NPTEL ONLINE CERTIFICATION COURSES

EARTHQUAKE SEISMOLOGY

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Module 12 : Seismology and Plate tectonics, Spreading centers, Subduction zones.
Lecture 01: Seismology and plate tectonics, Plate kinematics

CONCEPTS COVERED

- Plate tectonics
  - Plate boundaries
  - Thermal convection system
  - Evolution of Earth’s ocean and lithosphere
  - Seismology
- Plate kinematics
  - Relative plate motions
  - Absolute plate motions

Summary

Recap of Module 11

- **Geodetic methods using signals from space permits all three components of position to be measured to sub-centimeter precision and now give coseismic motion to high precision much more easily than was previously possible.**

- **Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), and Global positioning system (GPS) are popular geodetic techniques to measure ground deformation.**

- **GPS uses a constellation of satellites transmit coded timing signals on a pair of microwave carrier frequencies synchronized to very precise on-board atomic clocks.**

- **GPS data can be obtained for continuous period of time or short period of time. The later one is cheaper.**

- **The biggest limitation of geodetic data for earthquake studies is that the positions of geodetic markers before the earthquake are needed.**

Recap of Module 11

- For radar, d is the antenna length, so a radar a distance r above the earth's surface could resolve objects of size x, where $$\theta_d = \lambda/d = x/r$$

- The phase difference between radar signals with wavelength λ reflected from the Earth's surface and recorded by antennas at position A_1 and A_2 is $$\phi = (4\pi/\lambda)(r_2 - r_1)$$

  r_i is the range from the antenna at A_i to the reflection point.

- If differences in satellite positions between the measurements are removed, a vector surface displacement D causes a phase change

$$\phi \approx (4\pi/\lambda)\delta r, \quad \delta r = (D.\hat{r}),$$

  where δr is the projection of the vector displacement along, the look direction connecting the satellite and reflection point.

- The results are shown as a phase difference map, called a differential interferogram.

Recap of Module 11

- Static coseismic displacement contain $1/r^2$ terms, compared to $1/r$ terms for the propagating waves. Thus, it decay more rapidly with distance from the earthquake.

- For infinite length fault, the fault-parallel displacement in the x direction, u(y), varies with distance from the fault y as

$$u(y) = \pm D/2 - (D/\pi)\tan^{-1}(y/W)$$

- For finite length faults the displacement tapers off rapidly past the fault ends. If a fault is buried and extends from depth w to depth W

$$u(y) = (D/\pi)\left[\tan^{-1}(y/w) - \tan^{-1}(y/W)\right]$$

- A fault that does not reach the surface, the displacement is both reduced in amplitude and varies more smoothly with distance than it would for a fault extending to the surface.
- Estimation of fault parameter using geodetic data is an inverse problem and has highly non unique solutions.

Recap of Module 11

- **Seismic waves have an ambiguity in distinguishing between the fault plane and the auxiliary plane, the geodetic data do not as static displacements models do not have nodal plane perpendicular to fault plane.**

- **We use strong motion data, Teleseismic data and geodetic data that provides good constraints on fault geometry and slip on it.**

- **Geodetic data that depend on the difference in position before and after an earthquake provide no information about what happened during the earthquake, whereas seismological data can sometimes show how the rupture evolved**

- **The results for the different data types differ because each is sensitive to different features of the slip**

- **In post-seismic slip deformation goes on "silently" (without a seismic signal) for some time after an earthquake and its seismologically observed aftershocks**

Recap of Module 11

- **Fault-parallel interseismic motion s(y) is given as:** $s(y) = D/2 + D/\pi \tan^{-1}(y/W)$

- **The coseismic slip u(y) is less than D = vt except at the fault.**

- **Interseismic motion is the difference between the far-field motion and coseismic deformation, its variation with distance from the fault depends on the locking depth and farfield rate.**

- **Interseismic shear strain rate** $\dot{e}_{xy} = \dfrac{1}{2}\dfrac{ds(y)}{dy} = \dfrac{v}{2\pi W}\dfrac{1}{\left[1 + (y/W)^2\right]}$

- **Consider measuring the rate v of motion of a monument that started at position x_1 and reaches x_2 in time T. If the position uncertainty is given by its standard deviation σ, then the propagation of errors relation shows that**

$$v = (x_1 - x_2)/T \quad \Longrightarrow \quad \sigma_v = \sqrt{2}\sigma/T$$

where σ_v is the uncertainty of the inferred rate.

Plate tectonics

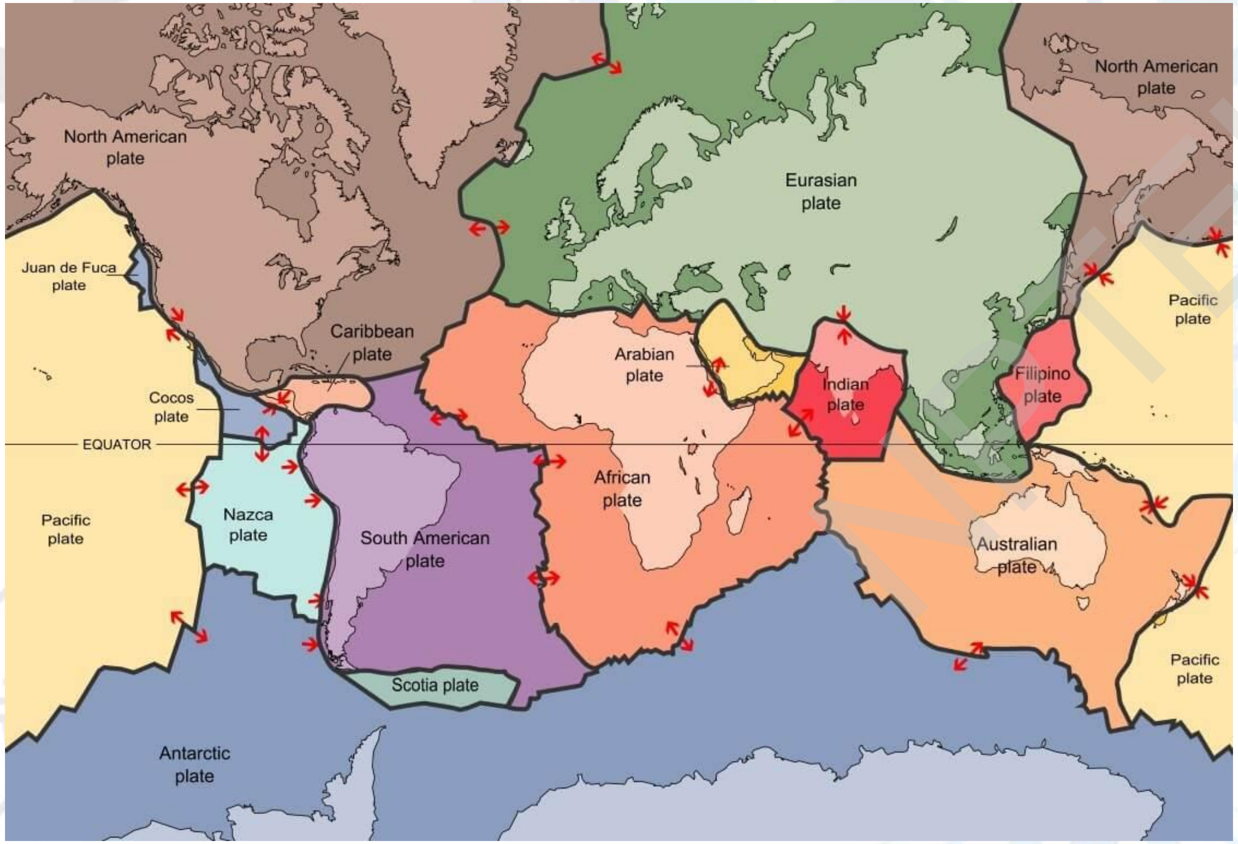
- **The theory of plate tectonics was given from the earlier theory of continental drift, proposed in its modern forms by alfred wegener in 1915.**

- **These ideas were based on remarkable fits between South American and African plates. Most geologist did not accept this claim due to the lack of evidences.**

- **By 1970s, the most geologists accept Wegener's ideas based on geometry and history of the earth's magnetic field. This led to the realization that outer shell of the Earth is moving.**

Plate tectonics

- **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.**



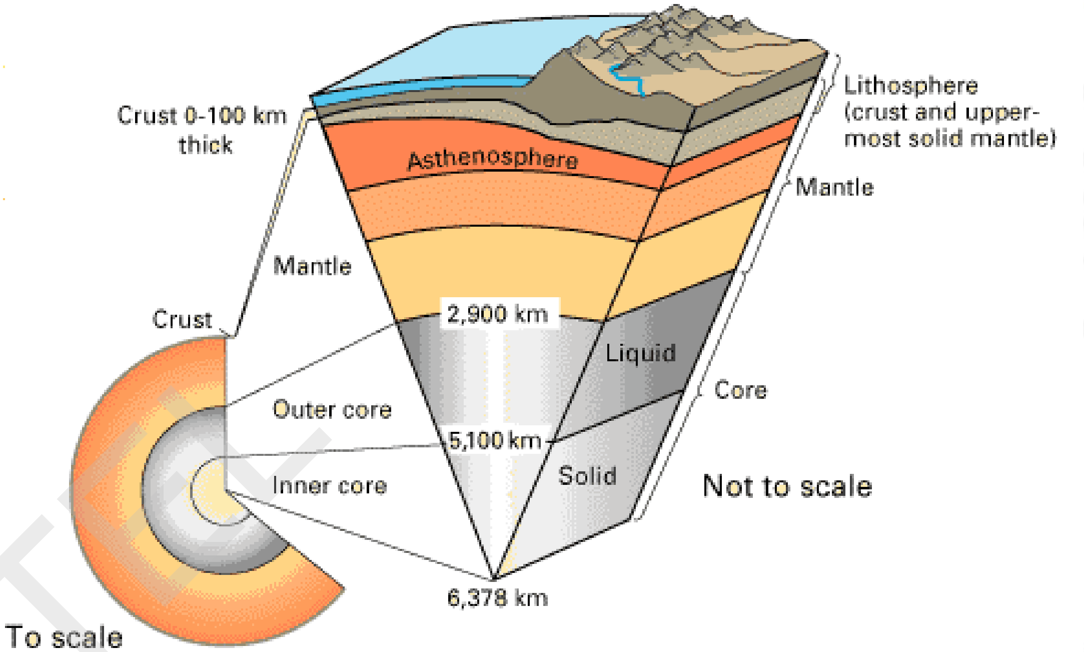
https://www.pmfias.com/plate-tectonics/

Plate tectonics

- The plates are rigid in the sense that little (ideally no) deformation occurs within them, so deformation occurs at their boundaries, giving rise to earthquakes, mountain building, volcanism, and other spectacular phenomena.

- These strong plates form the earth's lithosphere, and move over the weaker asthenosphere below

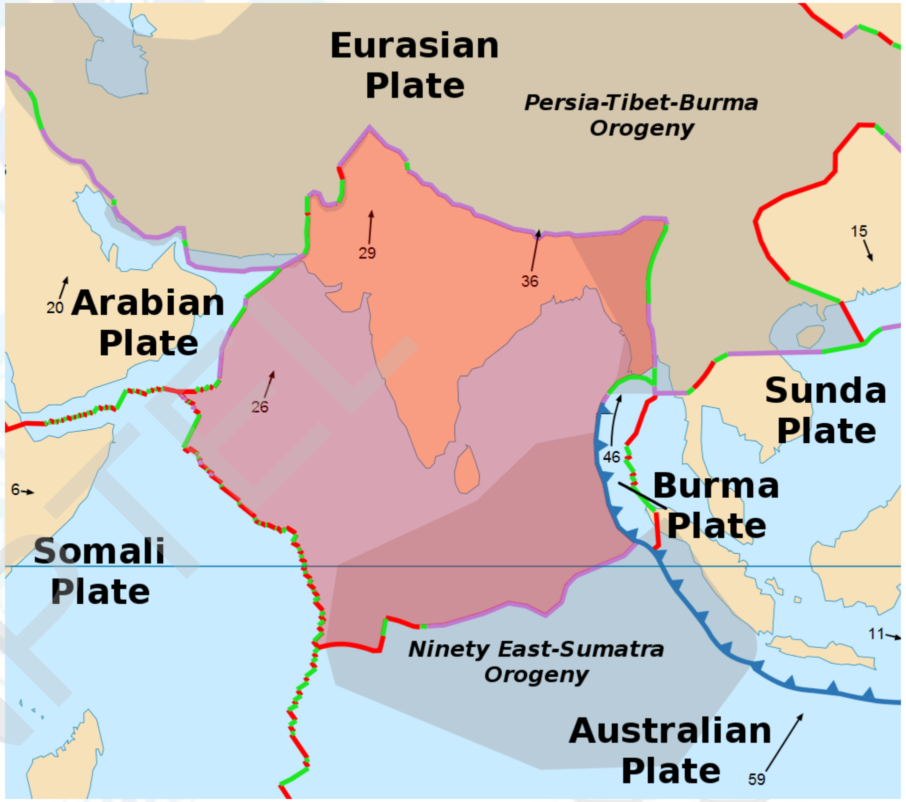
- The lithosphere and asthenosphere are mechanical units defined by their strength and the way they deform. The lithosphere includes both the crust and part of the upper mantle.



https://byjus.com/free-ias-prep/ncert-notes-geography-structure-of-the-earth/

Plate tectonics

- Indian Plate tectonics.
  - ➔ The Indian Plate (or India Plate) is a minor tectonic plate in the Eastern Hemisphere.
  - ➔ Originally a part of the ancient continent of Gondwana, the Indian Plate broke away from the other fragments of Gondwana 100 million years ago, began moving north and carried Insular India with it.
  - ➔ It was once fused with the adjacent Australian Plate to form a single Indo-Australian Plate.

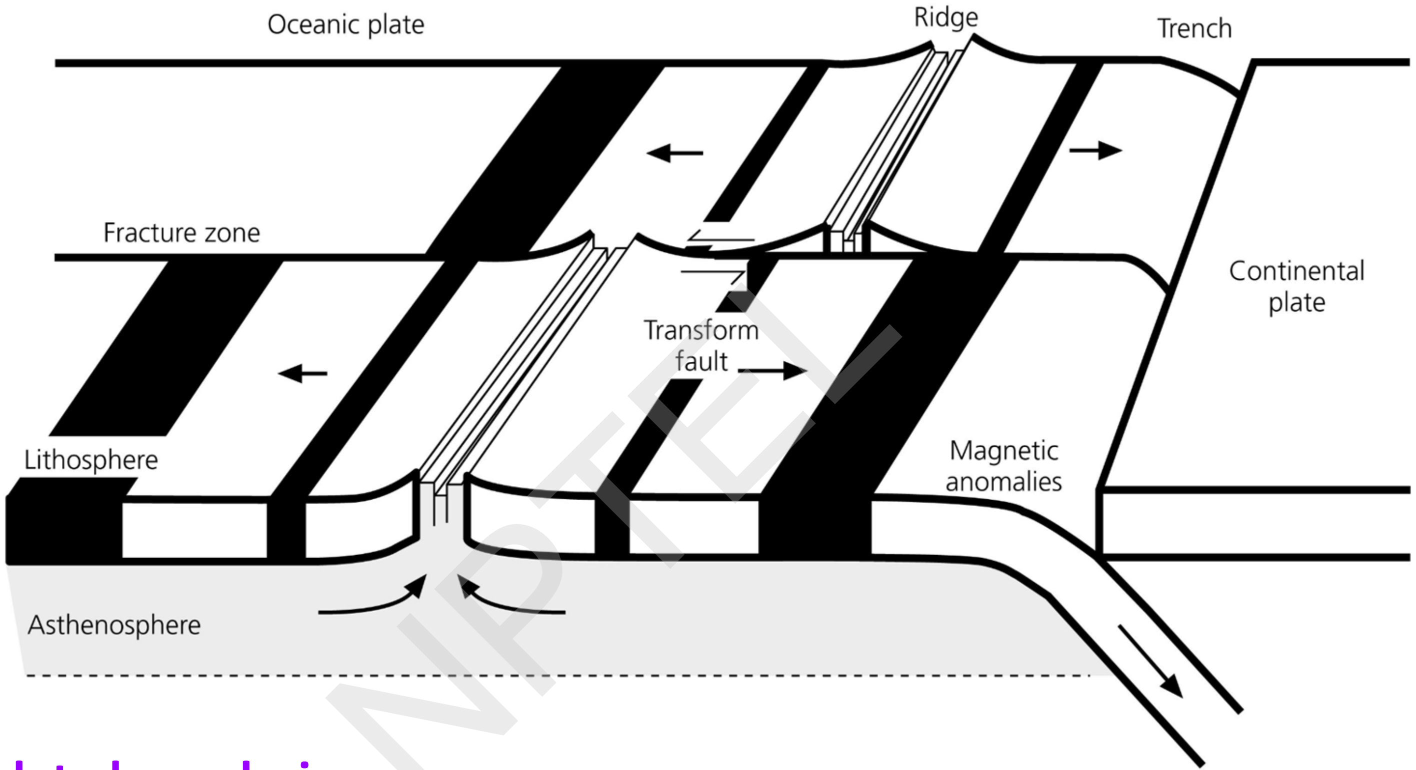


https://en.wikipedia.org/wiki/Indian_Plate

Plate tectonics

Plate boundaries

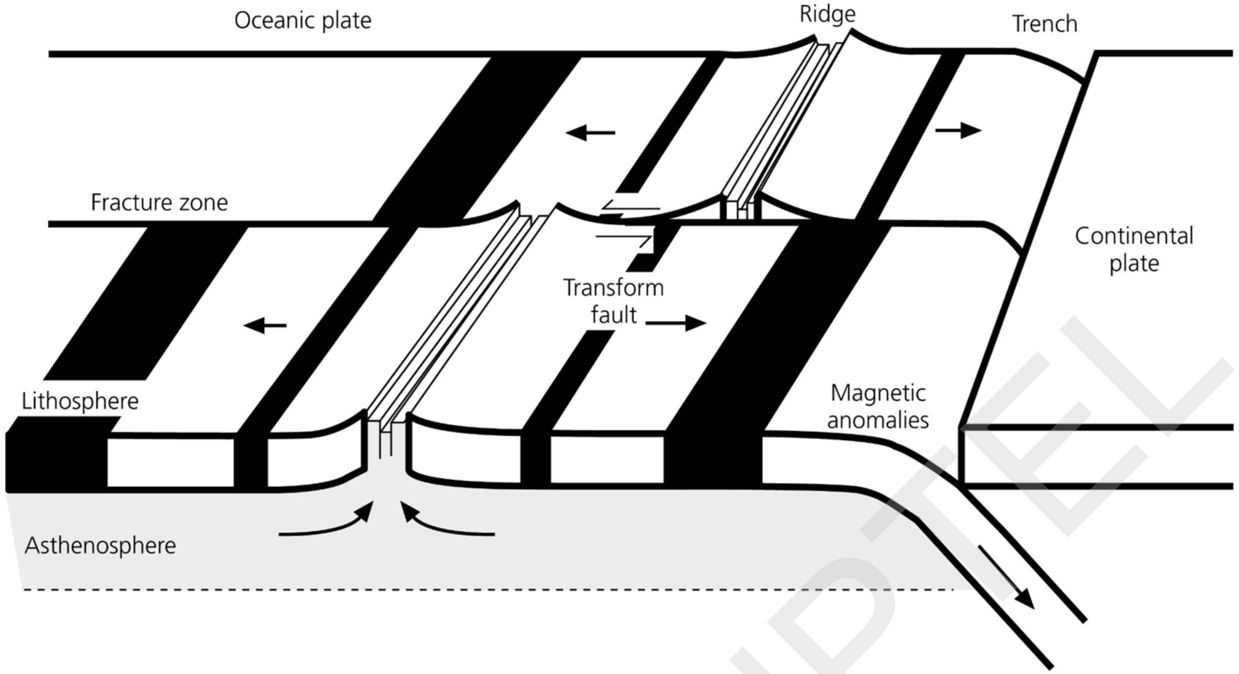
Figure 5.1-1: Cartoon of plate tectonics.



The basic three types of plate boundaries

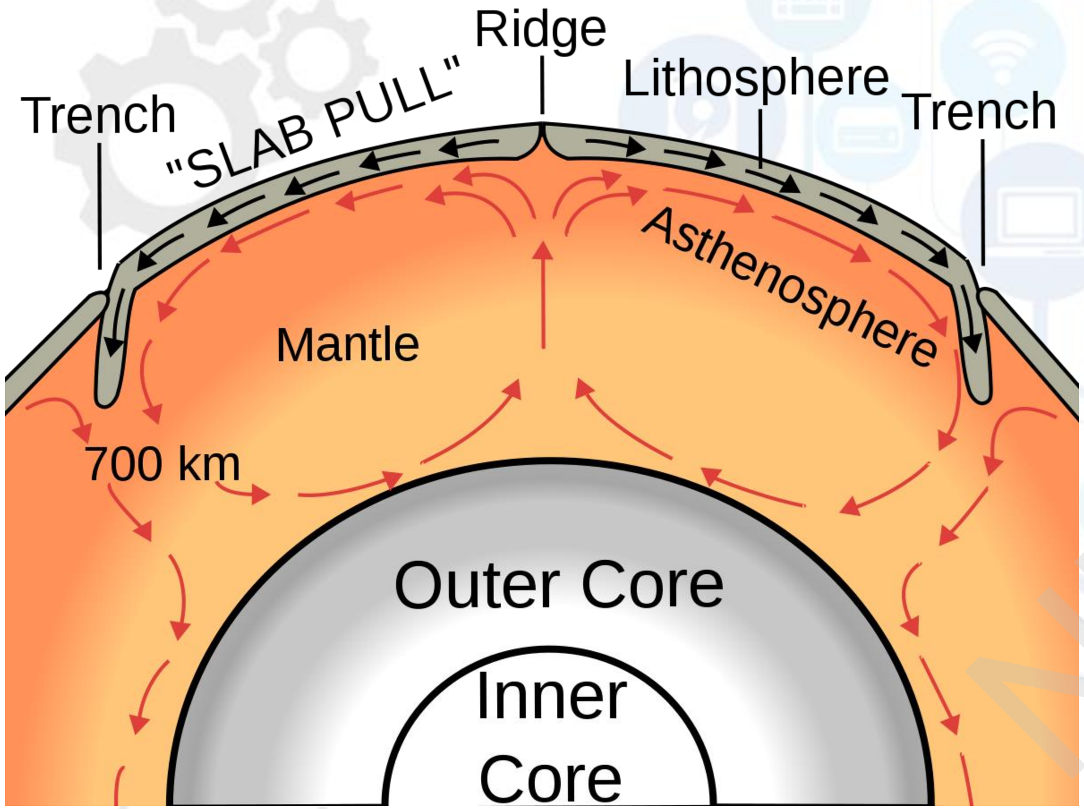
The direction of the relative motion between two plates at a point on their common boundary determines the nature of the boundary.

Figure 5.1-1: Cartoon of plate tectonics.



- ➔ spreading centers both plates move away from the boundary
- ➔ subduction zones the subducting plate moves toward the boundary.
- ➔ transform faults, relative plate motion is parallel to the boundary.
- ➔ The cooling oceanic lithosphere moves away from the ridges, and eventually reaches subduction zones, or trenches, where it descends in downgoing slabs back into the mantle.

Plate tectonics



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

Plate tectonics describes the behavior of the lithosphere, the strong outer shell of the mantle, which is the cold outer boundary layer of the thermal convection system involving the mantle and the core that removes heat from the Earth's interior.

Thermal convection system

At shallow depths the warm,and hence less dense, material rising below spreading centers forms upwelling limbs, whereas the relatively cold, and hence dense, subducting slabs form downwelling limbs

- **Lithosphere is only about 29th part of the entire mantle and largest temperature changes occur in this region only, from about 0 celsius to 1400 celsius at the 100km depth.**

- **That is why it is called a thermal boundary layer.**

- **Lithosphere is stronger than the underlying rock due to this temperature changes and it also referred as mechanical boundary layer.**

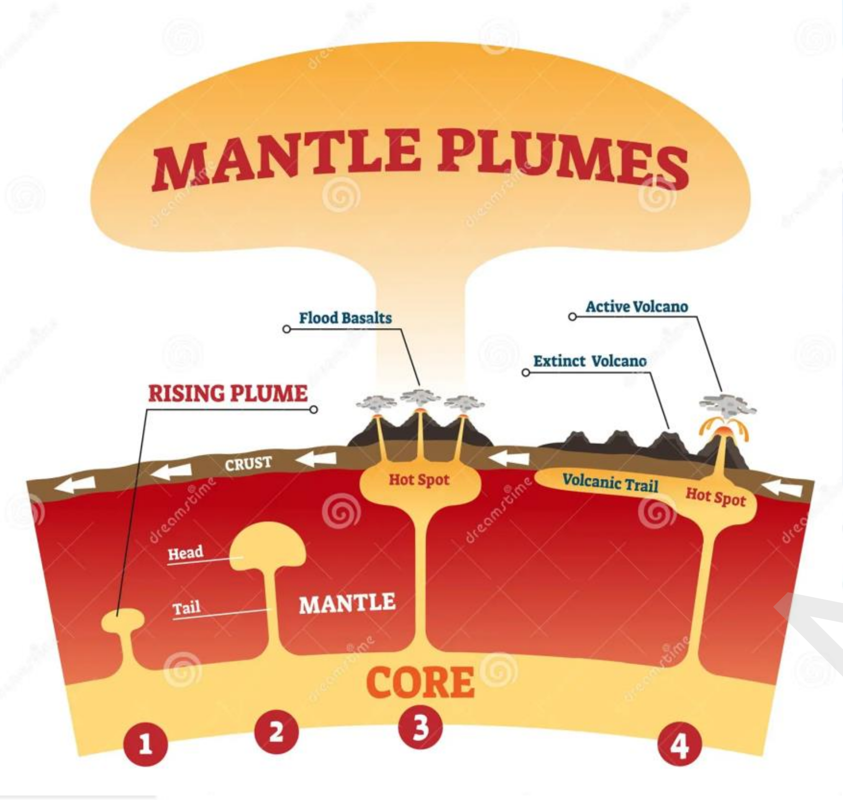
- **Generally, Basalt has higher density than granite so continental lithosphere does not subduct.**

- **Since oceanic lithosphere subduct and reformed at ridges, so it never gets older than 200 Myr. On the other hand, the continental lithosphere can be billions of years old.**

Earth's heat engine is characterized by the balance between three modes of heat transfer from the interior.

- **The plate tectonic cycle involving the cooling of oceanic lithosphere.**
- **Mantle plumes, which are thought to be a secondary feature of mantle convection.**
- **Heat conduction through continents that are not subducted and hence do not participate directly in the oceanic plate tectonic cycle.**

Based on estimates from sea floor topography and heat flow, terrestrial heat loss seems to occur primarily (about 70%) via plate tectonics, with about 5% via hotspots (mantle plumes)



https://www.dreamstime.com/mantle-plume-vector-illustration-labeled-explanation-magma-eruption-scheme-mantle-plumes-vector-illustration-labeled-explanation-image160043137

- ★ A mantle plume is an area under the crust, where magma is hotter than the surrounding magma.
- ★ The heat from this extra hot magma causes melting and thinning of the rocky crust, which leads to widespread volcanic activity on Earth's surface above the plume.

Plate tectonics

Evolution of Earth's ocean and atmosphere

Figure 5.1-3: Cartoon showing interactions between the solid earth and ocean/atmosphere system.

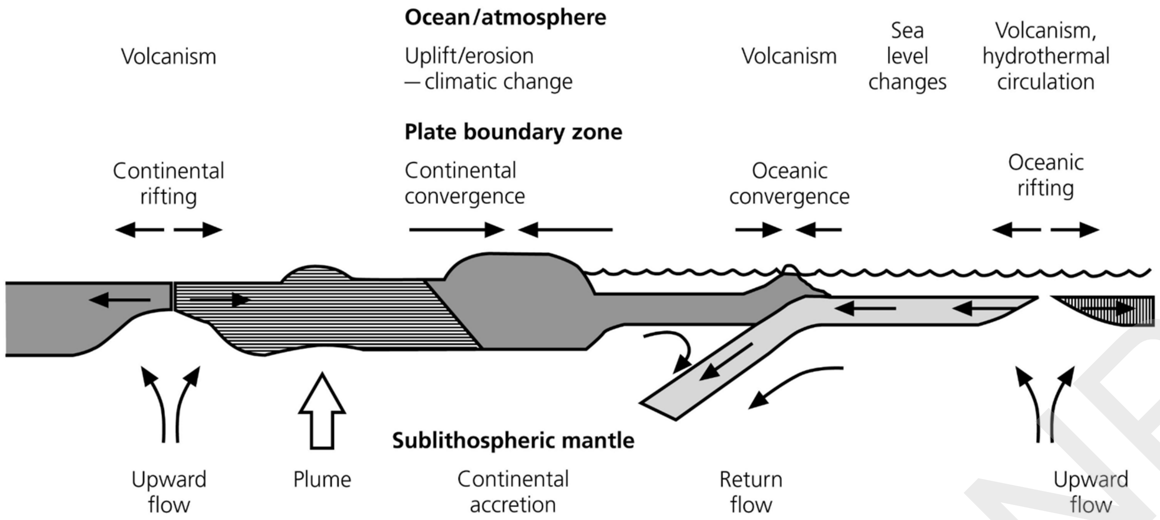


Plate tectonics is also crucial for the evolution of Earth's ocean and atmosphere, because it involves many of the primary means (including volcanism, hydrothermal circulation through cooling oceanic lithosphere, and the cycle of uplift and erosion) by which the solid earth interacts with the ocean and the atmosphere.

Plate tectonics

Seismology: Role of earthquakes

- The interplate earthquakes both delineate plate boundaries and show the motion occurring there.The direction of faulting reflects the spreading at mid-ocean ridges and subduction at trenches.

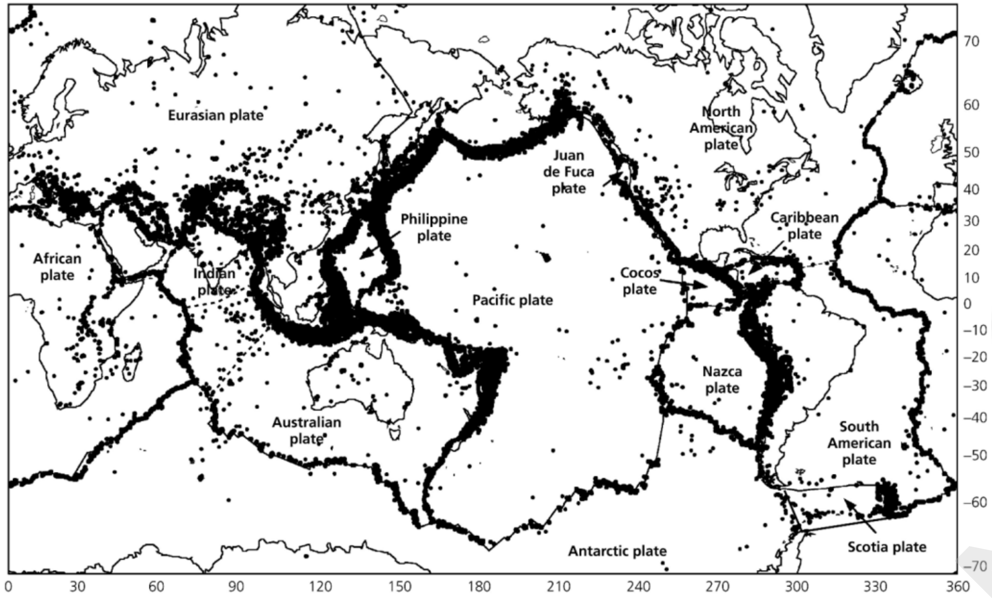
- The earthquake locations and mechanisms also show that plate boundaries in continents are often complicated and diffuse, rather than the simple narrow boundaries assumed in the rigid plate model that are a good approximation to what we see in the oceans.

- Intraplate earthquakes occur within plate interiors, far from boundary zones. Intraplate earthquakes are studied to provide data about where and how the plate tectonic model does not fully describe tectonic processes.

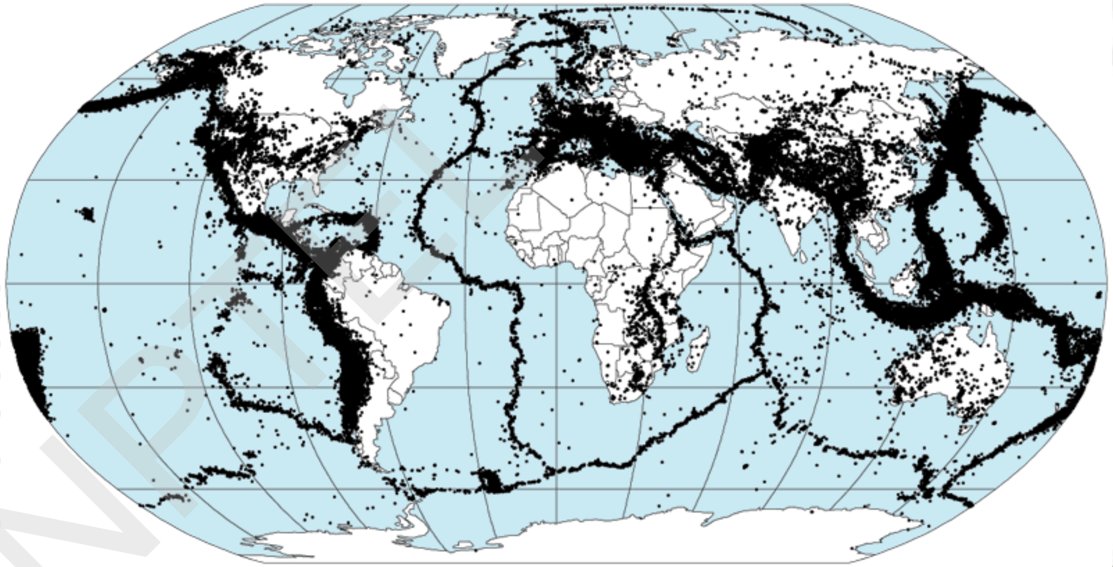
Plate tectonics

Role of earthquakes

Figure 5.1-4: Global seismicity: all depths (top), deep events (bottom).

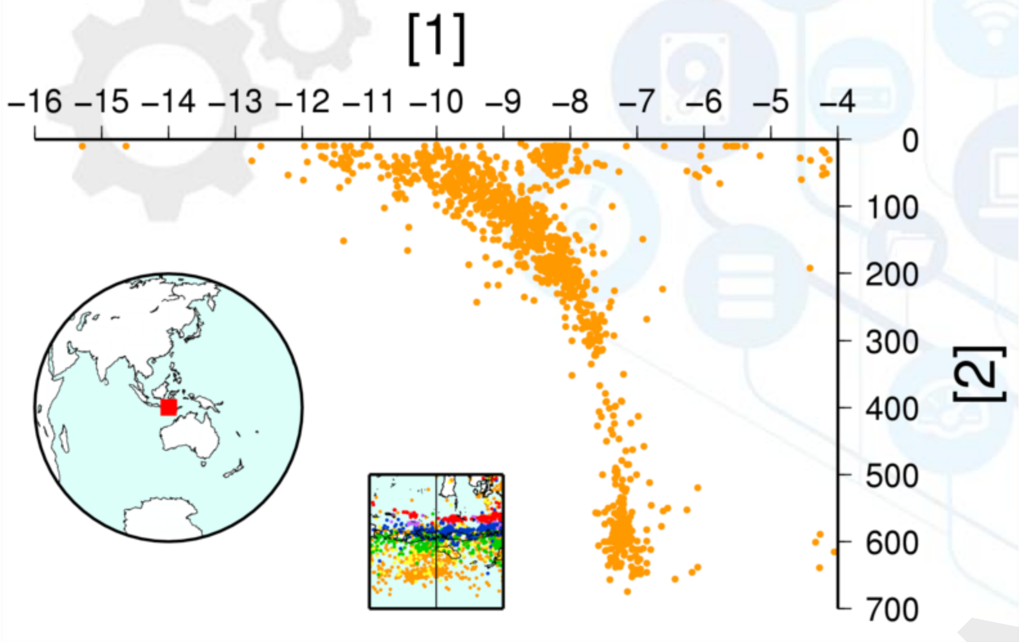


Preliminary Determination of Epicenters
358,214 Events, 1963 - 1998



The distribution of earthquakes provides strong evidence for the idea of essentially rigid plates, with deformation concentrated on their boundaries. it shows maps of global seismicity covering the time period 1964–97.

Wadati–Benioff zones



https://commons.wikimedia.org/wiki/File:Wadati-Benioff_zone.png

- **Inclined zones of seismicity delineate the subducting oceanic plates, which travel time and attenuation studies show to be colder and stronger than the surrounding mantle.**

- **These zones, identified before their plate tectonic significance became clear, are known as Wadati–Benioff zones.**

- ➔ **Seismology provides crucial information about both plate kinematics, the directions and rates of plate motions, and plate dynamics, the forces causing plate motions.**

- ➔ **Seismicity is one of the major tools used to identify and delineate plate boundary zones, and earthquake mechanisms are among the primary data used to determine the motion within plate boundary zones.**

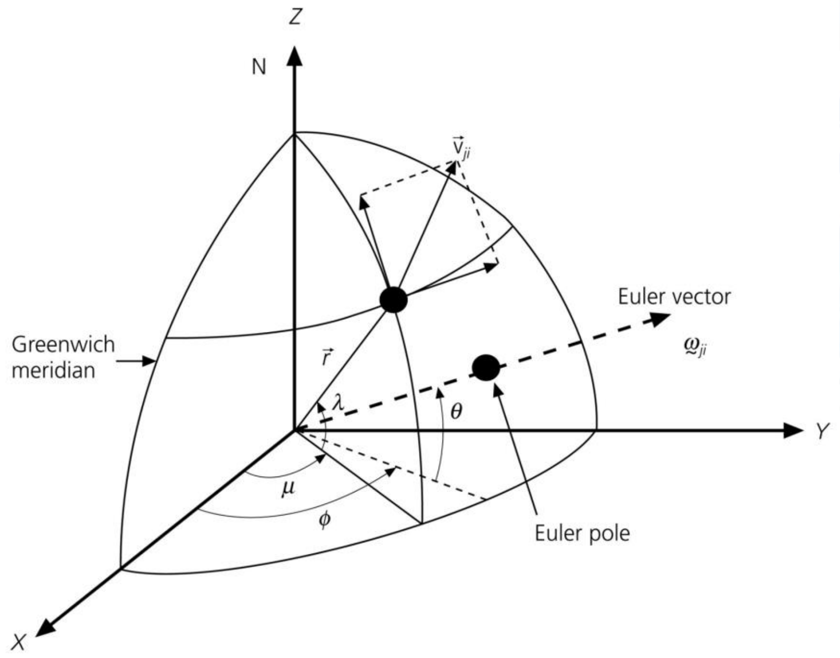
- ➔ **The mechanisms also provide information about the stresses acting at plate boundaries and within plates, which, together with earthquake depths and seismic velocity structure, are important in developing ideas about the forces involved and the physical processes by which rocks deform and cause earthquake.**

- ➔ **Conversely, plate motion data are used to draw inferences about the locations and times of future earthquakes and their societal risks.**

Plate kinematics

Relative plate motions

Figure 5.2-1: Geometry of plate motions.



Geometry of plate motions. Linear velocity at point r is given by $v_{ji} = \omega_{ji} \times r$. The Euler pole is the intersection of the Euler vector with the earth's surface. Note that west longitudes and south latitudes are negative.

Euler's theorem and Euler's pole

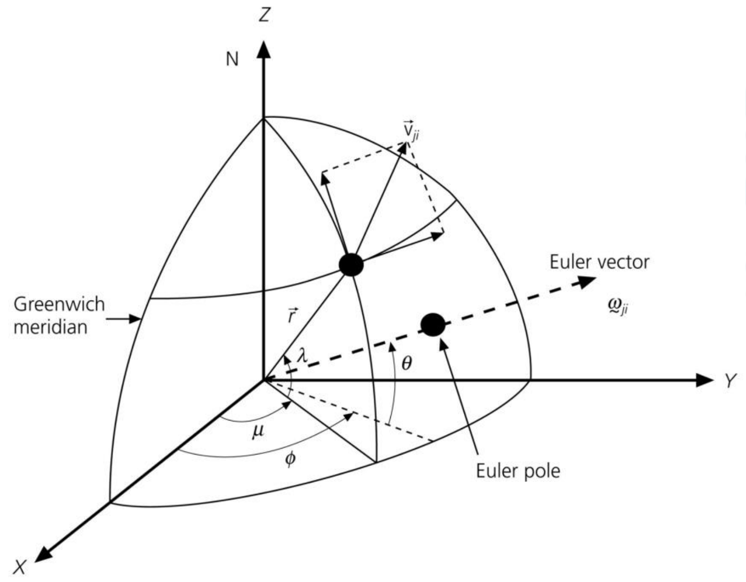
- Euler's theorem states that the displacement of any rigid body (in this case, a plate) with one point (in this case, the centre of the earth) fixed is a rotation about an axis.

- The relative motion between any two plates can be described as a rotation about an Euler pole.

Plate kinematics

Relative plate motions

Figure 5.2-1: Geometry of plate motions.



- At any point r along the boundary between plate i and plate j, with latitude λ and longitude μ , the linear velocity of plate j with respect to plate i is

$$\mathbf{v_{ji}} = \omega_{\mathbf{ji}} \times \mathbf{r}$$

- This is usual formulation for rigid body rotations in mechanics.

r is the position vector to the point on the boundary, and
ω_{ji} is the angular velocity vector, or Euler vector.

- Both vectors are defined from an origin at the centre of the earth.

Plate kinematics

Relative plate motions

- ➔ The direction of relative motion at any point on the boundary is a small circle, a parallel of latitude about the Euler pole (not a geographic parallel about the North Pole!)

- ➔ The convention used is that the first named plate (j = 2) moves counterclockwise (in a right-handed sense) about the pole with respect to the second named plate (i = 1).

- ➔ The segments of the boundary where relative motion is parallel to the boundary are transform faults.

- ➔ Other segments have relative motion away from the boundary, and are thus spreading centers.

Figure 5.2-2: Relationship between plate boundaries and the Eurer pole.

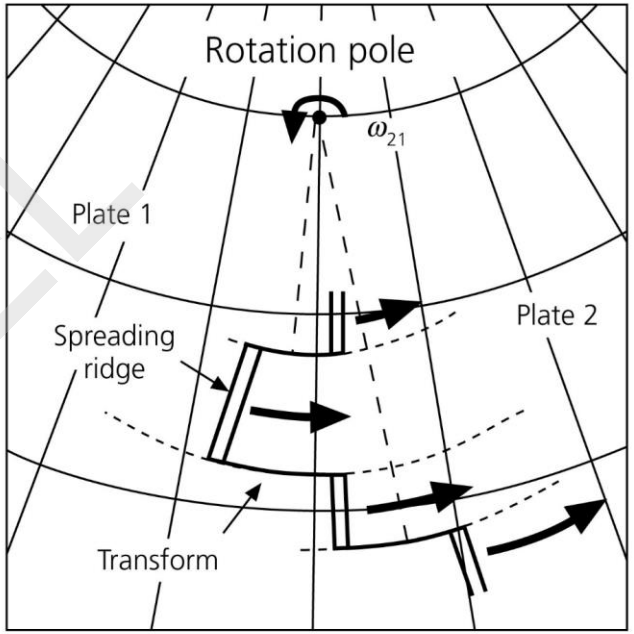
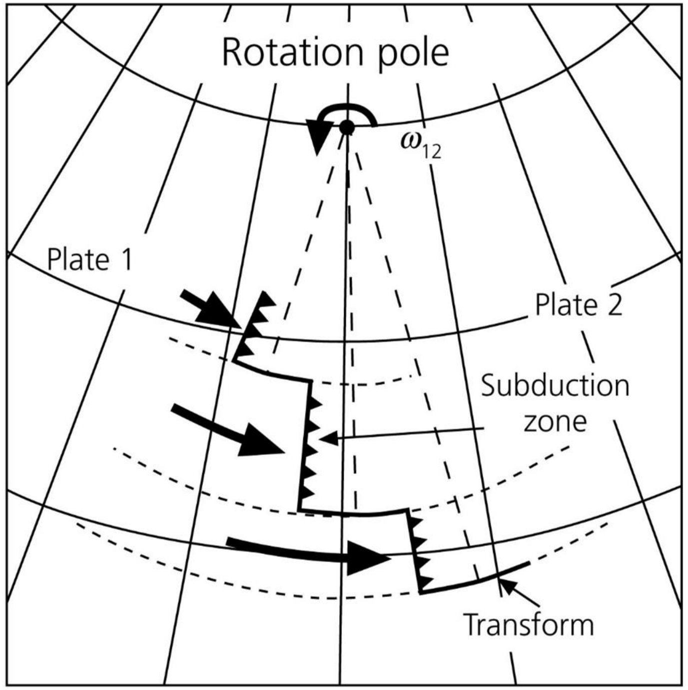


Plate kinematics

Relative plate motions



Shows an alternative case. The pole here is for plate 1 (j = 1) with respect to plate 2 (i = 2), so plate 1 moves toward some segments of the boundary, which are subduction zones.

The magnitude, or rate, of relative motion increases with distance from the pole because

$$|v_{ji}| = |\omega_{ji}|\ |r| \sin \gamma ,$$

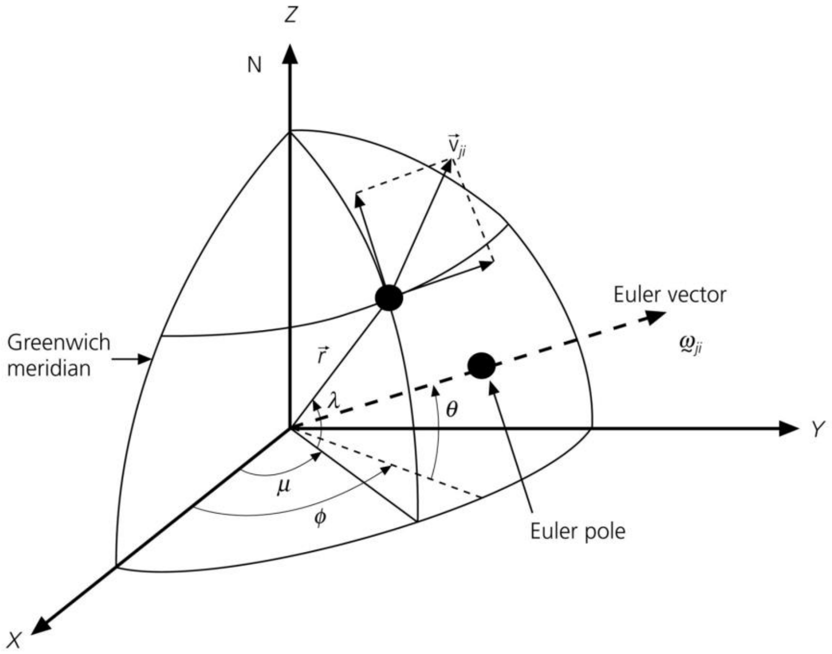
where γ is the angle between the Euler pole and the site (corresponding to a colatitude about the pole)

All points on a plate boundary have the same angular velocity, but the magnitude of the linear velocity varies from zero at the pole to maximum 90^0 away.

Plate kinematics

Relative plate motions

Figure 5.2-1: Geometry of plate motions.



The components of the vectors can be written in Cartesian (x, y, z) coordinates. The position vector is

$$\mathbf{r} = (a \cos\lambda \cos\mu,\ a\cos\lambda \sin\mu,\ a\ \sin\lambda)$$

where 'a' is the earth's radius. Similarly, if the Euler pole is at latitude θ and longitude ϕ, the Euler vector is written (neglecting the ij subscripts for simplicity) as

$$\omega = (|\omega| \cos\theta \cos\phi,\ |\omega| \cos\theta \sin\phi,\ |\omega| \sin\theta),$$

where the magnitude, | ω |, is the scalar angular velocity or rotation rate

Plate kinematics

Relative plate motions

To find the Cartesian components of the linear velocity v, we evaluate the cross product (Eqn 1) using its definition given beside, and find

$$\mathbf{a} \times \mathbf{b} = (a_2 b_3 - a_3 b_2)\hat{\mathbf{e}}_1 + (a_3 b_1 - a_1 b_3)\hat{\mathbf{e}}_2 + (a_1 b_2 - a_2 b_1)\hat{\mathbf{e}}_3,$$

$$\mathbf{v} = (v_x, v_y, v_z),$$

$$v_x = a|\omega|(\cos\theta \sin\phi \sin\lambda - \sin\theta \cos\lambda \sin\mu)$$

$$v_y = a|\omega|(\sin\theta \cos\lambda \cos\mu - \cos\theta \cos\phi \sin\lambda)$$

$$v_z = a|\omega| \cos\theta \cos\lambda \sin(\mu - \phi)$$

At the point r, the north–south and east–west unit vectors can be written in terms of their Cartesian components

$$\hat{e}^{NS} = (-\sin\lambda \cos\mu, -\sin\lambda \sin\mu, \cos\lambda)$$

$$\hat{e}^{EW} = (-\sin\mu, \cos\mu, 0)$$

Plate kinematics

Relative plate motions

Taking the dot products of its cartesian components with the unit vectors gives north-south and east-west components of V

$$v^{NS} = a|\omega|\cos\theta\sin(\mu-\phi)$$
$$v^{EW} = a|\omega|[\sin\,\theta\cos\lambda - \cos\,\theta\,\sin\lambda\cos(\mu-\phi)]$$

So, the rate and direction of plate motion is given by

$$rate = |\mathbf{v}| = \sqrt{(v^{NS})^2 + (v^{EW})^2}$$
$$\text{azimuth}{=}90^0 - \tan^{-1}\left[(v^{NS})/(v^{EW})\right]$$

such that azimuth is measured in the usual convention, degrees clockwise from North.

Plate kinematics

Relative plate motions

Figure 5.2-4: Relative plate motions and diffuse plate boundary zones.

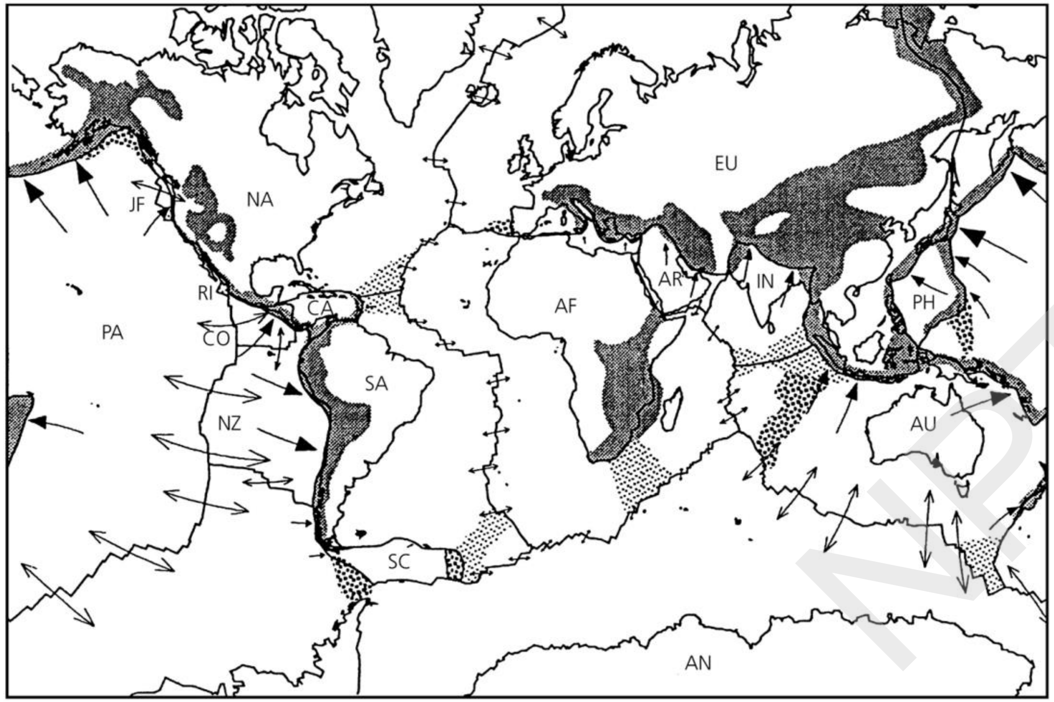


Figure 5.2-6: Correlation of current and history plate velocities.

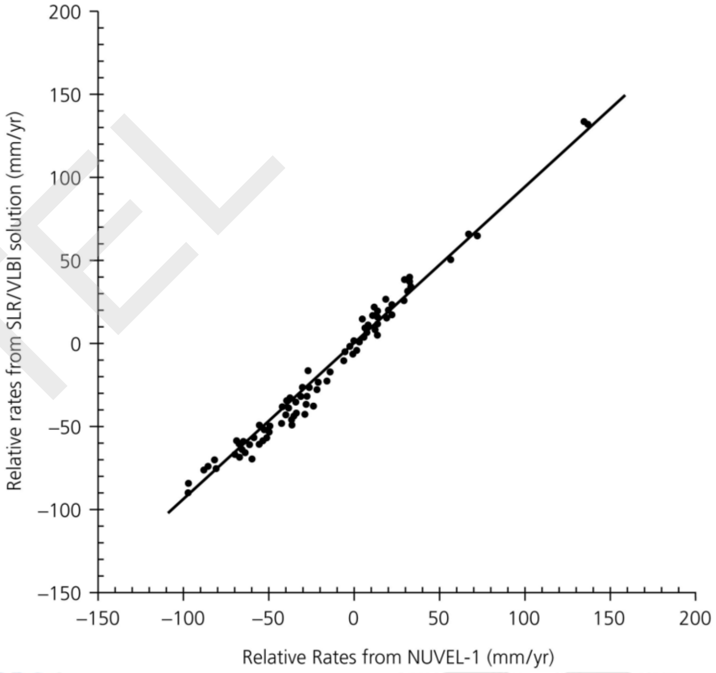


Plate kinematics

Absolute plate motions

We have discussed the relative motions between plates, which have traditionally been of greatest interest to seismologists because most earthquakes reflect these motions.

It is important to consider absolute plate motions, those with respect to the deep mantle.

We infer absolute plate motions in two ways :

1. **Hot spot hypothesis**

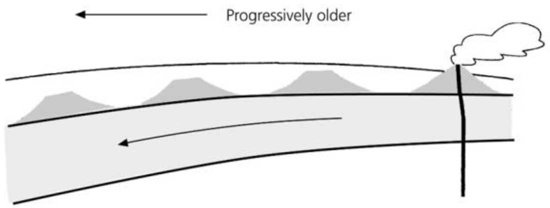
In which certain linear volcanic trends result from the motion of a plate over a hot spot, or fixed source of volcanism, which causes melting in the overriding plate. The direction and age of the volcanic chain give the motion of the plate with respect to the hot spot.

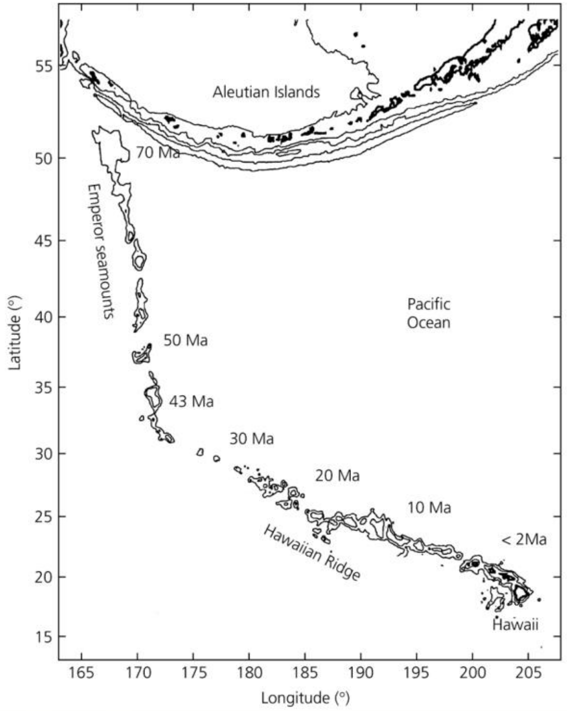
Hence using hotspot tracks beneath different plates, and assuming that the hot spots are fixed with respect to the deep mantle (or move relative to each other more slowly than plates), yields a hot spot reference frame.

Plate kinematics

Absolute plate motions

Figure 5.2-7: Formation of the Hawaiian-Emperor chain.





2. Deep mantle plume

It is often further assumed that hot spots result from plumes of hot material rising from great depth, perhaps even the core mantle boundary

- **The hot spot reference frame is similar to one obtained by assuming there is no net rotation (NNR) of the lithosphere as a whole.**
- **Hence that the sum of the absolute motion of all plates weighted by their area is zero.**

- **Thus despite unresolved questions about the nature and existence of hot spots and plumes, NNR reference frames are often used to infer absolute motions.**

Plate kinematics

Computation of absolute motions

Relative and absolute Euler vectors are simply related as

$\omega_{ij} = \Omega_i - \Omega_j$

The relative Euler vector for two plates, is the difference between their absolute Euler vectors. Thus, if we know one plate's absolute motion, we can find all the others from the relative motions.

Summary

- 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.

Summary

- 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
  $\omega_{ij} = \Omega_i - \Omega_j$

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THANK YOU !