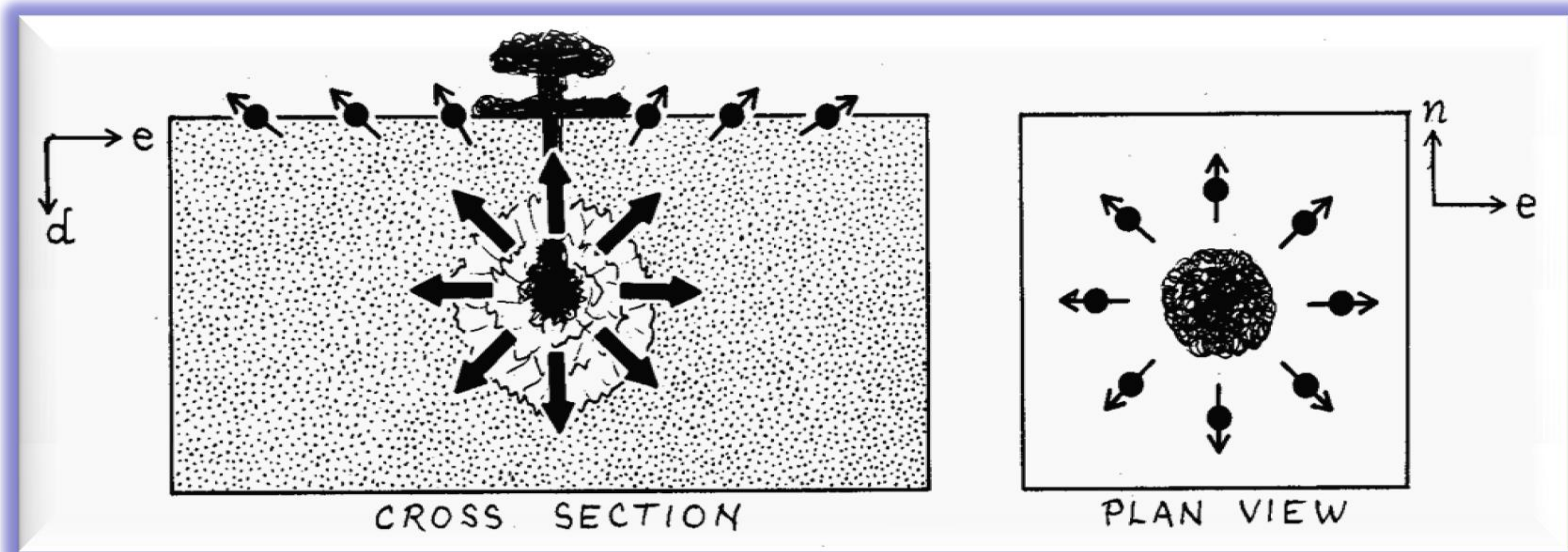


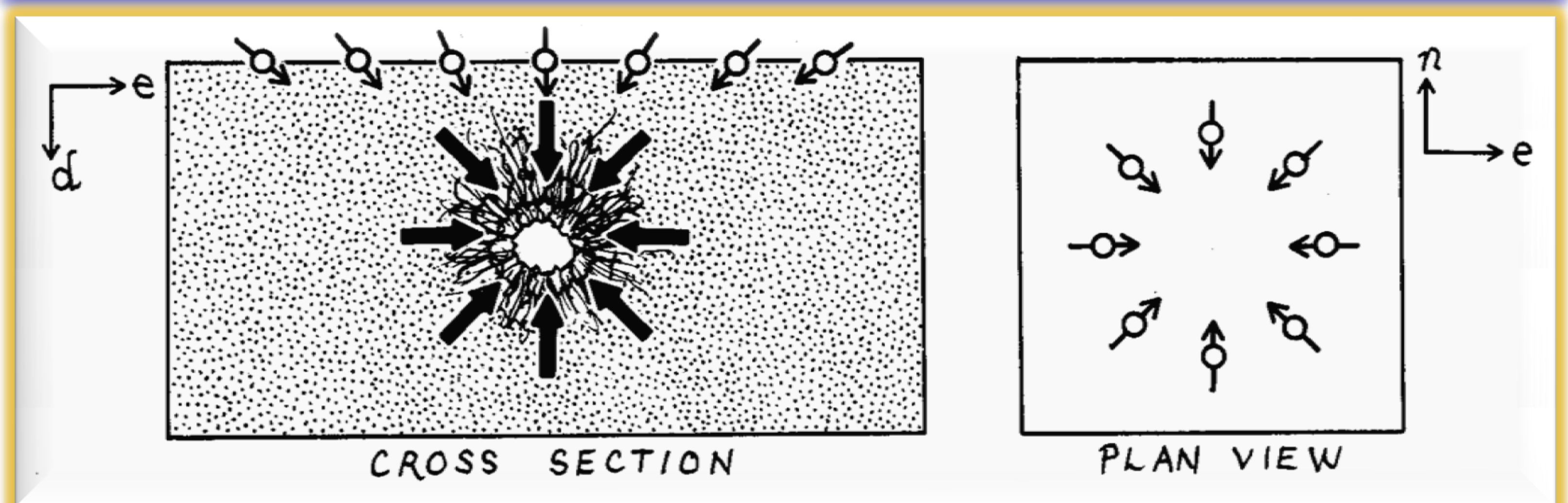
seismic stations





Energy and Polarity of "First Motions"





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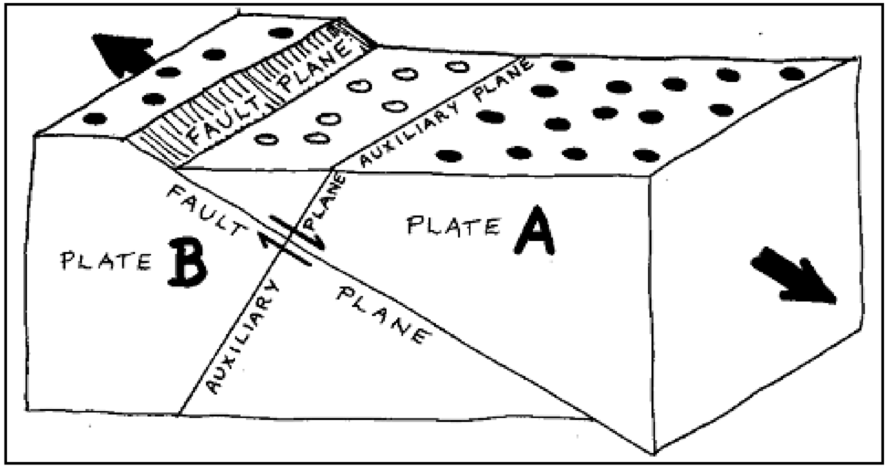
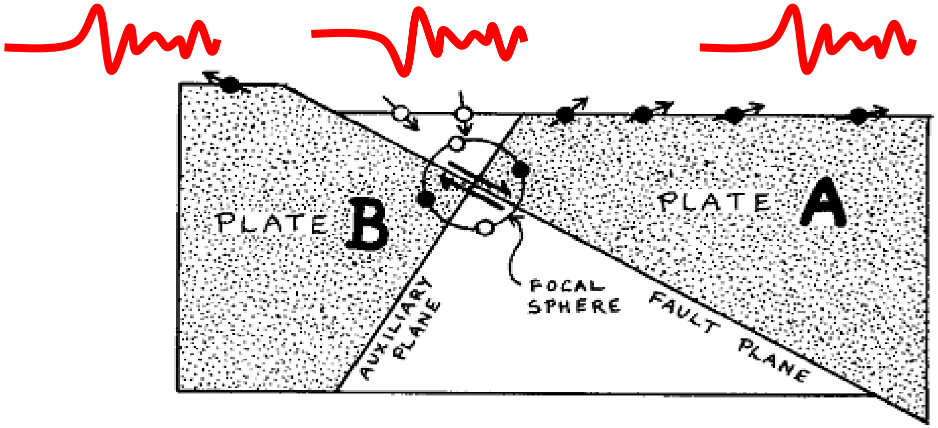
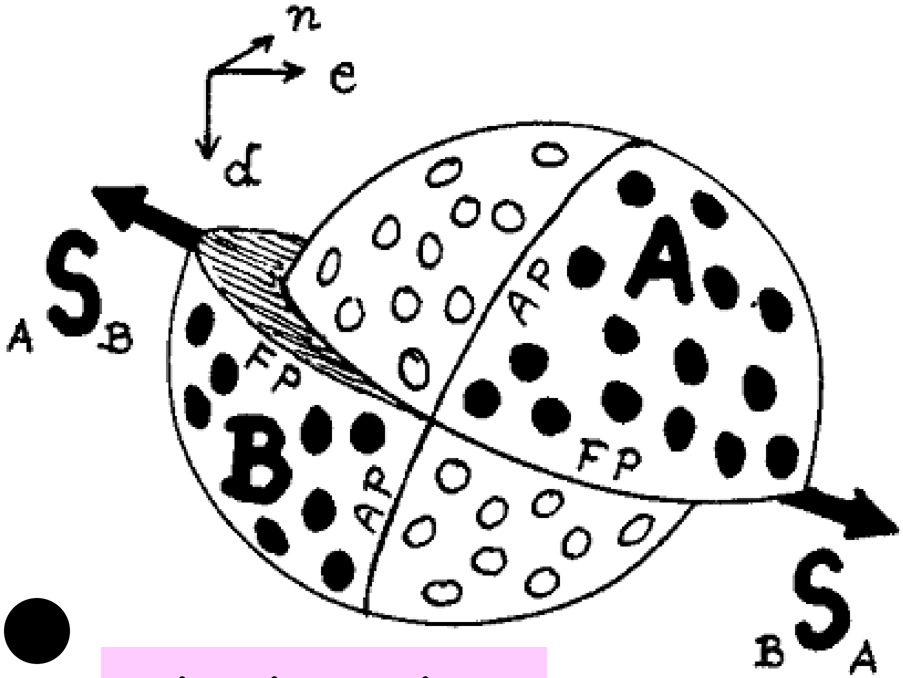
First Wave motion around a Normal Fault Plane

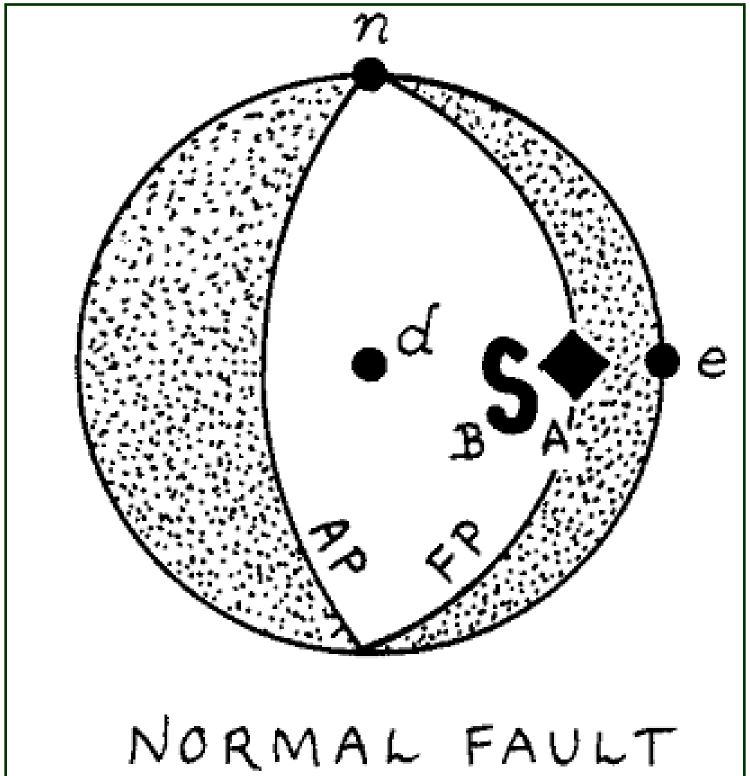
First Wave motions







seismic stations



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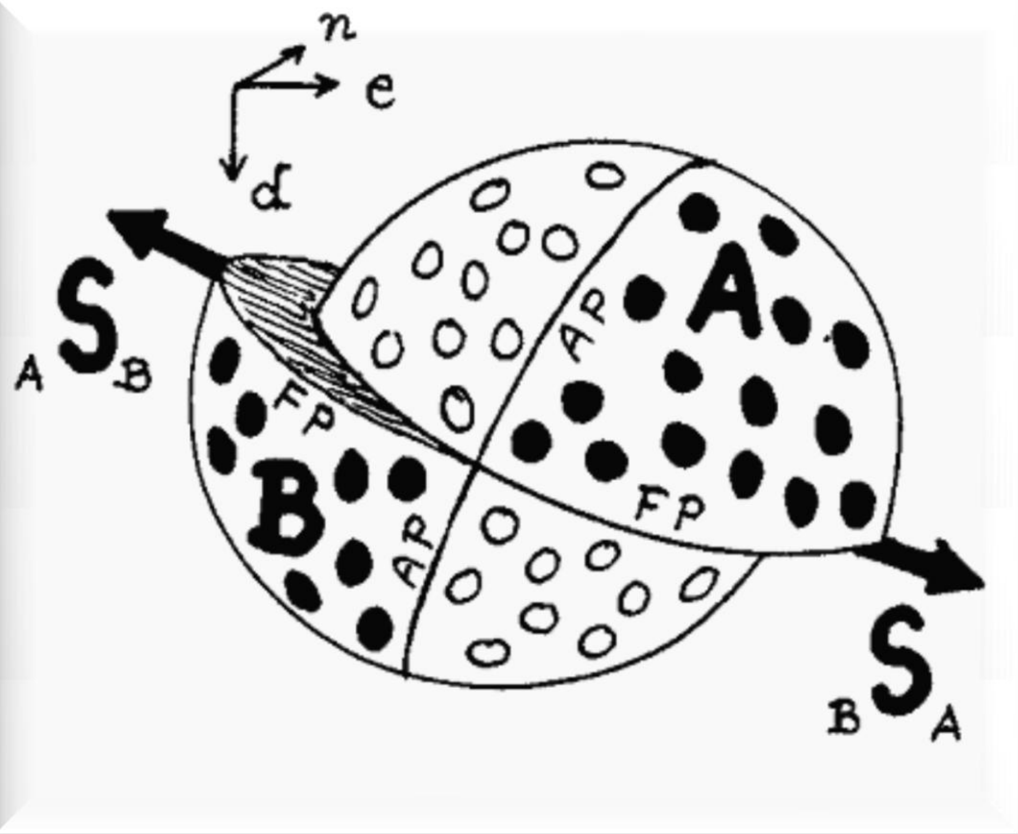

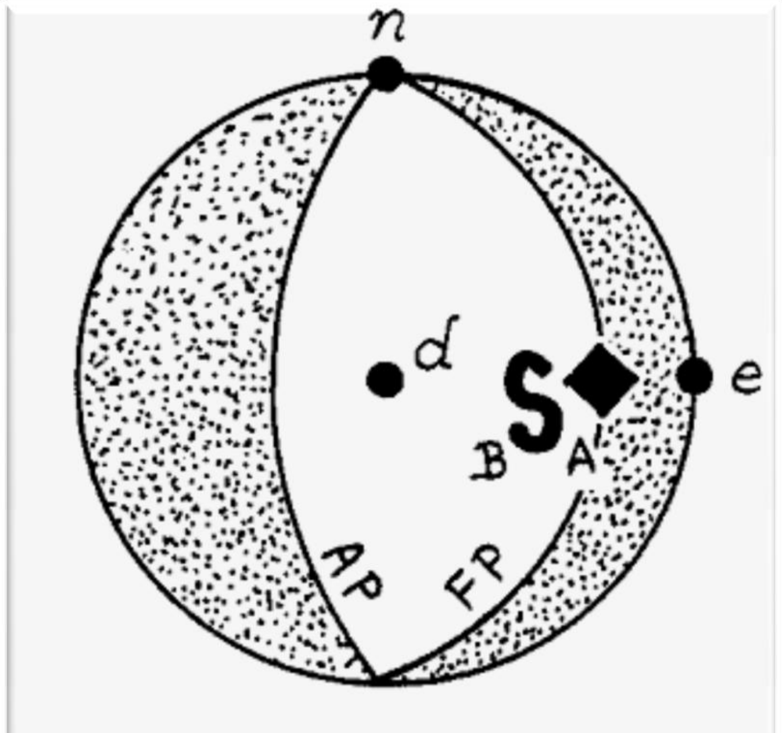

NORMAL FAULT

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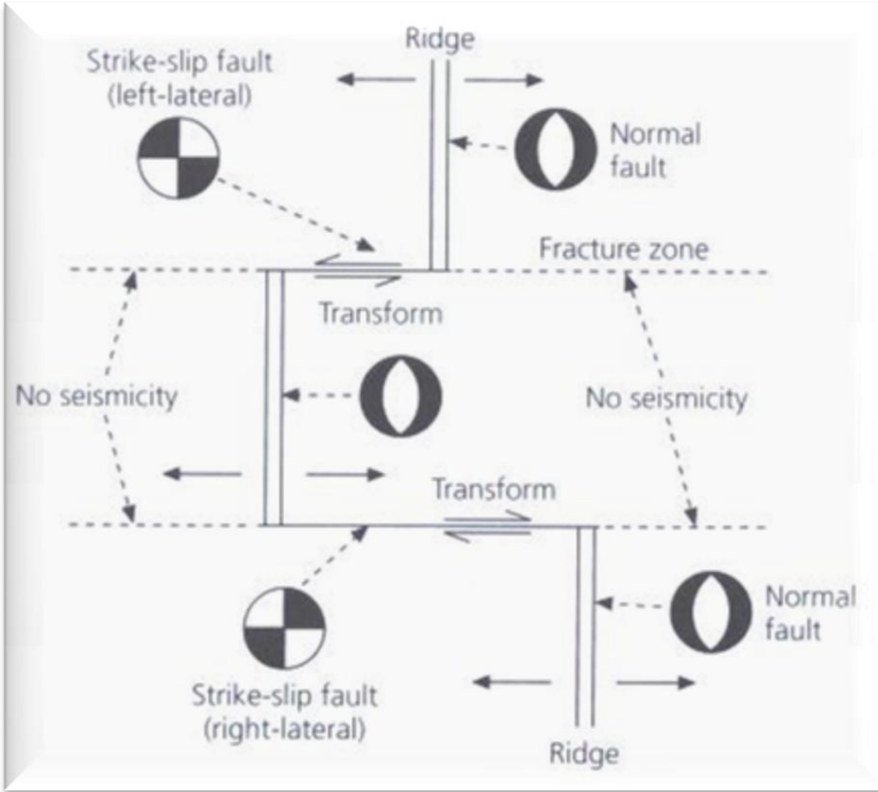
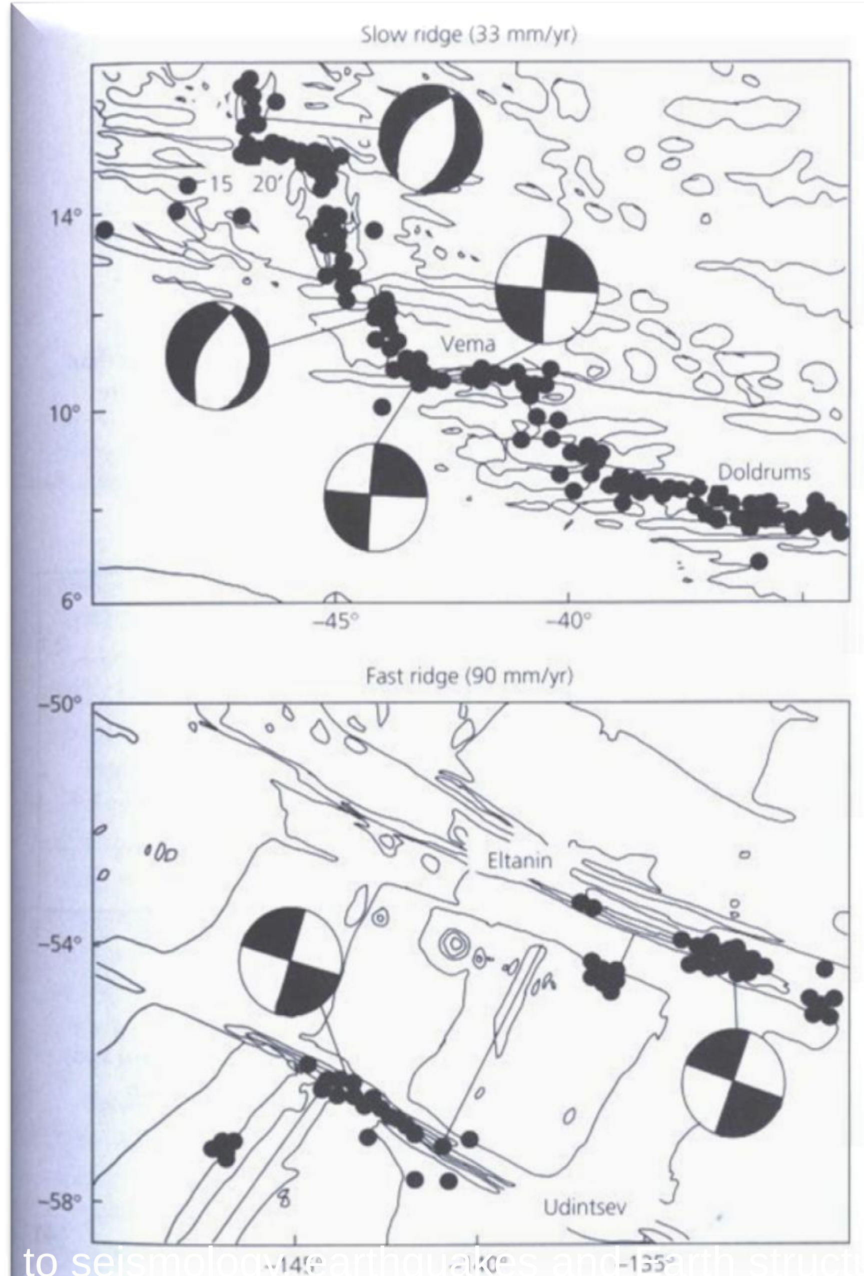
Example Focal mechanism diagrams on mid-ocean ridges





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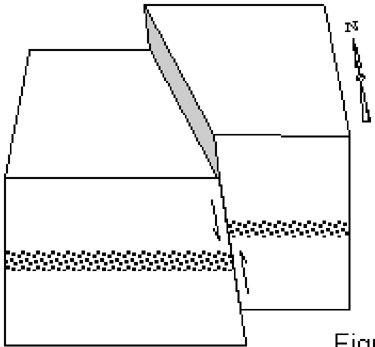


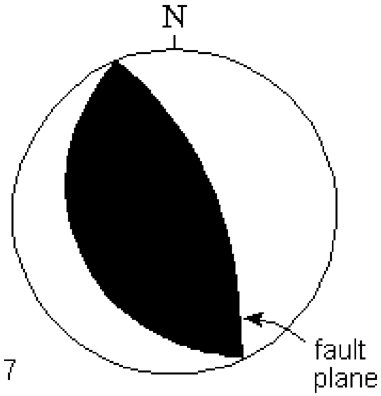


Figure 7

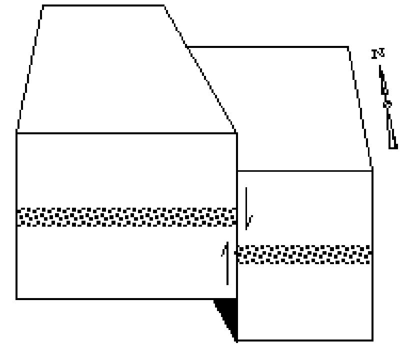


Figure 5

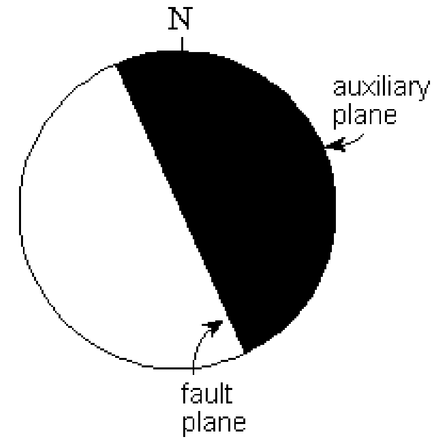
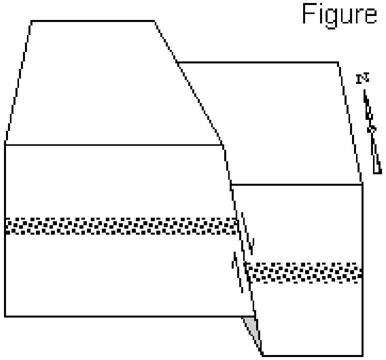


Figure 6



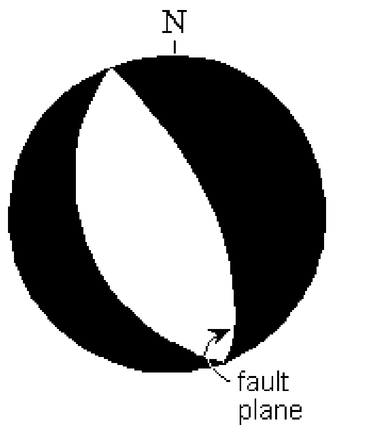
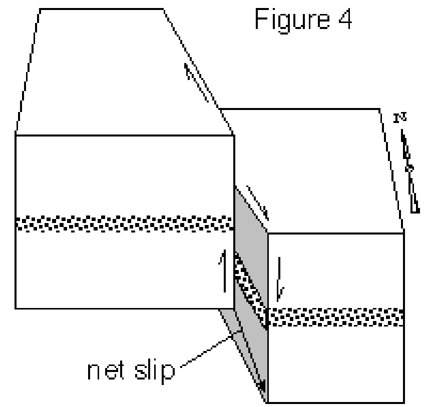
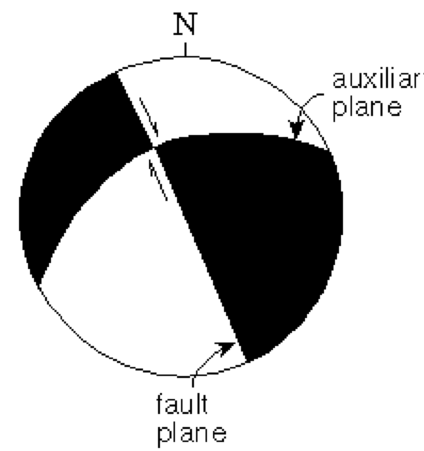
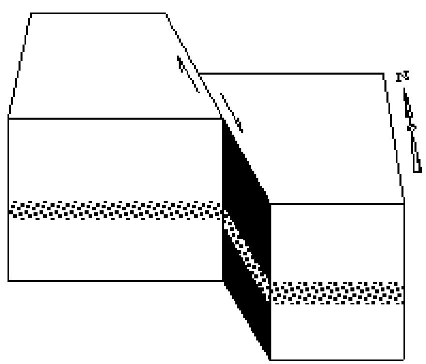


Figure 4







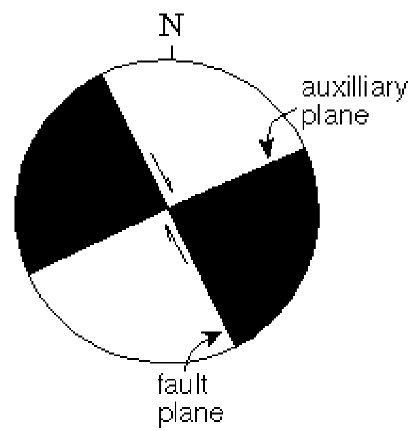


Figure 3

Stratigraphy of the Oceanic Crust

The Earth's Interior

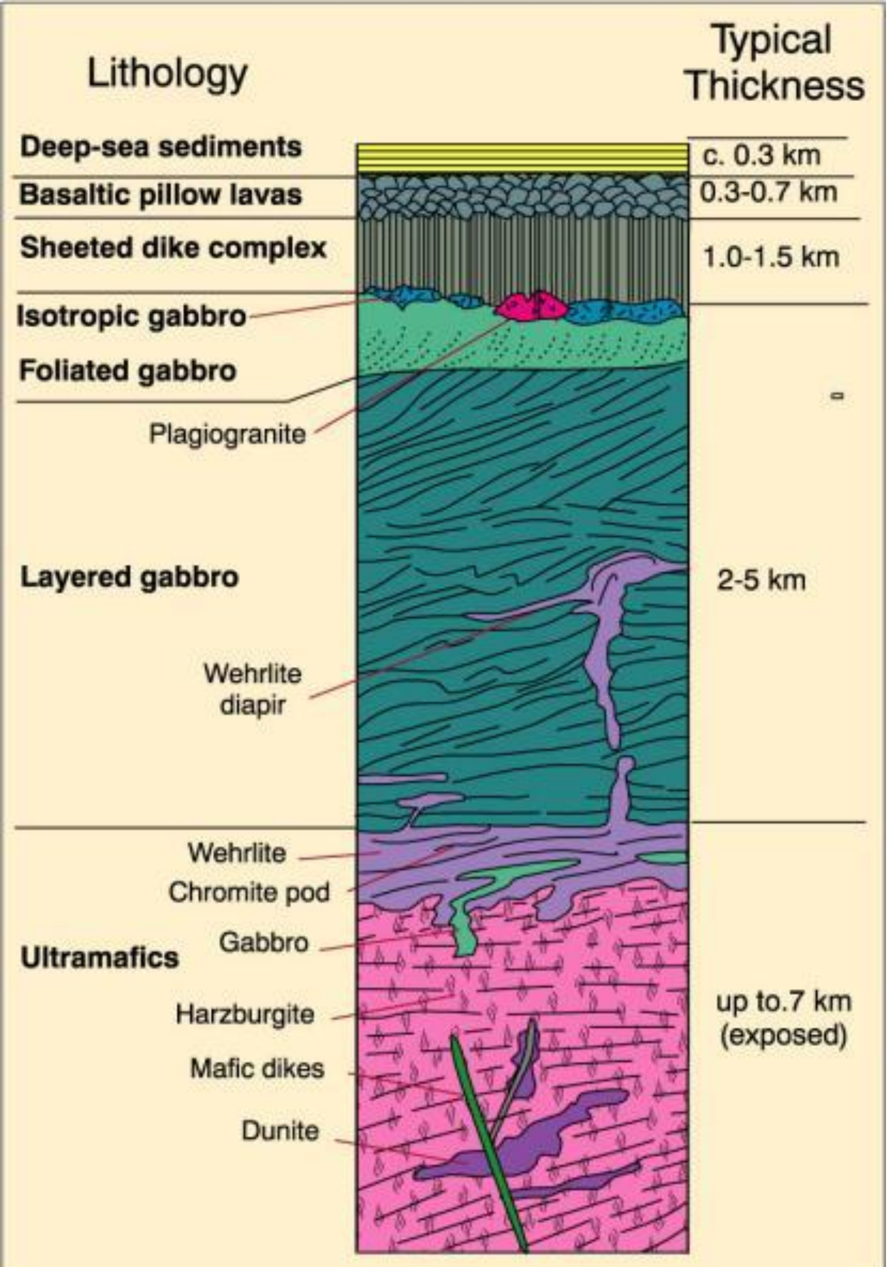
Oceanic Crust

- According to Airy Mechanism the oceanic and continental crusts are in isostatic equilibrium (Francheteau, 1983)
- The Oceanic crust is much thinner than the continental Crust.
- Indirect Seismic refraction indicates at average 6–7 km thickness of the oceanic crust
- The thickness of the oceanic crust depends on the amount of magma supply at the MOR
- Compare to continental crust ,the oceanic crust stratigraphy remains uniform
- The Oceanic crust based on direct (Ophiolites) and indirect (seismic refraction)observations has been divided into three layers.

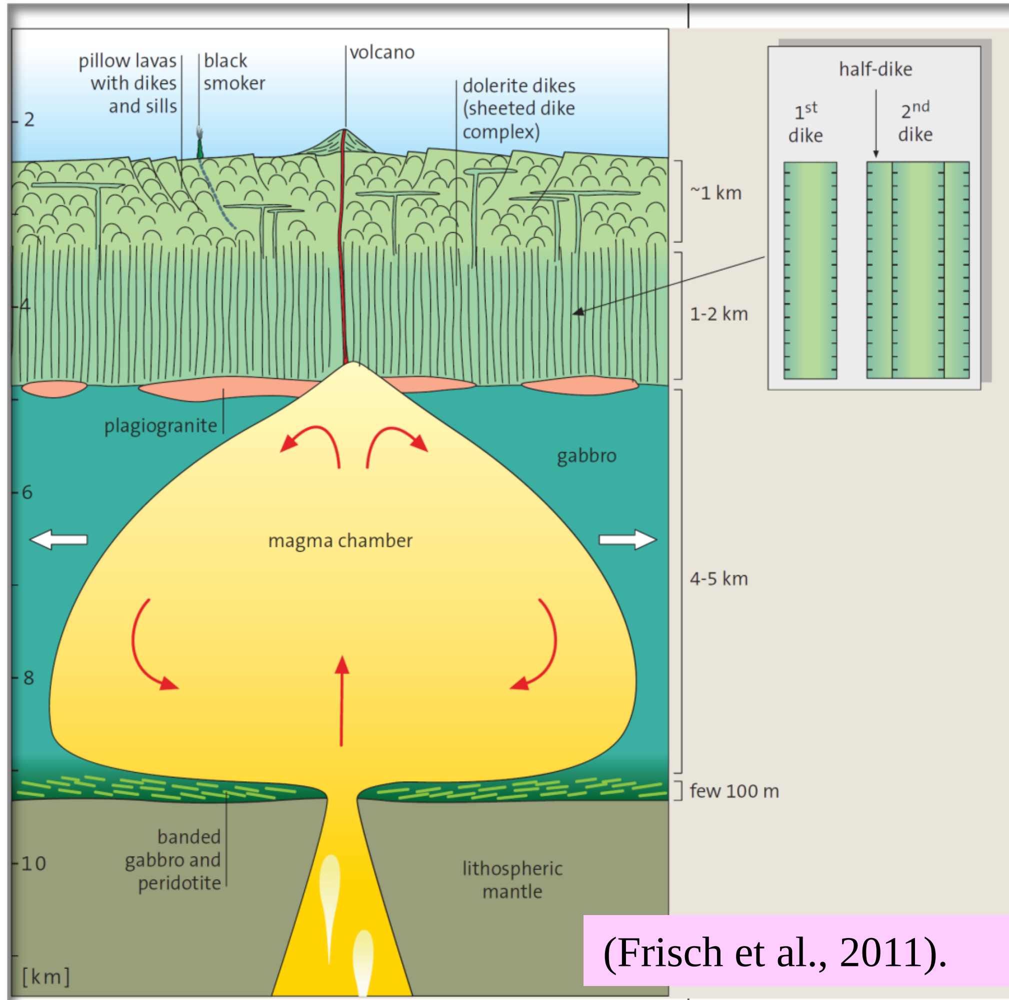
	P velocity ($km\ s^{-1}$)	*Average thickness (km)*
Water	1.5	4.5
Layer 1	1.6–2.5	0.4
Layer 2	3.4–6.2	1.4
Layer 3	6.4–7.0	5.0
	Moho	
Upper mantle	7.4–8.6	

Refraction study produced Oceanic crust structure (*Bott, 1982*)

Composition and Thickness of the entire Oceanic Crust and Upper Mantle



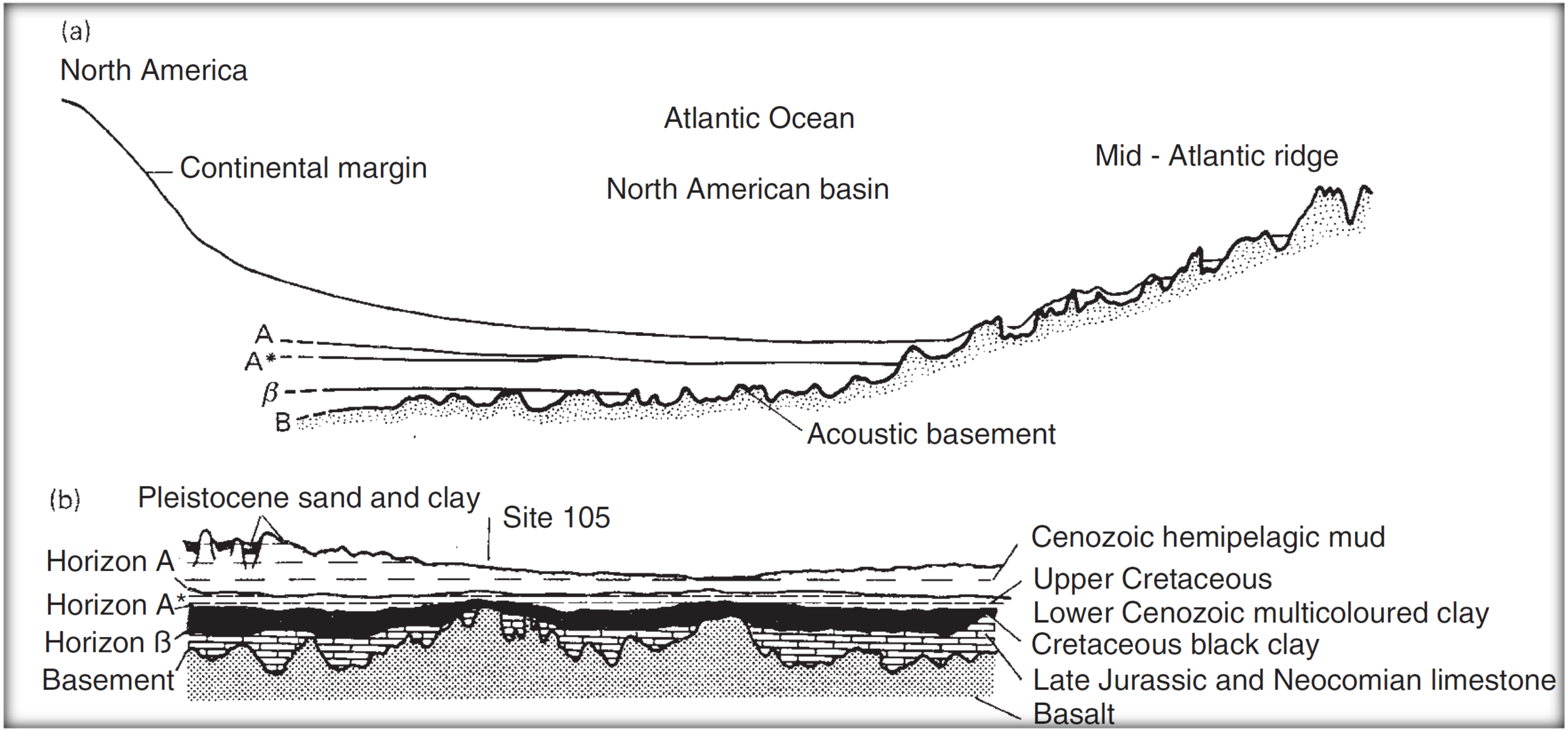
After Boudier and Nicolas (1985)



(Frisch et al., 2011).

Oceanic Layer 1

- Sampled by extensive drilling and coring (mostly studied in the Atlantic Ocean)
- It consists of unconsolidated pelagic and terrigenous sediments
- The Pelagic sediments comprise manganese nodules, silicic oozes, zeolite and calcareous oozes
- The terrigenous sediments bring by high velocity turbidity currents
- Layer 1 deposits are preserved in the form of contourites (Stow & Lovell, 1979)
- This layer is 0.4 Km thick
- The thickness of the Layer 1 increases away from the Mid Oceanic Ridge
- Layer 1 varies from Atlantic /Indian to Pacific ocean, the later has huge input of the terrigenous sediments
- Edgar (1974) divided Layer 1 into different horizon based on seismic refractors



Subdivision of the Atlantic Layer 1 (after Edgar, 1974)

(Kearey et al., 2013)

Oceanic layer 2

- Oceanic Layer 2 thickness varies from1.0– 2.5 km (the DSDP/ODP drill hole 504B; Costa Rica Rift)
- This layer comprises consolidated sediments and olivine tholeiitic basalt (enriched in Ca and poor in Na and K; Sun et al., 1979)
- Layer 2 has been divided into sublayer 2A, 2B and 2C based on seismic waves velocities
- Sublayer 2A thickness reaches up to 1km with 30 to 50% porosity. It is highly rubbly and porous (mostly porous basalt; Purdy, 1987)
- P -wave velocity of 2A is 2.1 km/s
- Away from Mid Oceanic Ridge this layer convert into sublayer 2B due to filling pores by secondary quartz , zeolite and calcite. The composition of the 2A is highly affected by hydrothermal fluids circulation.
- Sublayer 2B is less porous than 2A, it is suggested by higher P -wave velocity
- 4.8–5.5 km/s velocity suggests lower porosity for 2B
- Sublayer 3B is one kilometer thick
- 5.8–6.2 km/s velocity indicates high proportion of intrusive rocks (sheeted dikes)

Oceanic layer 3

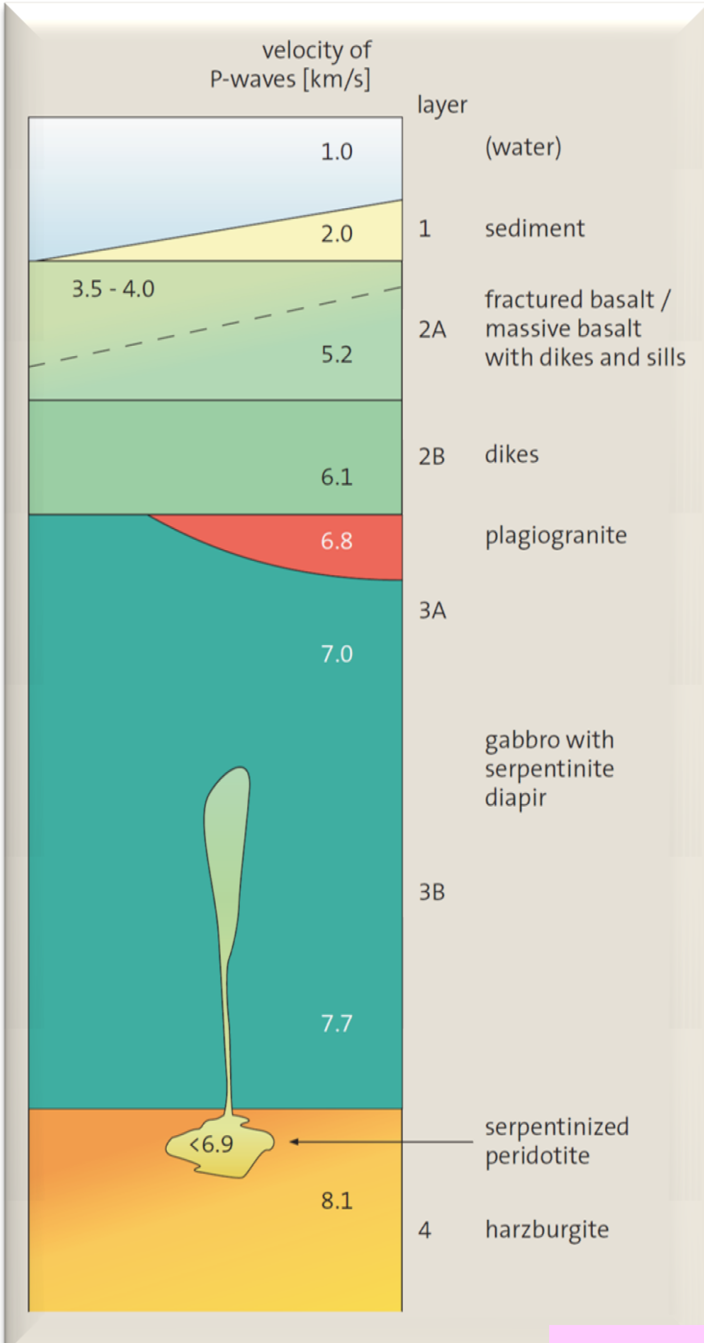
- Based on seismic velocity, the Layer 3, which is the main layer of the oceanic crust has been divided into sublayer 3A and 3B

- 6.5–6.8 km/s velocity range of the sublayer 3A indicates gabbroic composition

- 7.0–7.7 km/s velocity range of the sublayer 3B suggests serpentinized ultramafic nature of the layer

- This layer has been directly sampled in the North Atlantic by Auzende *et al.*, *(*1989)

P waves velocity structure of the Oceanic Layers



(Frisch et al., 2011).

OPHIOLITES

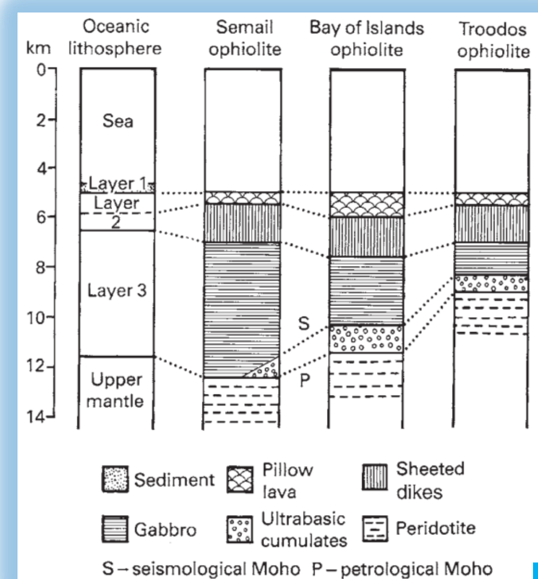
Obduction of a remnant oceanic and upper mantle rocks onto the continental crust in the continent-continent collision belts is called ophiolite (Dewey, 1976; Nicolas, 1989)

Complete ophiolite sequence		***Oceanic correlation***
Sediments		Layer 1
Mafic volcanics, commonly pillowed, merging into Mafic sheeted dike complex	}	Layer 2
High level intrusives Trondhjemites Gabbros	}	Layer 3
Layered cumulates Olivine gabbros Pyroxenites Peridotites	}	— Moho —
Harzburgite, commonly serpentinized ± lherzolite, dunite, chromitite		Upper mantle

after Gass, 1980

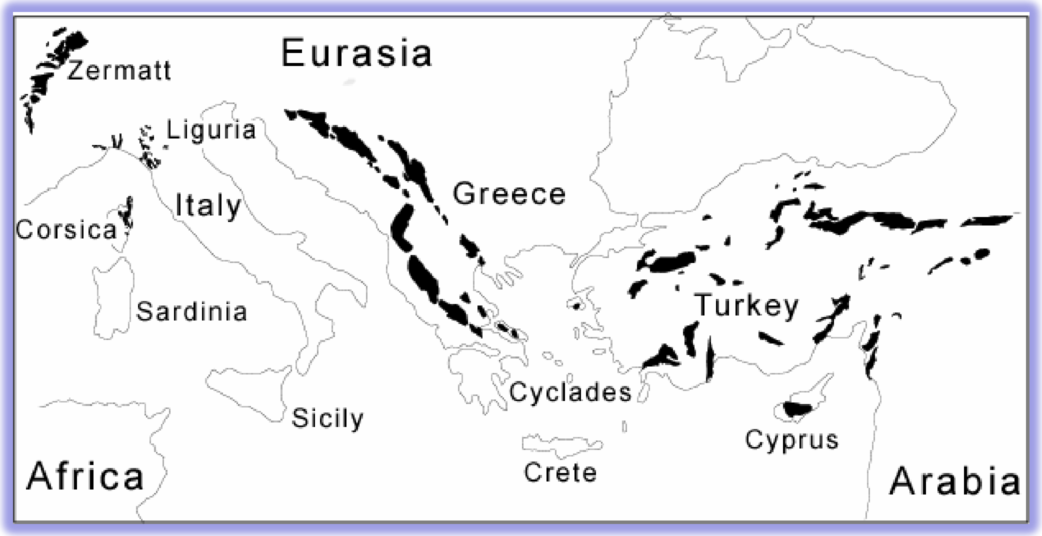
➢Ophiolites are similar in chemistry, temperature gradient, metamorphic grades and ore minerals to the oceanic crust (Moores, 1982).

➢Seismic velocity structure of ophiolite is identical to oceanic crust (Salisbury & Christensen1978)



after Mason, 1985

Comparison of Oceanic lithosphere and well studied ophiolite complexes

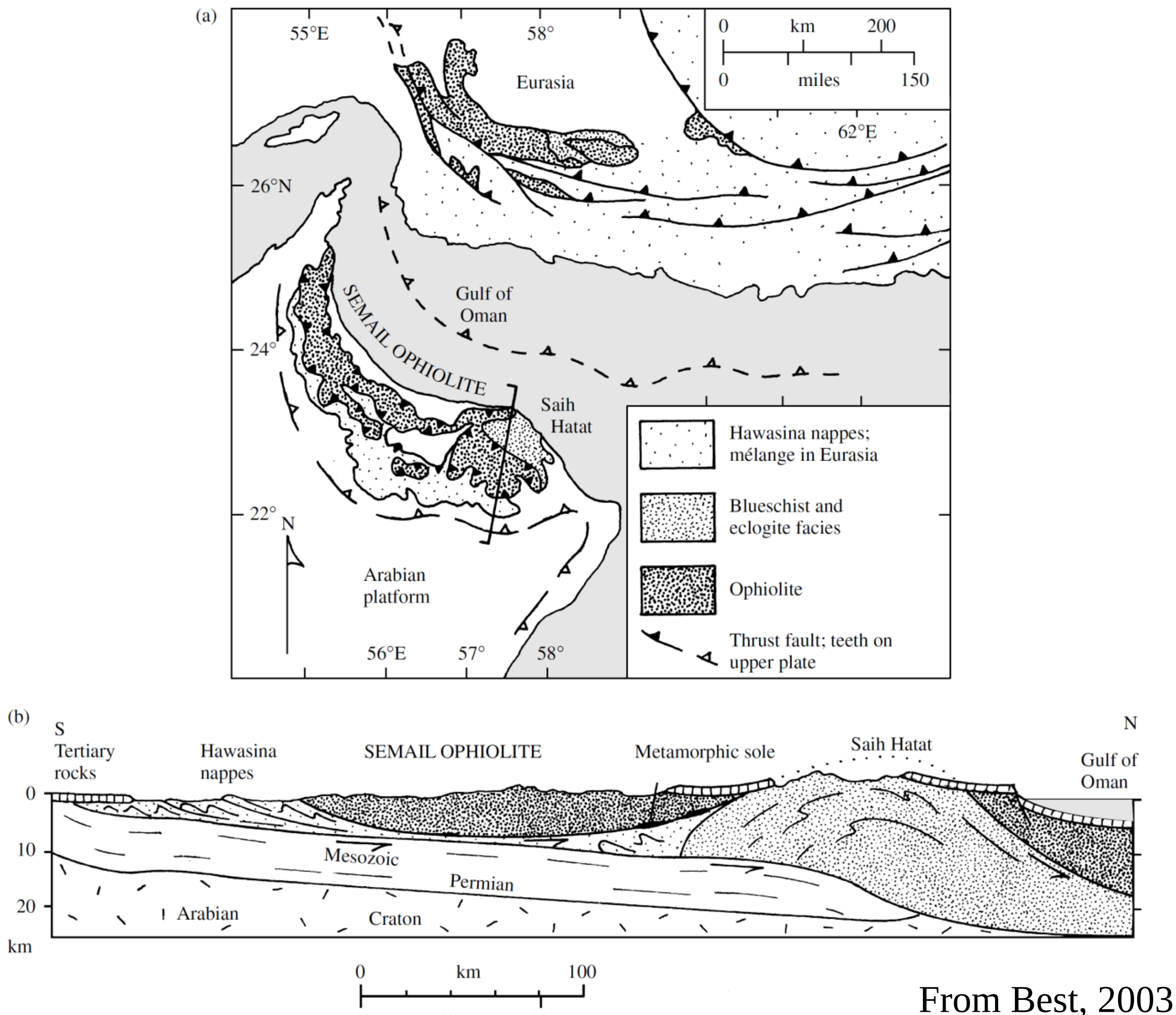


Tethyan Ophiolites exposed along the Alpine-Himalayan orogenic belt (Alpine-Mediterranean ophiolites)

- Ophiolite complexes render complete profiles of remnant oceanic crusts, which provide an excellent opportunity to directly study the complete profile of the oceanic crust and upper mantle

- Ophiolites have been reported from California, Cyprus, Oman, Pakistan, Newfoundland, New Zealand, Australia and New Guinea etc

- 550-km-long and 150-km wide Semail Ophiolite of Oman is the most studied ophiolite in the word based on its best exposure, volume and preservation (Searle and Cox, 1999).



From Best, 2003

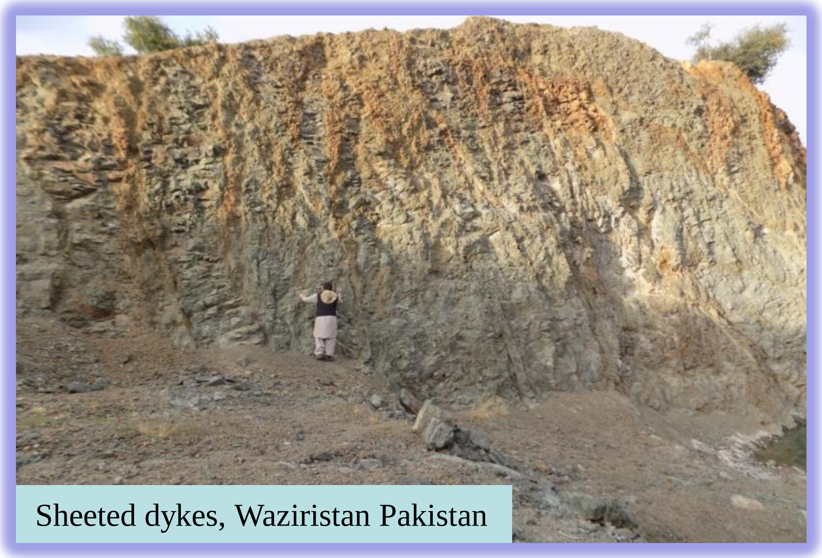
Map and cross section of the Semail Ophiolite (after Michard et al. 1995)

Ophiolite composition

Ophiolites are distinctive assemblage of marine sedimentary, Metamorphic and magmatic rocks

Ophiolite Sequence from top to bottom

(1) Marine Sedimentary Layer consists of chert (rich in Fe and Mg), deep marine limestone, shale, submarine volcanogenic sediments and turbidites
(2) Pillow basalt and breccia
(3) Sub-parallel sheeted dikes. These dikes feed basaltic lava above . They form a huge portion of the oceanic crust. These dikes form at actively expending oceanic crust around active mid oceanic ridges
(4) Massive Isotropic Gabbro. This layer of ophiolite also consists of plagiogranite (trondhjemite, albite granite, or granophyre)
(5) Layered ultramafic-mafic cumulates comprises from bottom to top pyroxene and olivine cumulate (dunite and peridotite) and Olivine+ Clino-pyroxene + Plagioclase cumulates (Gabbro)
(6) Mantle Peridotite, they usually metamorphosed to serpentine, also called alpine peridotite (Best, 2003).



Sheeted dykes, Waziristan Pakistan

Serpentine, Waziristan Pakistan

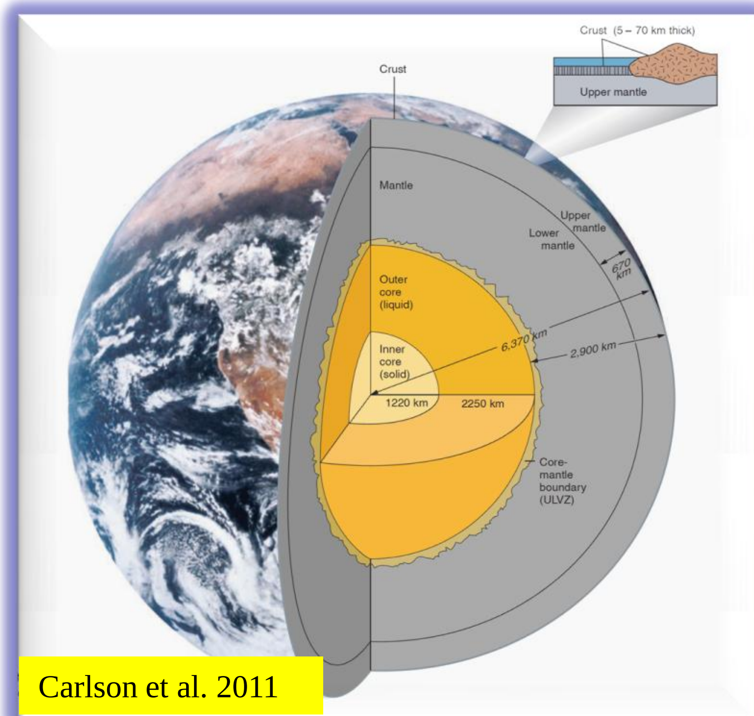
Explosive Breccia, Waziristan Pakistan

Pillow basalt, Waziristan Pakistan

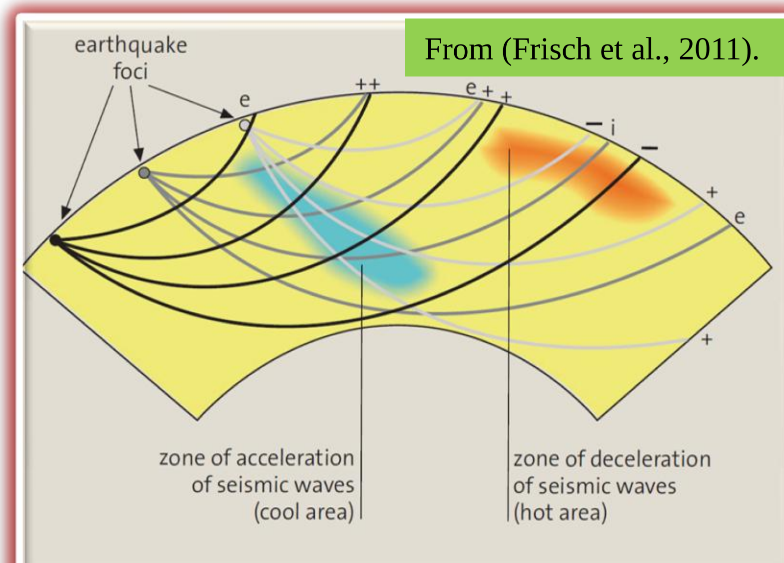
Internal Structure of Entire Earth

Seismic tomography

Seismic tomography involves to differentiate anomalous warmer and cooler zones through accelerated or decelerated earthquake seismology (Anderson and Dziewonski, 1984)

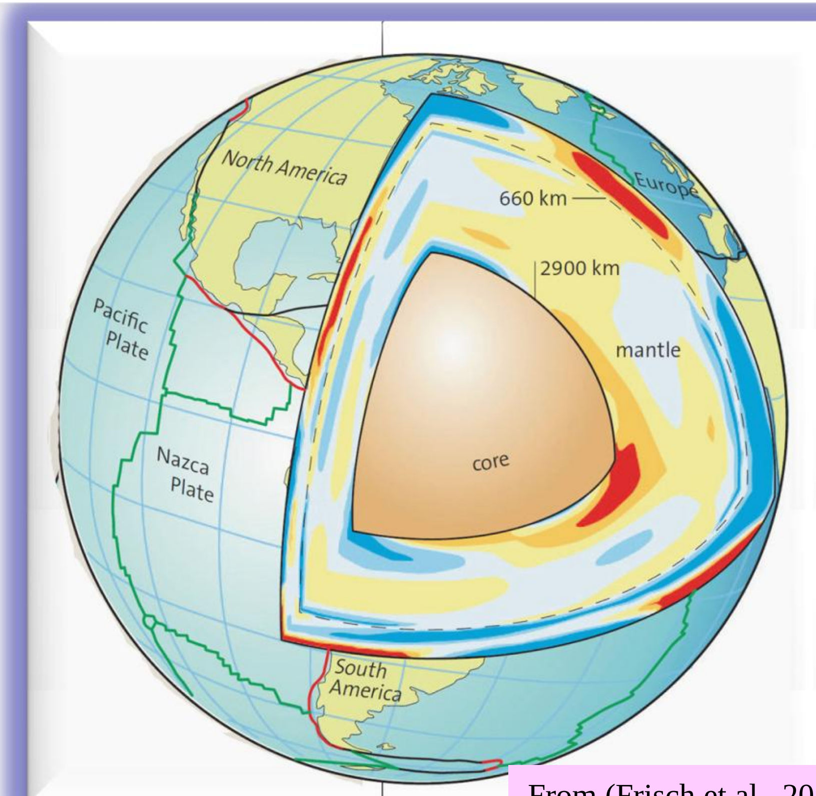


Carlson et al. 2011



From (Frisch et al., 2011).

Accelerated vs decelerated earthquake tomography

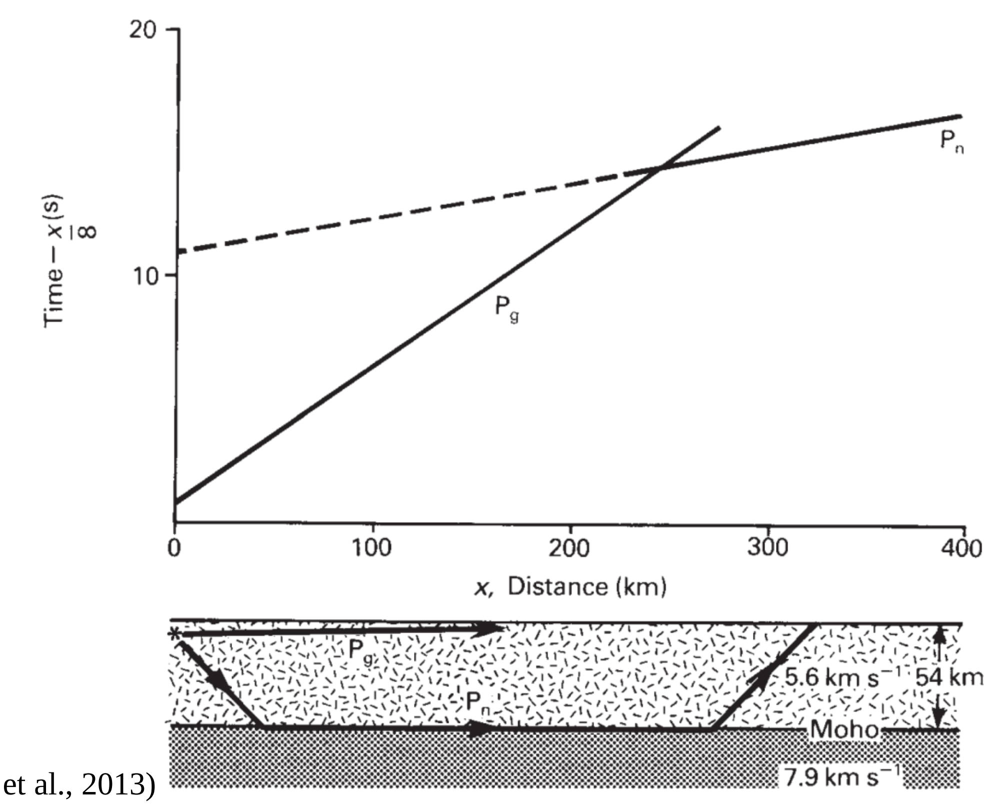


From (Frisch et al., 2011).

Seismic Tomographic Map of the Atlantic Ocean (after Dziewonski,http://www.seismology.harvard.edu/projects/3D/)

Velocity structure of the earth

- ➢Derived by earthquake seismology
- ➢Earth deeper layers have been studied using earthquake seismic waves that traversed the entire earth
- ➢The continental crust is ascertained by Andrija Mohorovicic in from the seismic waves produced by the 1909 Croatia earthquake
- ➢Mohorovicic or Moho is universally present beneath the Continental Crust (seismic velocity ~8 km/s)



(Kearey et al., 2013)

Mohorovicic Boundary between the Continental Crust and Upper Mantle

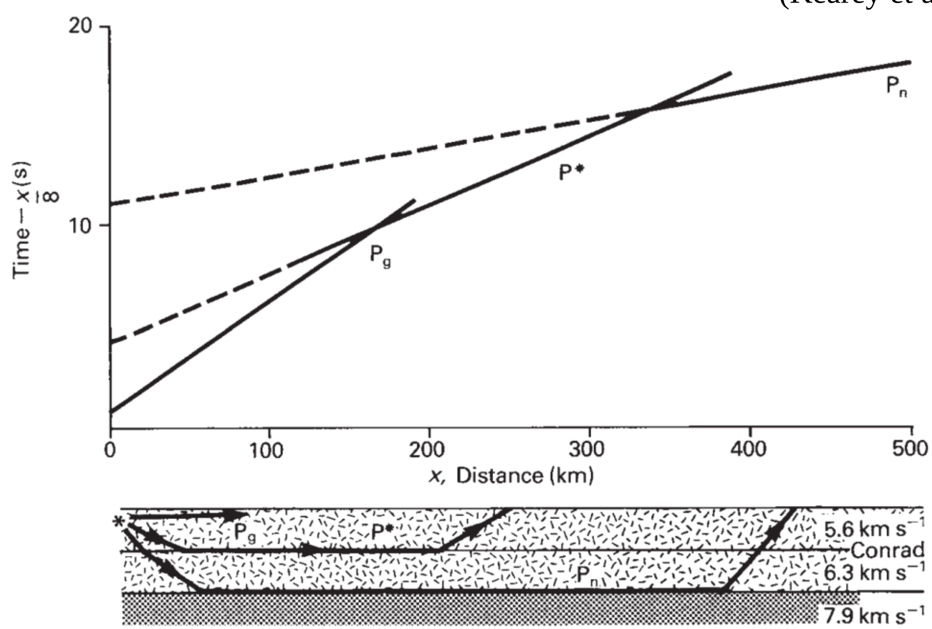
Conrad discontinuity

➢Conrad discontinuity was established by Conrad from earthquake seismicity in 1925

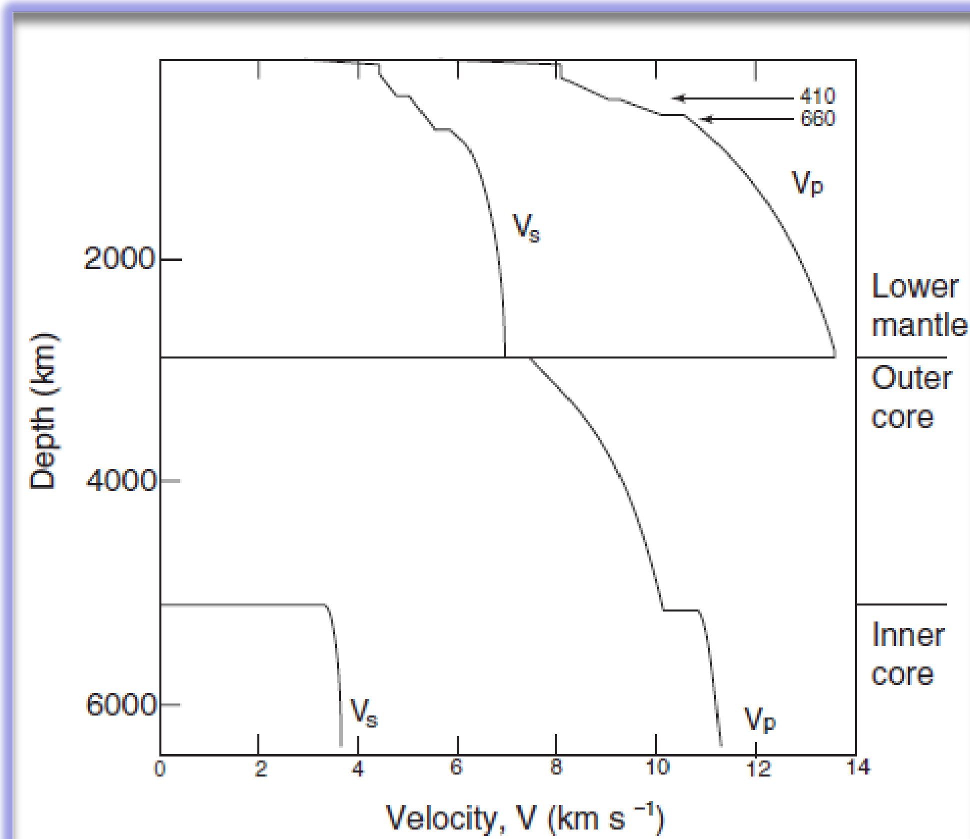
➢The Seismic wave velocity increases from 5.6 to 6.3 Km/s

➢The continental crust was divided into Silica-Alumina rich layer (SIAL) and Silica-magnesium rich layer (SIMA). The SIAL is the source of granitic magma and SIMA is the source of basaltic magma (Conrad is not present universally)

(Kearey et al., 2013)



Conrad discontinuity with the continental crust



After Helffrich & Wood, 2001

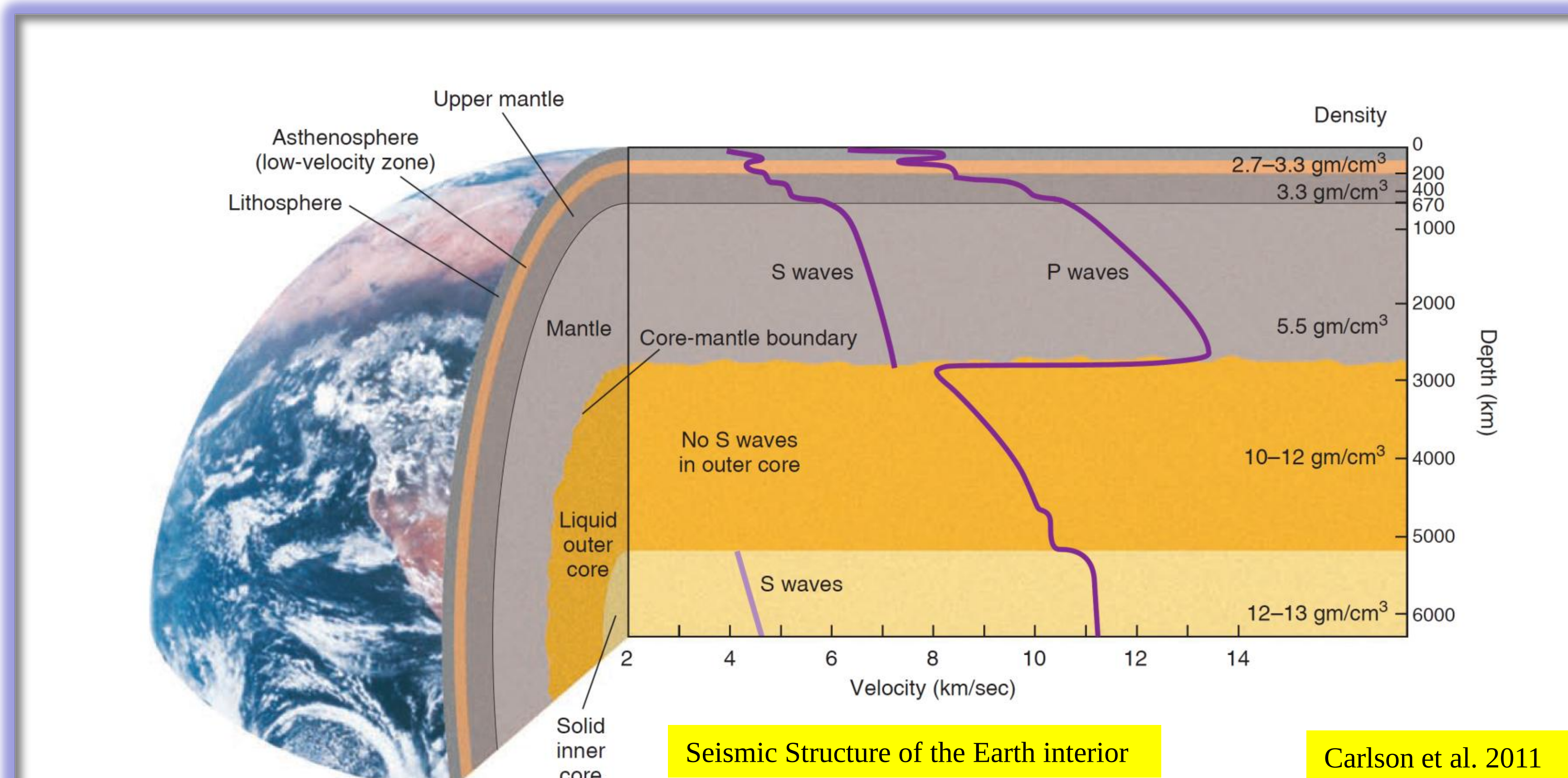
Variation in seismic wave velocities showing the major discontinuities of Earth

- The low velocity zone (LVZ) is universally present for S-waves at 100 and 300 km depth

- Between 410 and 660 km the mantle has been divided into upper mantle and Lower mantle based on rapid velocity increase associated with phase change

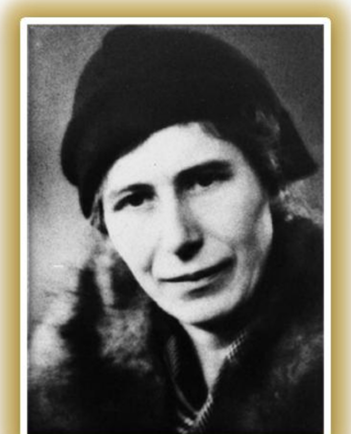
- The Gutenberg discontinuity separate the outer liquid core from the lower mantle at ~2891 km depth (S waves do not transmit in the liquid outer core

- S-waves transmission and increase in P-waves velocities at ~ 5150 km depth indicate solid inner core



Seismic Structure of the Earth interior

Carlson et al. 2011



- ➢ Inge Lehmann separated the liquid outer core from the solid inner core using the *P-wave* refraction pattern in 1936