NPTEL ONLINE CERTIFICATION COURSES

EARTHQUAKE SEISMOLOGY

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Module 12 : Seismology and Plate tectonics, Spreading centers, Subduction zones.

Lecture 03: Subduction zones

CONCEPTS COVERED

- **Subduction zones**
  - **Forms of plate convergence**
  - **Classification of earthquakes at subduction zones**
- **Earthquakes in subducting slabs**

Recap

- Plate tectonics treats the earth's outer shell as made up of about 15 rigid plates, about 100 km thick, which move relative to each other at speeds of a few cm per year.

- We observe spreading centres, subduction zones and transform fault as three types of plate boundaries.

- Volcanism, hydrothermal circulation through cooling oceanic lithosphere, and the cycle of uplift and erosion) are the processes by which the solid earth interacts with the ocean and the atmosphere.

- The interplate earthquakes both delineate plate boundaries and show the motion occurring there.

Recap

- Euler’s theorem states that the displacement of any rigid body (in this case, a plate) with one point (in this case, the centre of the earth) fixed is a rotation about an axis.

- Hotspots and deep mantle plume are used to track the absolute plate motion.

- Relative and absolute Euler vectors are simply related as
  $\omega_{ij} = \Omega_i - \Omega_j$

Recap

- The temperature as a function of depth and time is given by the one-dimensional heat flow equation

$$\frac{\partial T(z,t)}{\partial T} = \frac{k}{\rho C_p}\frac{\partial^2 T(z,t)}{\partial z^2} = \kappa\frac{\partial^2 T(z,t)}{\partial z^2}$$

The solution of the heat equation is:

$$T(z,t) = T_s(T_m - T_s)erf\left(\frac{z}{2\sqrt{\kappa t}}\right), \quad erf(s) = \frac{2}{\sqrt{\pi}}\int_0^s e^{-\sigma^2}d\sigma$$

- Temperature at a depth z for material of age t:

$$T(z,t) = T_m erf\left(\frac{z}{2\sqrt{\kappa t}}\right),$$

- An isotherm is a curve on which the argument of the error function is constant,

$$\frac{z_c}{2\sqrt{\kappa t}} = c \ or \ z_c = 2c\sqrt{\kappa t}$$

Recap

- The temperature and thus density in the cooling lithosphere vary, such that at the point (z,t) the temperature is T(z,t) and the corresponding density is

$$\rho(z,t) = \rho_m + \frac{\partial \rho}{\partial T}[T(z,t) - T_m] = \rho_m + \rho'(z,t)$$

- Density perturbation for the halfspace cooling model is

$$\rho'(z,t) = \alpha\rho_m[T_m - T(z,t)] = \alpha\rho_m T_m\left[1 - erf\left(\frac{z}{2\sqrt{\kappa t}}\right)\right]$$

- The isostatic condition for ocean depth,

$$h(t) = \frac{1}{(\rho_m - \rho_w)}\int_{h(t)}^{m(t)} \rho'(z,t)dz$$

Recap

- **Ocean depth should increase as the square root of plate age,**

$$h(t) = 2\sqrt{\frac{\kappa t}{\pi}}\frac{\alpha \rho_m T_m}{(\rho_m - \rho_w)}$$

- **For plate model, temperature vary as a position and depth is given as:**

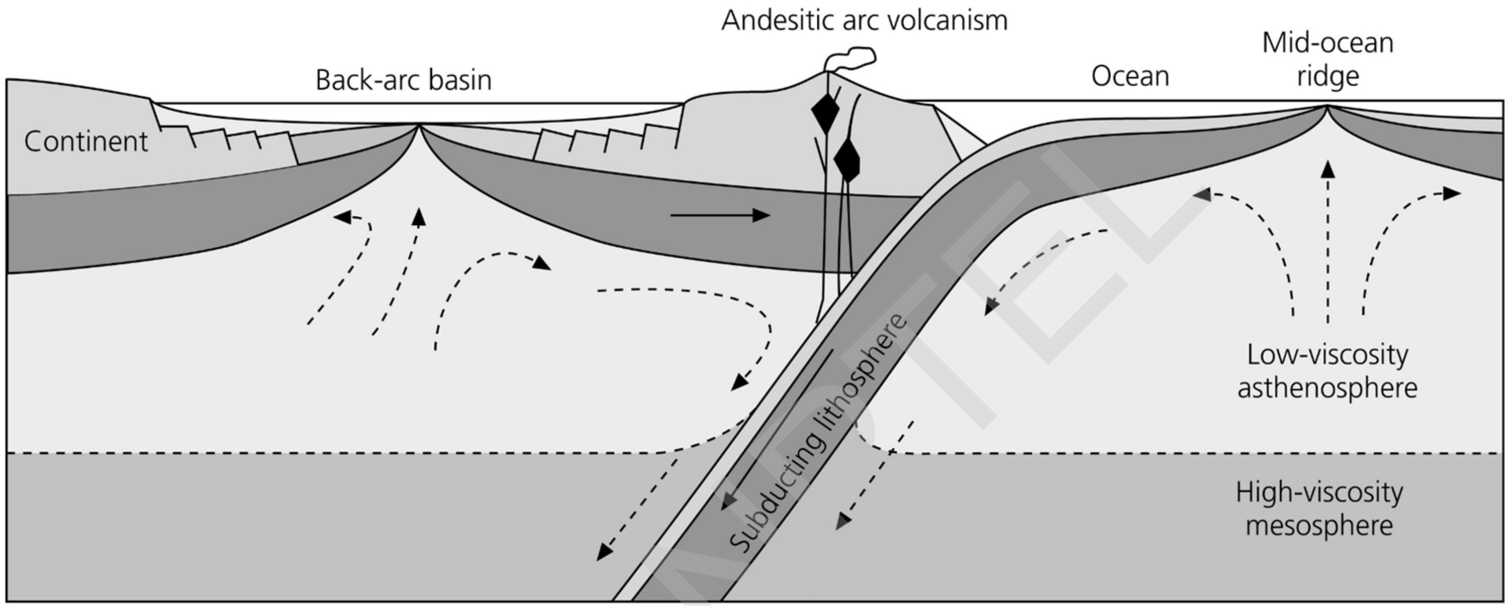
$$T(x, z) = T_m\left[\frac{z}{L} + \sum_{n=1}^{\infty} c_n \exp\left(\frac{-\beta_n x}{L}\right)\sin\left(\frac{n\pi z}{L}\right)\right]$$

Subduction zones

- ➔ Shallow depth earthquakes at spreading centers are upwelling limbs of the mantle convection system, reflects the processes forming oceanic lithosphere there.
- ➔ In a similar way, earthquakes at subduction zones, downwelling limbs of the convection system, reflect the processes by which oceanic lithosphere re-enters the mantle

Subduction zones

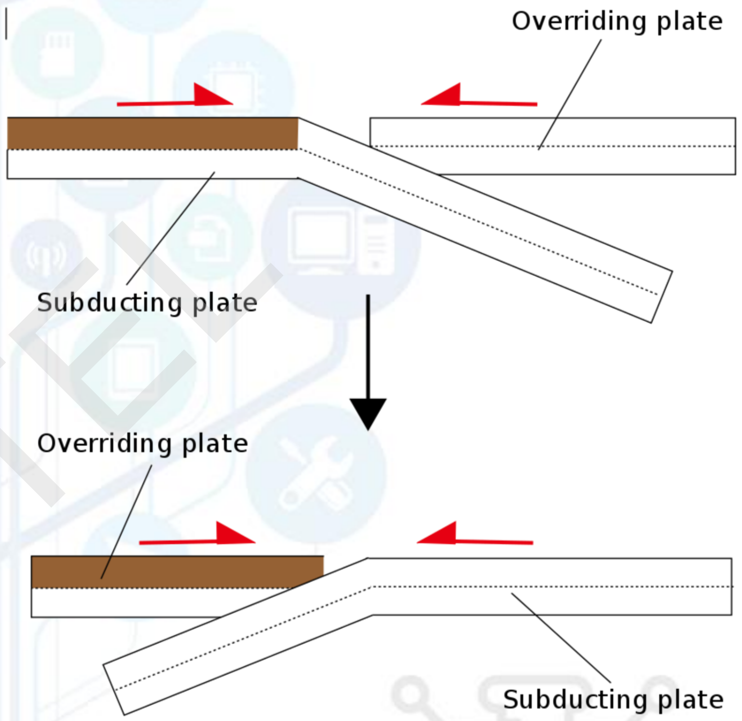
Figure 5.4-1: Cartoon of a subduction zone.



Schematic diagram of processes associated with the subduction of one oceanic plate beneath another.

Different kinds of subduction zones: Flip-flop/ Polarity reversal subduction

- ➔ **Subduction polarity reversal is a geologic process in which two converging plates switch roles: The over-lying plate becomes the down-going plate, and vice versa.**
- ➔ **This phenomenon is called subduction switch, the flipping of subduction polarity or subduction polarity reversal.**
- ➔ **For example Caledonides in Ireland and Alps-Apennines in Italy.**

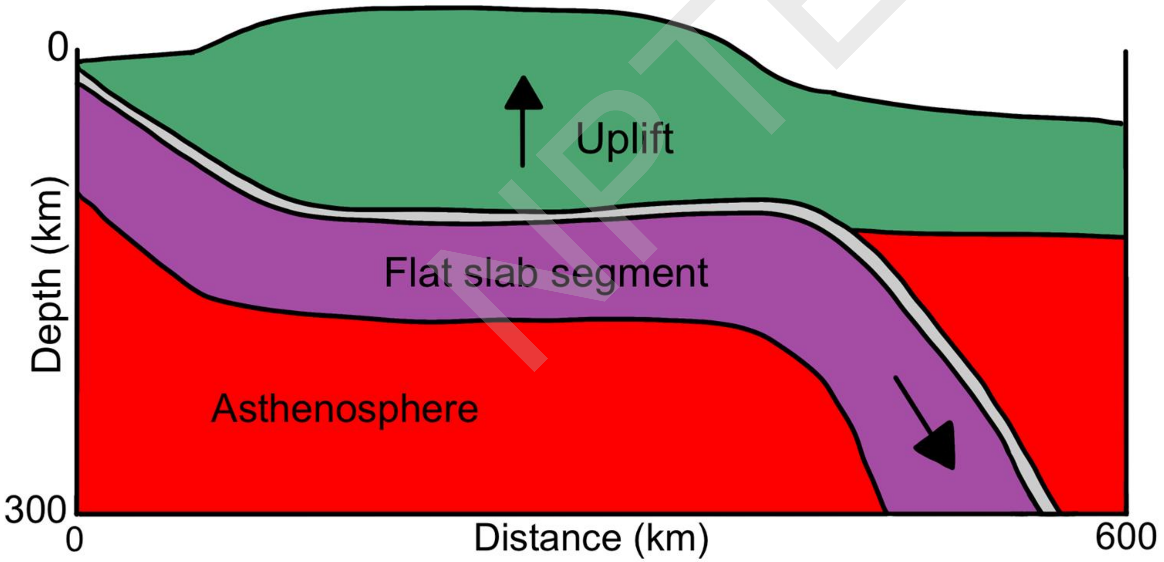


https://en.wikipedia.org/wiki/Subduction_polarity_reversal#/media/File:Subduction_polarity_reversal.svg

Different kinds of subduction zones: Flat Slab Subduction

- ➔ Characterized by a low subduction angle (<30 degrees to horizontal) beyond the seismogenic layer and a resumption of normal subduction far from the trench.

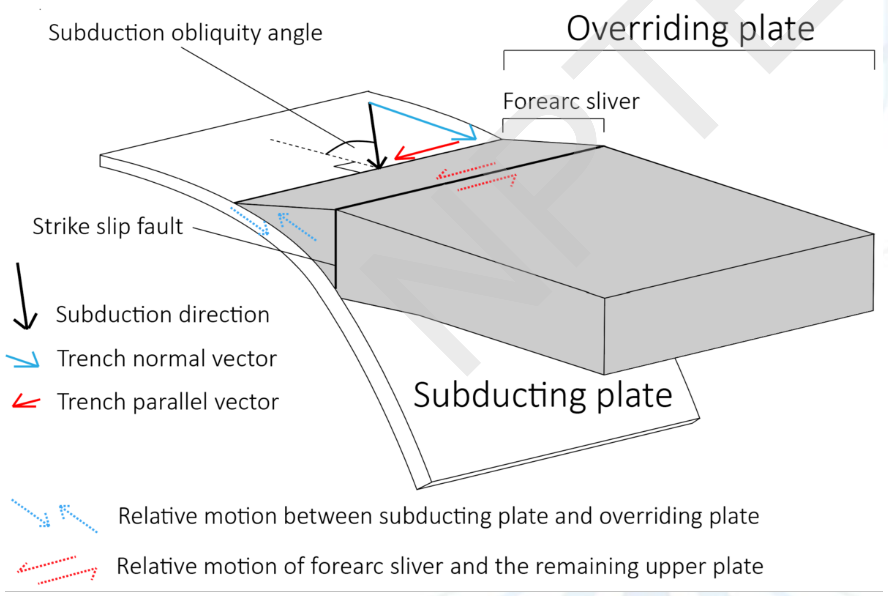
- ➔ A broader definition of flat slab subduction includes any shallowly dipping lower plate, as in western Mexico. (Wikipedia)



https://upload.wikimedia.org/wikipedia/commons/5/53/Flat_slab_subduction.png

Different kinds of subduction zones: Oblique Subduction

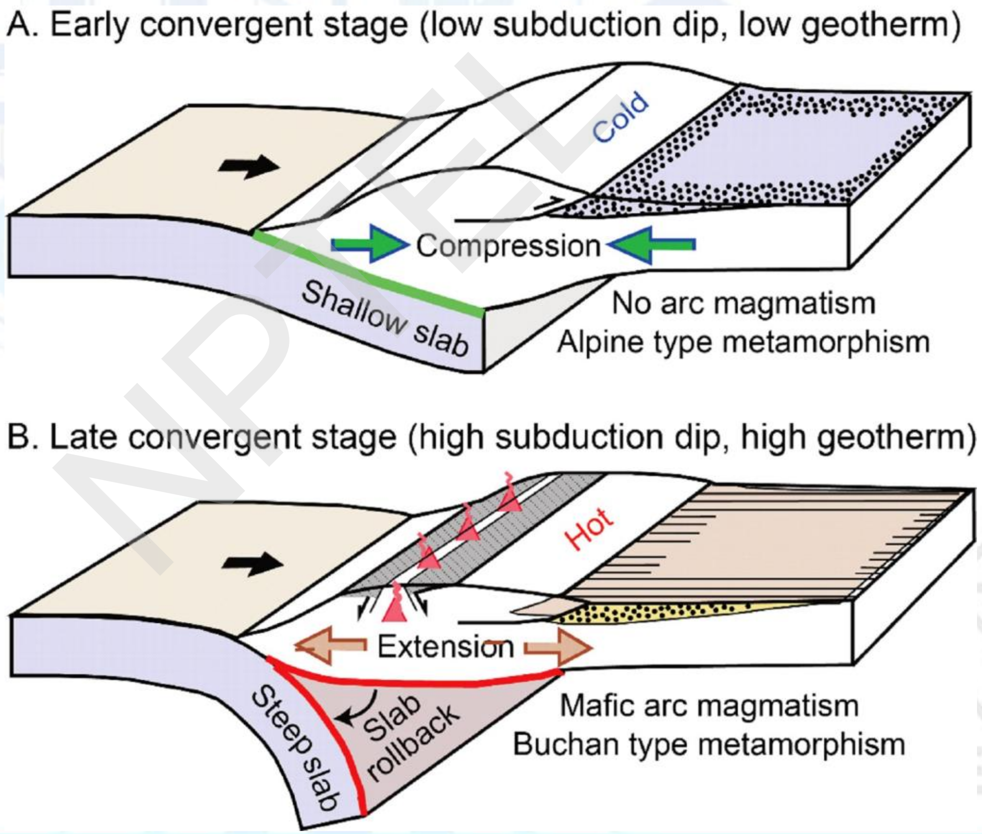
- Oblique subduction is a form of subduction (i.e. a tectonic process involving the convergence of two plates where the denser plate descends into Earth's interior) for which the convergence direction differs from 90° to the plate boundary. (Wikipedia)
- In general, the obliquity angle is between 15° and 30°. Subduction zones with high obliquity angles include Sunda trench (ca. 60°) and Ryukyu arc.



https://en.wikipedia.org/wiki/Oblique_subduction

Different kinds of subduction zones: Roll-back subduction

➔ **When the negatively buoyant slab (compared to the asthenosphere) is long and heavy, or anchored in the mantle, it can sink more rapidly than the rate of plate convergence. The gravitationally unstable slab becomes steeper, which produces a migration of the hinge zone and the bulge, where the slab bends, away from the arc.**



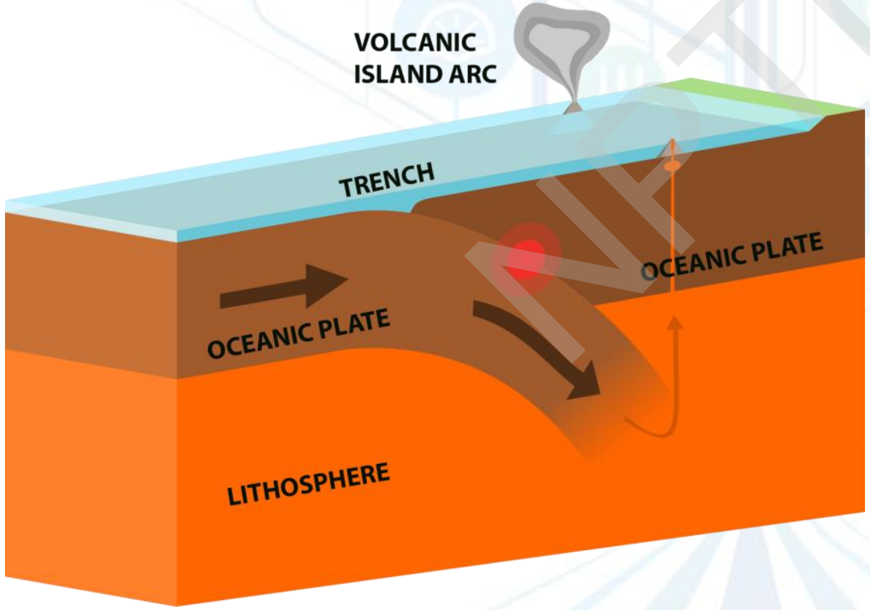
https://phys.org/news/2022-06-tectonics-convergent-plate-margins-insights.html

Subduction zones: Forms of plate convergence

a. Oceanic-Oceanic lithosphere

→ A volcanic island arc forms, and seafloor spreading occurs behind the arc, forming a back-arc basin or marginal sea.

→ The Mariana Trench, deepest ocean trench, is more than 35,000 feet below sea level. It is the result of the Pacific Plate moving beneath the Mariana Plate.

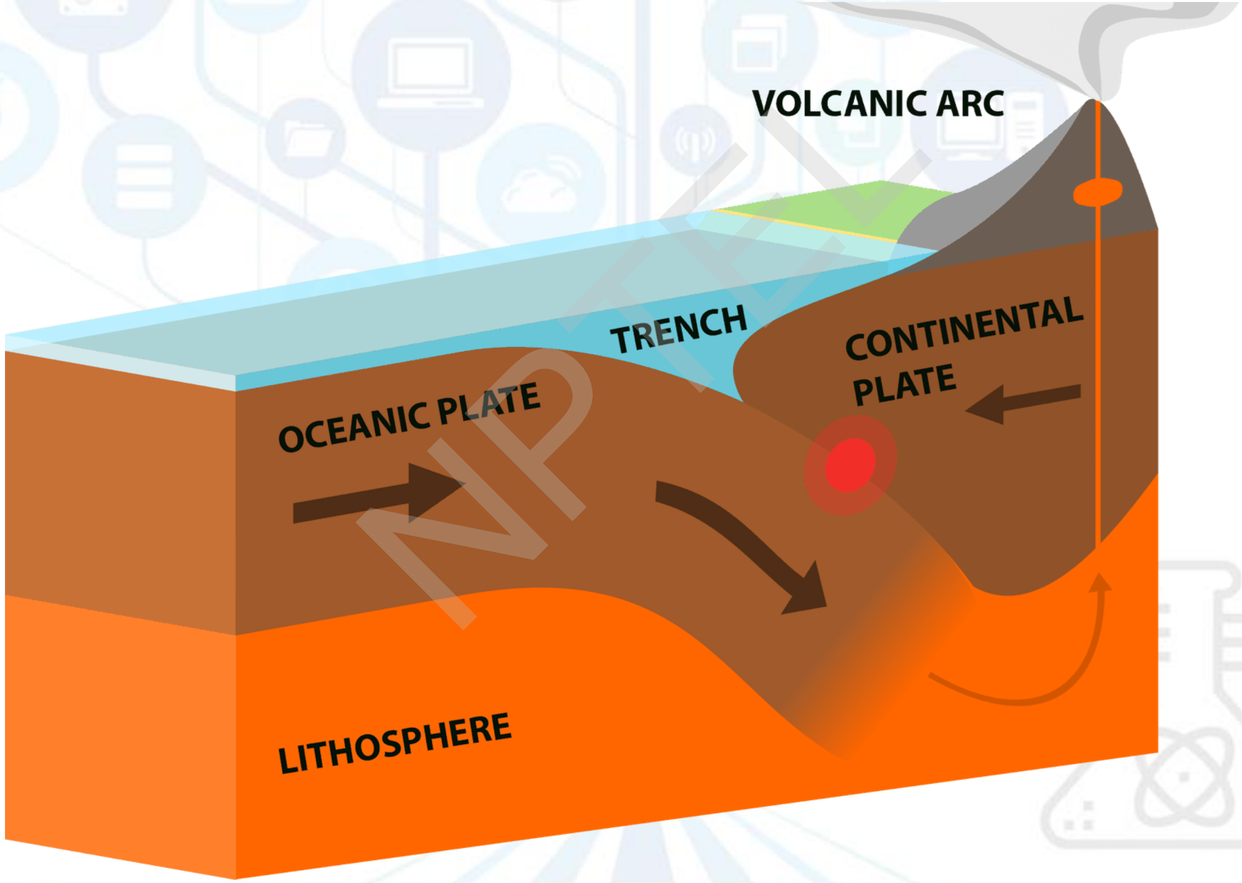


https://www.thoughtco.com/convergent-plate-boundaries-3866818

Subduction zones: Forms of plate convergence

b. Oceanic -Continental lithosphere

When oceanic lithosphere subducts beneath a continent, a mountain chanin like the Andes forms on the continent, and oceanic lithosphere forms a Wadati-Benioff zone.



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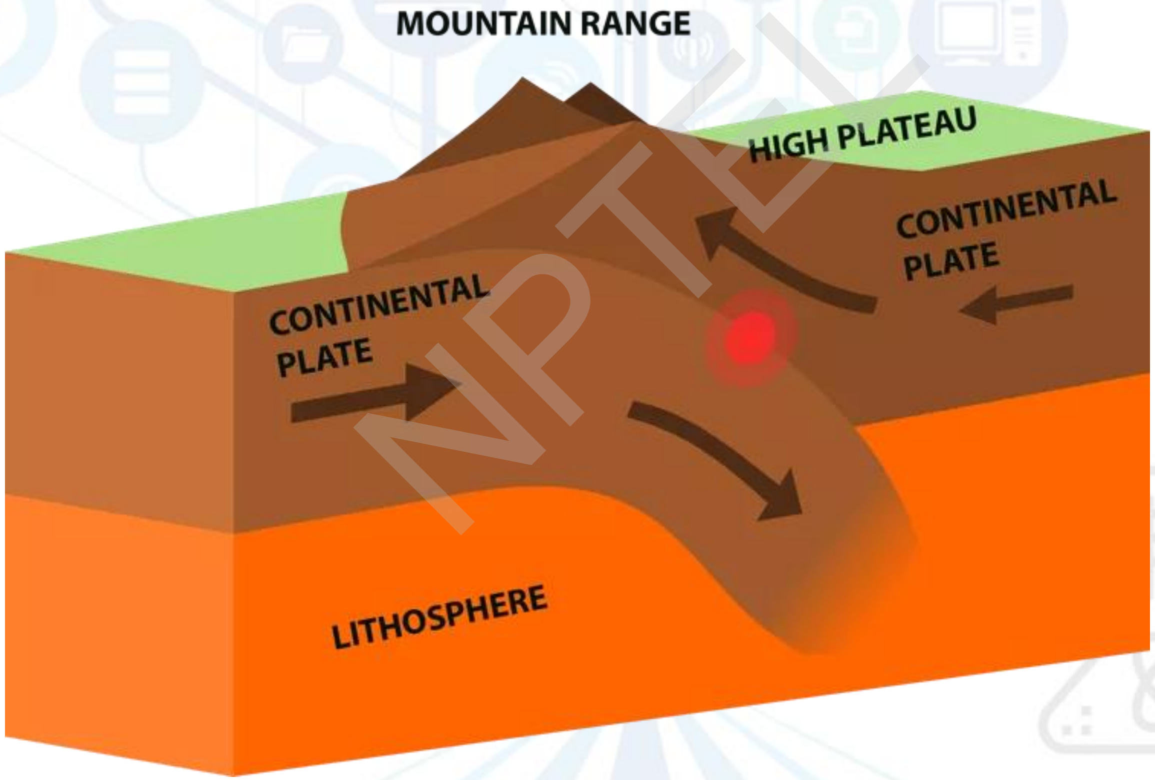
Subduction zones: Forms of plate convergence

c. Continental-Continental convergence

As the continental crust can not subduct, convergence between two continental plates,as in the Himalayas, causes crustal thickening, mountain building, and shallow earthquakes but does not create a Wadati Benioff zone.



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Classification of earthquakes at subduction zones

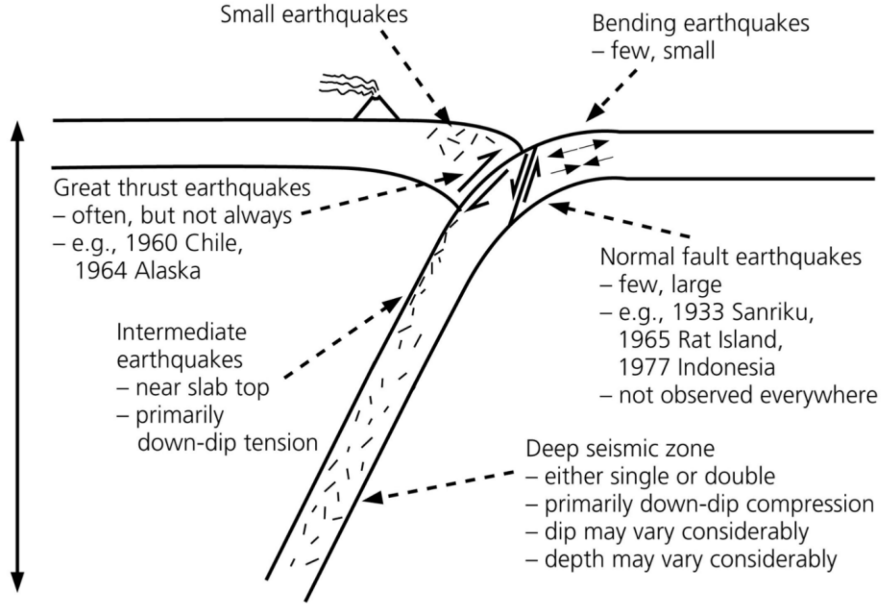
- Subduction zone earthquake can differ in depths, tectonic environments and focal mechanism.

- Based on depth, earthquakes at subduction zone can be classified as

  Shallow (less than 70 km deep) focus earthquakes
  Intermediate (70-300 km deep) focus earthquakes
  Deep (more than 300 km deep) focus earthquakes

Tectonic environments

Figure 5.4-2: Various earthquake types observed at subduction zones.



➔ **The shallow earthquakes are associated with the interaction between the two plates.**

➔ **The largest and most common of these shallow earthquakes occur at the interface between the plates, and release the plate motion that has been locked at the plate interface**

➔ **In addition, shallow earthquakes can occur within both the overriding and the subducting plates.**

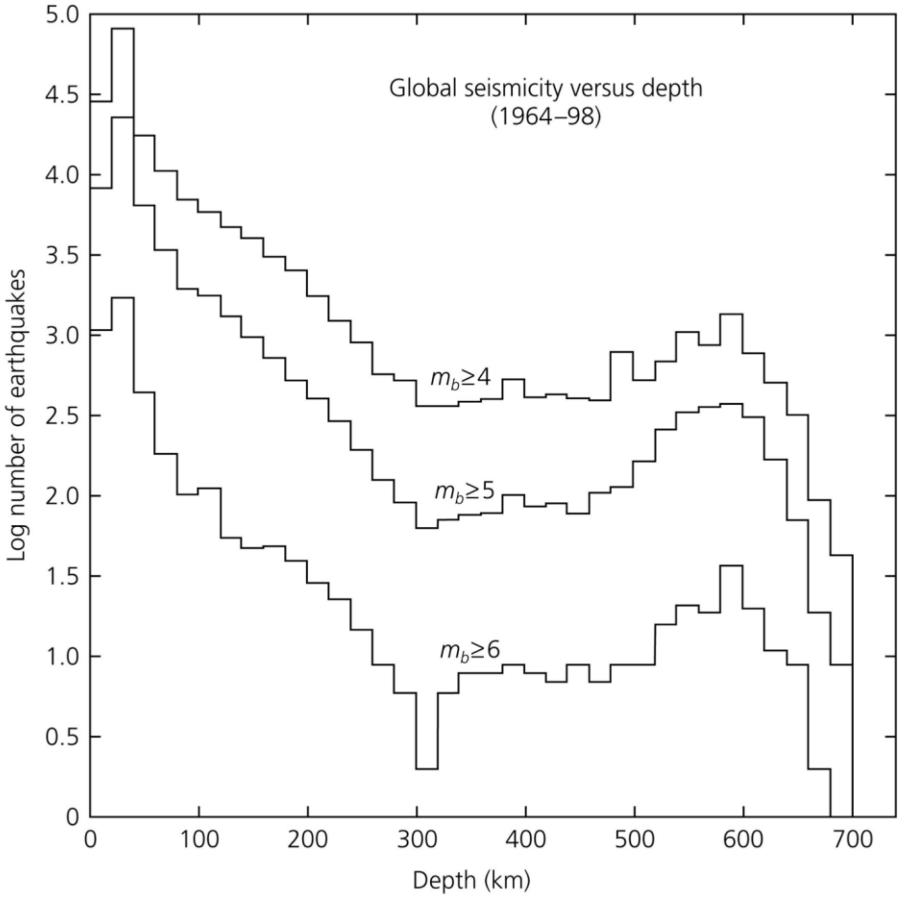
➔ **The intermediate and deep earthquakes forming the Wadati–Benioff zone occur in the cold interiors of downgoing slabs.**

Thermal evolution of subduction

- ➔ The thermal models for subduction, is used to gain insight into earthquake and seismic velocity observations.
- ➔ Moreover, seismological observations, thermal models, and calculation of behaviour of materials at high temperature and pressure are combined to investigate the complicated regions.
- ➔ The essence of subduction is the penetration and slow heating of a cold slab of lithosphere as it descends into the warmer mantle.
- ➔ Slabs subduct rapidly compared to the time needed for heat conducted from the surrounding mantle to warm them up. Thus they remain colder, denser, and mechanically stronger than the surrounding mantle.
- ➔ Consequently, slabs transmit seismic waves faster and with less attenuation than the surrounding mantle, making it possible to map slabs and to show that deep earthquakes occur within them.

Earthquakes in subducting slabs

Figure 5.4-9: Distribution of seismicity with depth in subduction zones.



why we distinguish intermediate and deep earthquakes ?

- → **Seismicity decreases to a minimum near about 300 km, and then increases again.**
- → **Deep earthquakes, those below about 300 km, are thus generally treated as distinct from intermediate earthquakes. Deep earthquakes peak at about 600 km, and then decline to a minimum before 700 km**

Possible reason for this distribution of earthquakes may be…………..

- Near the surface the slab is extended by its own weight, whereas at depth it encounters stronger lower mantle material, causing down-dip compression.

- Another possible factor may be mineral phase changes that occur at different depths in the cold slab than in the surrounding mantle.

Slab pull

- ➔ The thermal model gives the force driving the subduction due to the integrated negative buoyancy of a slab resulting from the density contrast between it and the warmer and less dense material at the same depth outside.

- ➔ This force, known as "slab pull," is the plate driving force due to subduction. Specifically, it is the negative buoyancy associated with a cold downgoing limb of the convection pattern. Its significance for stresses in the downgoing plate and for driving plate motions depends on its size relative to the resisting forces at the subduction zone

- ➔ "slab pull" force is balanced by local resistive forces, a combination of the effects of the viscous mantle and the interface between plates.

Summary

- Earthquakes at subduction zones, downwelling limbs of the convection system, reflect the processes by which oceanic lithosphere re-enters the mantle.

- There are basically three types plate convergence we observe, oceanic-oceanic, oceanic-continental and continental-continental plates.

- Earthquake at subduction zones are classified into shallow(<70 km), intermediate(70-300 km) and deep focus(>300 km) earthquakes based on the depth of occurrence.

- On the basis of tectonic environment at subduction zones we classify the earthquakes into one which occur due to interaction between the plates(shallow focus) and other which occurs in cold interior of downgoing slabs.

- In subduction zones, focal mechanism for shallow earthquake(<300 km) shows downdip tenson and downdip compression is observed deeper than 300 km.
- “slab pull,” is the plate driving force due to subduction. Specifically, it is the negative buoyancy associated with a cold downgoing limb of the convection pattern.

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THANK YOU !