Whole Earth Geophysics

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- **Geophysical techniques** provide information on the internal structure and tectonics development of the earth.
- Some of the **geophysical methods** are: refraction, reflection, earthquake, gravity, magnetism, and heat flow.
- **Travel time**: is the time it takes the waves to get from their source to a seismometer:
- **Seismic velocity**: the speed of the waves passed through a region of the earth.
- **Attenuation "Q":** the amount and type of ground motions reveals how readily the region absorbed/scattered wave energy.

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- **Refraction**: when waves encounter regions of changing velocity.
- **Reflection**: when waves due to changes in acoustic impedance (density, time, velocity).
- **Volcanic eruption and igneous intrusion**: come from magma that originated at lower crustal or upper mantle depths, generally within the upper 200km.
- **Seismic reflection data** shows details within sedimentary basin, lower crust, and "Moho" the crust/mantle transition.
- **Seismic refraction data** provide constraints on crustal thickness changes and seismic velocities within the crust.

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- **Seismic velocities** give constraints on the composition and physical state of portions of the earth.
- **Plate tectonic theory** explains the origins of many mountains ranges, earthquakes, volcanoes, and the metamorphism of rocks.
- **Classic divisions of earth interior**:

1. Crust "hard solid".
2. Mantle "soft solid".
3. Core "liquid".

- **Modern divisions of earth** "which describe physical state of those chemical under high P and T"**:** 1. Lithosphere. 2. Asthenosphere. 3. Mesosphere. 4. Outer core. 5. Inner core.

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- **Crust 'lithosphere"**: comprised of silicates that are so cold that they are rigid.
- **Mantle "Asthenosphere"**: include of iron/magnesium-rich silicate and relatively cold and rigid.
- Asthenosphere: the same mantle materials undergo slight partial melting, forming the softer layer.
- **Outer core**: composed of heavy (iron-rich) materials which are liquid.
- **Inner core**: the same material exists as a solid.
- The rock undergoes increasing degrees of a partial melting until it becomes totally liquid at about 1900^{o} C.

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a) In the upper 100 km, the peridotite is cold and rigid, resulting in a solid **lithosphere**.
b) Between about 100 and 350 km the temperature rise causes a small amount of partial melt, giving the softer **asthenosphere**
c) Below about 350 km the pressure is so great that, even though the temperature is hooter, there is a transition (increasing strength) to the solid **mesosphere**.

- The lithosphere consists of both the crust and uppermost mantle.
- The boundary between the crust and mantle, called the **Moho discontinuity**.

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- **Compressional seismic waves** travel at about 6.5 km/s in the lower crust were refracted along the higher velocity in the uppermost mantle of about 8.2 km/s and slow down to about 7.8 km/s at depth of 75 to 200 km, indicating a transition to the softer asthenosphere. The velocity jump to 12 km/s in the mesosphere
- The **lower crust** in generally **gabbroic** (≈50% silica), while the **upper mantle** is composed of **peridotite** (≈30% silica).
- Peridotite comprises the three zones of the mantle: lower lithosphere, asthenosphere, and mesosphere.

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- Lithosphere plates are though to be driven by convection currents within the upper mantle. Where magma is generated and the cooling of it forms new lithosphere.

Types of plate boundaries:

1. Divergent plate: where plates moves away from one another the lithosphere thin, so that underlying, buoyant asthenosphere elevates a broad region. The elevated regions are **continental rift zones** or **mid-ocean ridges**, depending on whether the lithosphere is capped by continental or oceanic crust. Divergent plate boundaries are characterized by tensional forces that produce fissures, ..

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.. normal faults, and rift valleys.

- New oceanic lithosphere is created between the continents, at a mid-ocean ridge. If the process continues long enough, a large ocean basin forms.

- Continental rift zones: as content pulls apart it stretches, thinning the crusts and entire lithosphere. The region is raised to high elevation because the underlying asthenosphere is hot and buoyant. The upper part of the crust deform in a cold, brittle fashion, causing earthquakes and elevated ridges, separated by down-dropped valleys. Areas of this kind are **East African Rifts** and Basin and Range Province.

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- **Mid-Ocean Ridges**: when continents completely rift apart, new oceanic lithosphere forms, as in the **Red Sea** separating Saudi Arabia from Africa. With continues divergence the buoyant asthenosphere elevates a ridge on the seafloor that may be a few hundred to as much as 4000 km wide, depending on how fast the plates move apart. Although the region of the ridge is hot, the upper part of the oceanic crust can be cold and brittle, causing earthquakes and normal faults.

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2. Convergent plate: where lithospheric plates converge, the plate with thinner, less buoyant crust commonly dense beneath the other plate. The region where a lithospheric plate descends deeply within the mantle is called a **subduction zone.** Two types of subduction zone are common; depending on whether the overriding plate is capped by thin (oceanic) or thick (continental) crust.

- Ocean/ocean subduction zone: if both of the converging plates contain oceanic crust, one plate subduct beneath the other. Magma that makes it to the surface erupts as a chain of volcanic ….

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… islands, called an island arc. Examples of that are The Aleutian and Philippine islands.

- Ocean/continent subduction zone: continental crust is thicker, and therefore more buoyant, than oceanic crust; a plate with oceanic crust will subduct beneath one capped by continental crust. The volcanic arc is on the continental crust, because that crust is part of the overriding plate. Examples include Japan, western South America, and the Pacific Northwest of the US.

- **Continental collision zone:** at collisional mountain ranges, two plates that both thick (continental or island arc)

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.. crust converge. Collision occurs after the thinner, oceanic crustal part of the downgoing plate is consumed through subduction. Example is the Indian subcontinent extends beneath Asia that results the highest mountains on Earth, the Himalayas.

3. Transform plate: where plate slide horizontally past one another, lithosphere is neither created nor destroyed. A common example is the San Andreas Fault, the Alpine Fault of New Zealand.

- **Fracture zones** are the inactive extensions of transform boundaries.

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- **Plume**: the heat rise from deep within the mantle.
- **Hotspot**: is a region in the mantle where magma forms due to a plume. As a lithosphere plate moves over a hotspot, the line of volcanoes forms, examples include Hawaiian Islands and the Columbia Plateau. Hotspots provide the determination of the absolute motions of plates.
- Mantle plumes and associated hotspots are thought to be fixed relative to the deep mantle

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- **Earthquakes:** earthquakes occur because materials are stresses to their breaking point. Two factors are important: 1. the presence of brittle material; and 2. motion that builds stress in the brittle material. Most earthquakes occur along or near plate boundaries, within the brittle regime near the top of the rigid plates.
- **Shallow earthquakes** occur in the upper depth of 70 km. deep ones can extend as deep as 700 km.
- **Very large earthquakes** occur due to sudden stress release where the two plates are locked together, at their boundary.

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- **Earth materials commonly melt in two situations**: 1. the presence on hot material drops. 2. cold material is subjected to higher temperature.
- Most volcanic eruptions are associated with divergent or convergent plate boundaries. Volcanism is normally absent from transform plate boundaries because materials remain at their normal depth; there is no significant temperature rise or presence drop.

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- A great deal of what we know about the interior of the earth comes from the recording of **seismic waves** that have traveled through various portions of the earth. Controlled source seismic techniques provide seismic velocity information, as well as some detail of layering, for the crust.
- **Seismic refraction data** are useful for mapping depth to bedrock, crustal thickness, and uppermost mantle velocity.
- **Seismic reflection profiles** show details of layering within sedimentary basins and gross structure of the deeper crust.

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- Earth materials may be **elastic** under some conditions, inelastic under others: 1. the magnitude and orientation of the deforming stress (amount of compression, tension, or shearing). 2. the length of time the material takes to achieve a certain amount of distortion (strain rate)
- Deformation beyond the elastic limit may be **ductile**, whereby the material flows like silly putty, or **brittle**, like a pencil breaking or the lithosphere rupturing as an earthquake.

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- **Seismic waves** can be categorized by whether they travel through the earth (**body waves**) or along earth's surface (**surface waves**).
- **Isotropic**: means that the material has the same physical properties (density and rigidity) in all directions.
- **Elastic constant**: describes the strain of a material under a certain type of stress. The **bulk modulus** describes the ability to **resist** being compressed. The **strain** is the change in volume divided by the original volume. The bulk modulus is the stress divided by the strain.
- **Shear modulus**: refers to the ability of a material to **resist** shearing.

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- **Young's modulus** describes the behavior of a rod that is pulled or compressed.

Types of body waves:

1. **Compressional wave**: is a "primary" or "P" wave because compressional waves arrive first from earthquakes; they also called "longitudinal" and "push-pull" waves because particles of the material move back and forth, parallel to the direction the wave is moving.
2. **Shear wave**: particle motions are perpendicular to the direction of propagating. Shear waves are also referred to as "secondary" or "S" because they arrive from an earthquake

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.. after the initial compressional waves, and as "transverse" waves because of their particle motions.

- **Seismic velocities depend on** the elastic constants (bulk modulus, shear modulus, Young's modulus, and Poisson's ratio) and density of the material.
- S-wave always travels slower than P-wave.
- S-wave can not travel through fluids, however P-wave travel slower through liquid.

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Factors that lead to an increase in seismic velocity:

1. Increasing depth within the earth.
2. Increasing in density.
3. Decreasing porosity.
4. Change from liquid to solid.

Types of surface waves:

1. **Rayleigh waves:** have retrograde elliptical motion; at the top of the ellipse, particles move opposite to the direction of wave propagation.
2. **Love waves**: are surface waves that behave like shear waves; the particles move horizontally in directions perpendicular to the direction of propagation.

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- Seismic waves can be used to determine depths to interfaces within the earth and velocities of layers between the interfaces.
- The **sources of the seismic waves** can be natural (earthquake) or produced artificially (controlled source).
- The receivers used on land, called **geophones**, measure ground movement (either the displacement, the velocity, or the acceleration of the ground surface).
- At, sea, **hydrophones** measure changes in water pressure caused by passing seismic waves.

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- The **travel time** of a seismic wave from a source to a receiver depends on the seismic velocities of the earth materials traversed, the distance from the source to the receiver, and the geometry of boundaries separating earth materials.
- For many earth materials:

$\mathbf{V_s \approx 0.6\ V_p}$ [P-wave is faster than S-wave], $\mathbf{V_R \approx 0.9\ V_s}$ [Rayleigh wave is slower than S-wave], and $\mathbf{V_R \approx 0.5\ V_p}$ [Rayleigh wave is about half the speed of P-wave].

- A **wave front** is a surface along which portions of a propagating wave are in phase.

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- In a homogenous medium (constant seismic velocities), the body waves (P and S) radiate outward along spherical wavefronts, while Rayleigh waves (R) roll along the surface.
- Seismic energy travels along trajectories perpendicular to wavefronts, known as **raypaths**.
- A **seismic trace** is the recording of ground motion by a receiver, plotter as a function of time.
- Arrival of each of the P, S, and R waves starts as initial movements of the ground, followed by reverberations that die out with time.

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- Travel time is commonly increasing downward in refraction and reflection studies.
- **Acoustic impedance**: the product of seismic velocity and density.
- **Direct Arrival**: the compressional wave that goes directly from the source to a receiver is a body wave traveling very close to the surface.
- Snell's Law describes three situations:
1. If the velocity decreases across the interface, the ray is refracted away from the interface. 2. If the velocity remains the same, the ray is not bent. 3. If the velocity increases across the interface, the ray is bent toward the interface.

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- **Critical refraction** occurs when the angle of refraction (θ_2) reaches 90^o, and it only occurs when $V_2 > V_1$
- The angle of incidence (θ_1) necessary for critical refraction is called the critical angle (θ_c)
- **Waves refract because** they encounter changes in seismic velocity. Velocity changes relate to changes in bulk modulus, rigidity and density; measuring how waves refract thus tells us something about those properties traversed by the seismic waves.
- **The refraction methods illustrates on two problems**: 1. crustal thickness. 2. depth of bedrock.

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- **Receivers must extend well beyond the crossover distance** fro the deepest refractor of interest. A general rule is that the length of the array of receivers "spread length" should be at least twice the crossover distance.
- Unlike reflection experiments, where the spread length is about equal to the depth of the deepest refractor, seismic refraction spread lengths are about five to ten times the depth of the deepest refractor.
- The single-layer case illustrates the utility of the seismic refraction method to **map changes in crustal thickness**.

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- **The depth to the crust/mantle boundary** often relates to **tectonic history**. Regions of plate divergence commonly have shallow Moho depths (continental rift zones, passive continental margins, mid-ocean ridges). Low mantle refraction velocities can indicate zones where hot asthenosphere is shallow at mid-ocean ridges and continental rifts. In continental collision zones, the crust may thicken to twice its normal value for continual areas.
- The seismic reflection method is popular for tow areas: 1. Resembling geologic cross sections.2. Offering high resolution of subsurface detail

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- The **seismic reflection method** is a tool for oil and gas exploration in sedimentary basins. Reflections occur when there are changes in seismic velocity and/or density; boundaries or layers that are nearly flat and continuous are especially resolvable.
- **The rifting of a continental craton thins the crust as well as the entire lithospheric plate.** As a continental rifts apart, the upper and lower crusts thin, but through different mechanisms (brittle and ductile failure)

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- **Earthquakes** show to the fact that dynamic forces are operating within the earth. Stress builds up though time, storing strain energy; earthquakes represent sudden release of the strain energy.
- Most tectonic activity occurs due to interaction between plates; the distribution of earthquakes thus dramatically outlines lithospheric plate boundaries.
- There are only **shallow** earthquakes at **divergent** and **transform** plates, but earthquakes occur over a **broad range** from shallow to deep where **plate converges**.

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- **For earthquake to occur**, two factors are thus necessary: 1. there must be some sort of movement that will stress the material beyond its elastic limit. 2. the material must fail by brittle fracture. The region of the earth that fits the above criteria is the lithosphere.
- **Elastic rebound theory** state that rock can be stresses until it reaches its elastic limit.
- The location of an earthquake can be described by the latitude, longitude, and depth of the zone of rupture. The **focus** is the actual point within the earth where the earthquake energy is released.

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- The **focal depth** is the distance from the epicenter to the focus.
- The **epicenter** is the point on earth's surface directly above the focus.
- Earthquakes occur in the upper 700 km of the earth, because they are confined to the rigid lithosphere, which can undergo brittle failure.
- Most earthquakes are shallow focus, from the surface to 70 km depth; shallow focus earthquake occur at all types of plate boundaries.

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- Most **intermediate** focus (**70 to 300 km depth**) and virtually all **deep** focus earthquakes occur in convergent (subduction) settings, where lithosphere extends deeply through the asthenosphere.
- **Magnitude** is related to the amount of energy released by the earthquake. It is based on precise measurements of the amplitude of seismic waves. It is expresses according to a **logarithmic** scale, whereby an increase in magnitude by one unit correspond to a 10-fold increase in amplitude of the seismic waves. **Richter scale**, reports of earthquakes magnitude, is based on ….

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… P-wave amplitude and It is a base-10 logarithmic scale

- **Intensity** is qualitative, describing the severity of ground the severity of ground motion at a given location. It is based on effects at the surface, as witnessed by people. Intensity is reported as Roman Numerals according to the **Mercalli Scale** which is a base-12 scale.
- Factors tend to increase intensity: 1) magnitude of the earthquake. 2) proximity to the earthquake focus. 3) loose soil as opposed to firm bedrock.
- Seismic wave amplitude get smaller with increasing distance from the earthquake source, so that intensity …..

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…. generally decrease with distance from the focus.

- **Seismic stations** typically have at least three seismometers, each sensitive to a different direction of ground motion. The directions are perpendicular to one another, responding to vertical, north-south, and east-west motions.
- When there are many, very thin layers, critically refracted rays emerge at steeper angles for deeper, higher velocity interfaces. Each angle of emerged relates to the velocity the ray traveled horizontally at the top of the critically refracting layer

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Major Divisions of Crust, Mantle, and Core:

- Lithosphere: the crust has P-wave velocities generally below 7 km/s. in many areas the crust consists of sedimentary rock with velocities from 2 to 5 km/s, underlying by igneous and metamorphic rocks with velocities slightly greater than 6 km/s. Across the Moho, P-wave velocities increase abruptly, from 6-7 km/s to about 8 km/s. The Moho is about 10 km deep beneath oceans, but much deeper (20 to 70 km) under continents. The uppermost mantle has P-wave velocities just over 8 km/s to 100 to 200 km depth.

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- **Asthenosphere**: it can be broken into two parts. In the upper part (about 100 to 300 km depth), P and S wave velocities are about 6% lower than for the overlying lithosphere and underlying material. The upper asthenosphere is thus a soft substratum, over which the more rigid lithospheric plates ride. In the lower part of the asthenosphere (about 300 to 700 km), P and S wave velocities gradually increase, suggesting an increase in shear strength.

- If waves arrive late, the lithosphere is thin. Early arriving waves suggest a thick lithosphere.

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- **Mesosphere:** at the top (about 700 km depth) there is an abrupt increase in velocity; pressure is so great that the mantle reverts back to a harder solid. Through the depth range of 700 to 2900 km, there is a gradual increase in P- and S- wave velocities, as the shear and bulk moduli increase.

- **Outer Core:** extends from about 2900 to 5100 km depth. A region where no initial S-wave is recoded extends beyond 103^o angular distance; this “shadow zone” is evidence that S-wave is not transmitted through the outer core. At the mantle/core boundary P-wave velocity drops from 13.5 to 8 km/s.

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- A P-wave shadow zone develops between 103^o and 143^o due to abrupt, inward bending of seismic rays.

- Inner Core: Some weak P-waves arrive on the other side of the earth earlier than expected “PKIKP”, suggesting an abrupt increase in velocity at about 5100 km depth. This higher velocity suggests that the inner core is solid. Some weak arrivals have been interpreted as waves that travel through the inner core as (converted) S-wave energy “PKJKP”. The inner core has the same chemical compositions as the outer core, but is solid because it is under greater pressure.