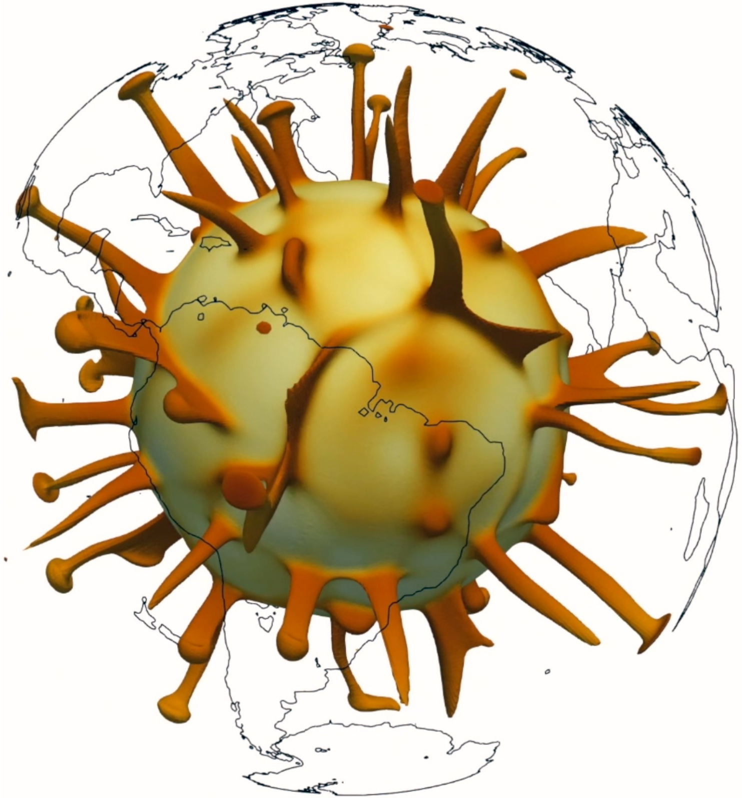
The Earth’s Structure

Earth’s present-day structure

- Knowledge of the Earth’s present-day structure and dynamics is often limited to shallow, lithospheric depths (100-200 km), namely, plate tectonics.
- Knowledge of Earth’s dynamics is often qualitative, while a quantitative approach through physical and numerical analysis is warranted.
- The Earth’s can be considered an analogue of many terrestrial planets, moons, exoplanets. Thus, understanding and being able to reproduce the Earth’s dynamical behaviour is indispensable for planetary exploration.



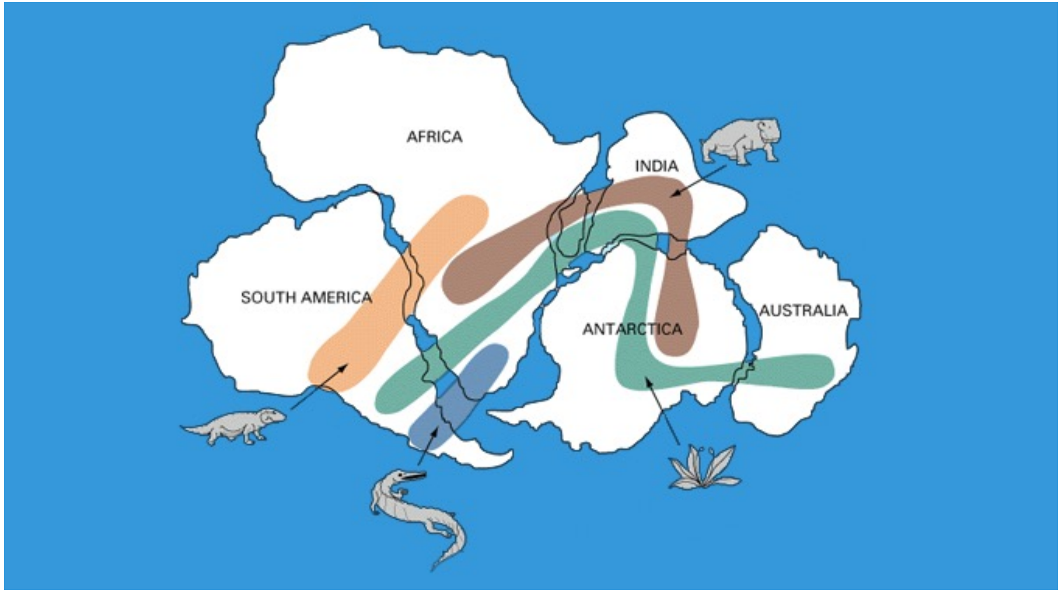
Present-day Earth’s composition, thermal structure, and dynamics

WHAT AND HOW DO WE KNOW?

Field geology:

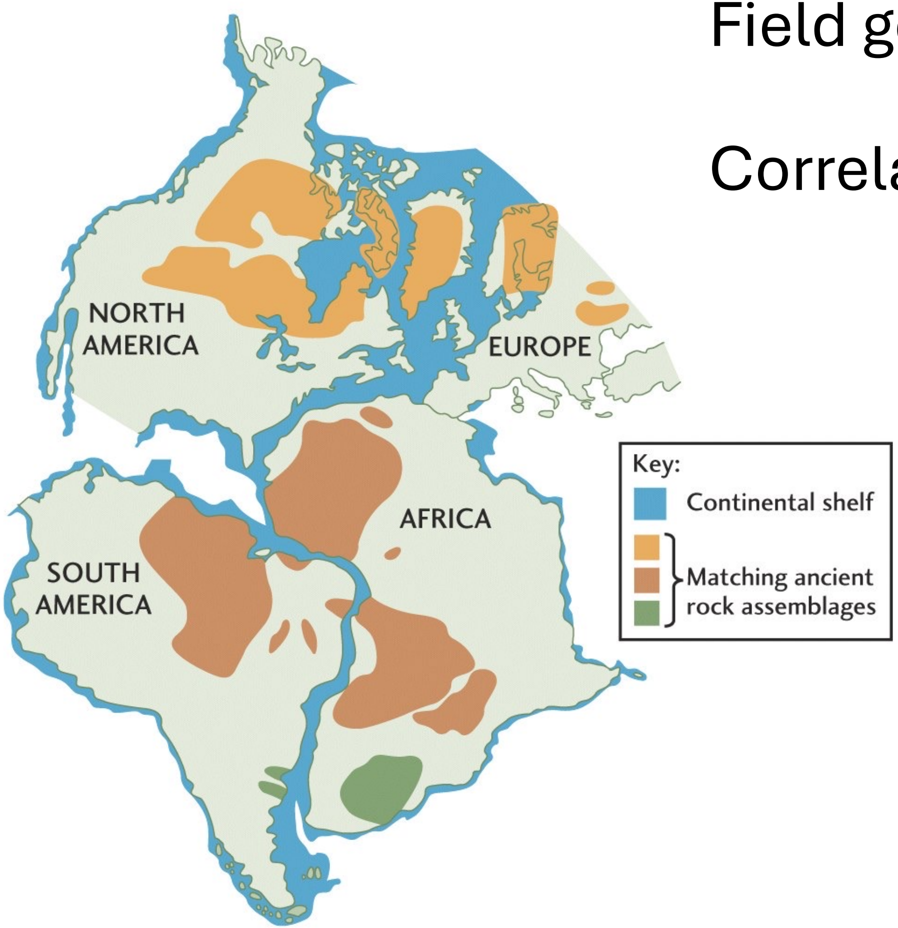
Fossil record
Sediment record

Climate	Rock type
Swampy	coal
Desert	salt, desert sandstone
Tropical seas	limestones
Glaciated	moraine



Field geology:

Correlations

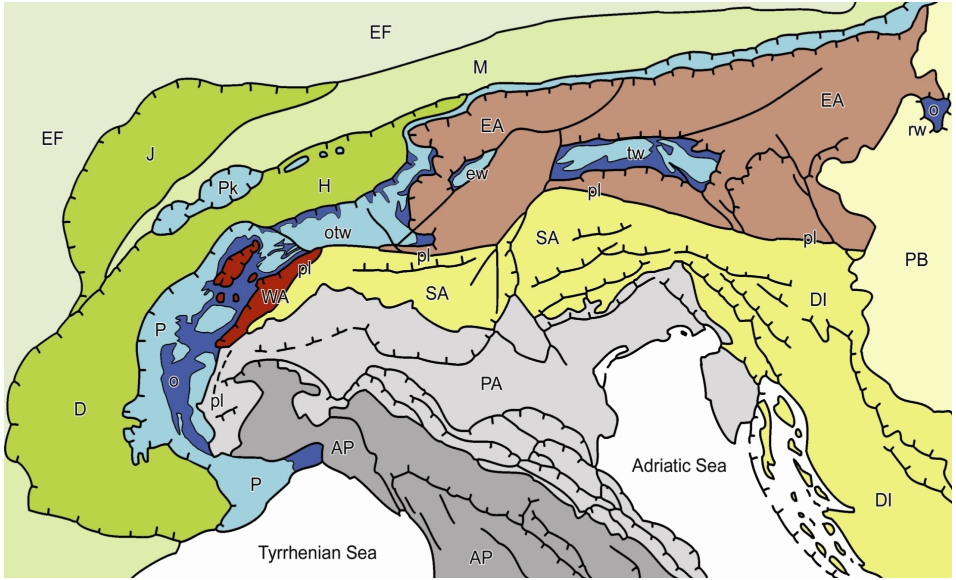


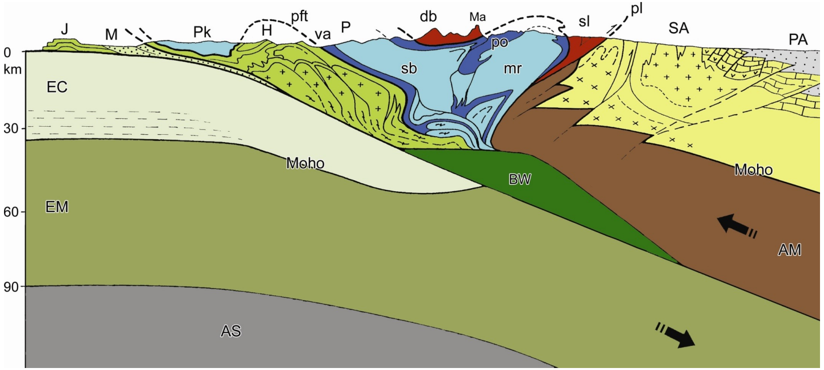
Field geology shows that continents once fit together. Matching belts of ancient rocks and mountain chains appear on coastlines that are now oceans apart. These correlations reveal that the continents were joined in past supercontinents like Pangaea.

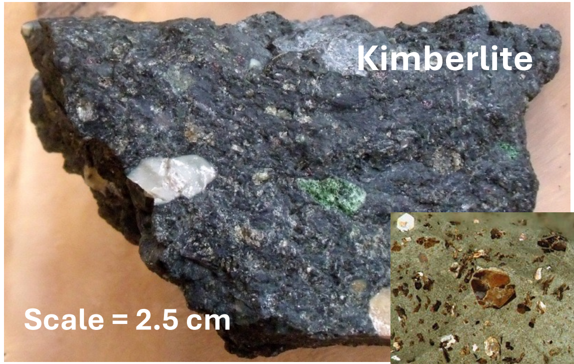
Boreholes and mines

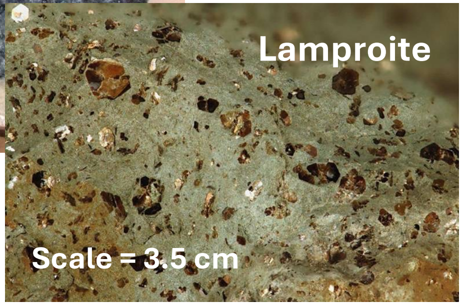
1970-1992

Field geology: exhumed minerals and rocks



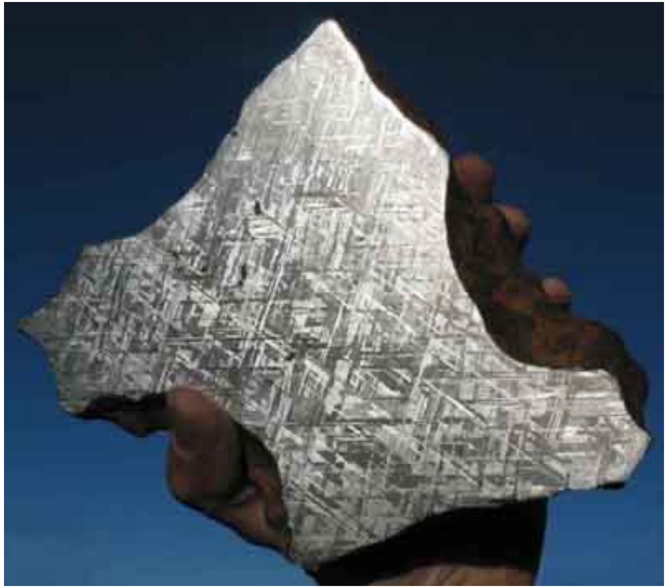






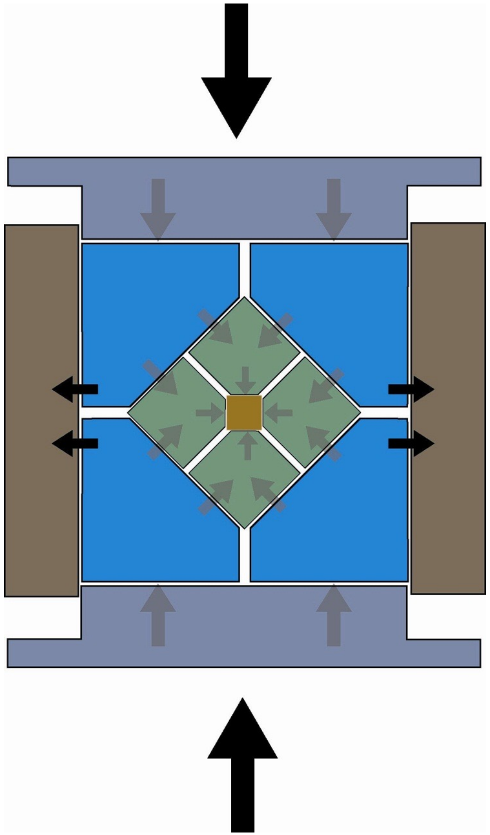
Field geology: exhumed minerals and rocks

Meteorites

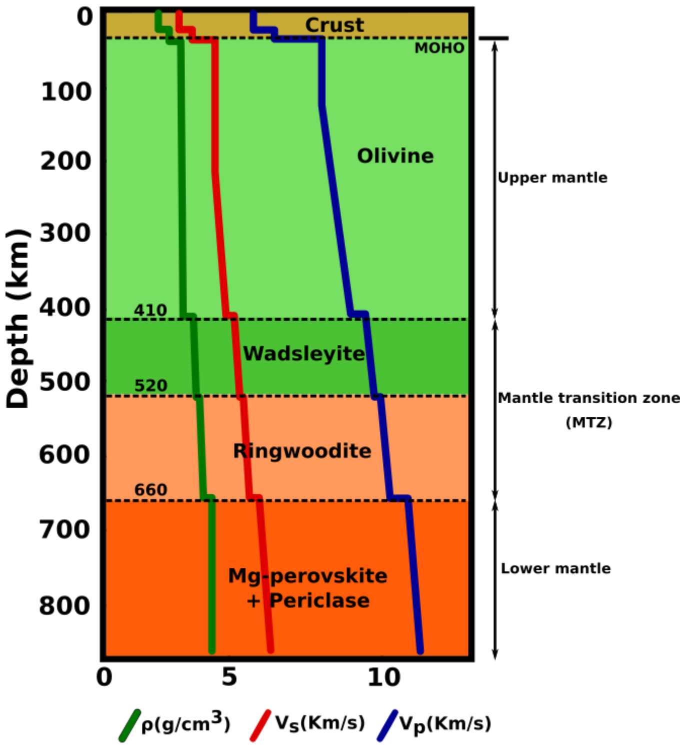


Composition of most meteorites (chondrites) is supposed to represent the Earth's average composition.

Laboratory experiments

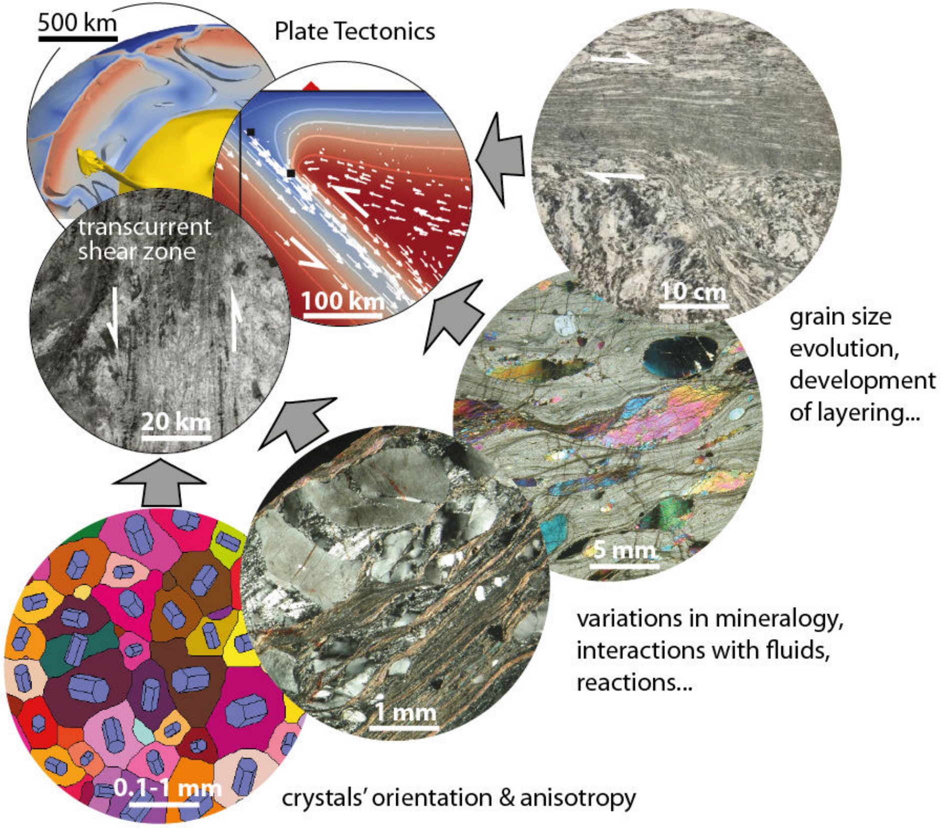


Mineral physics



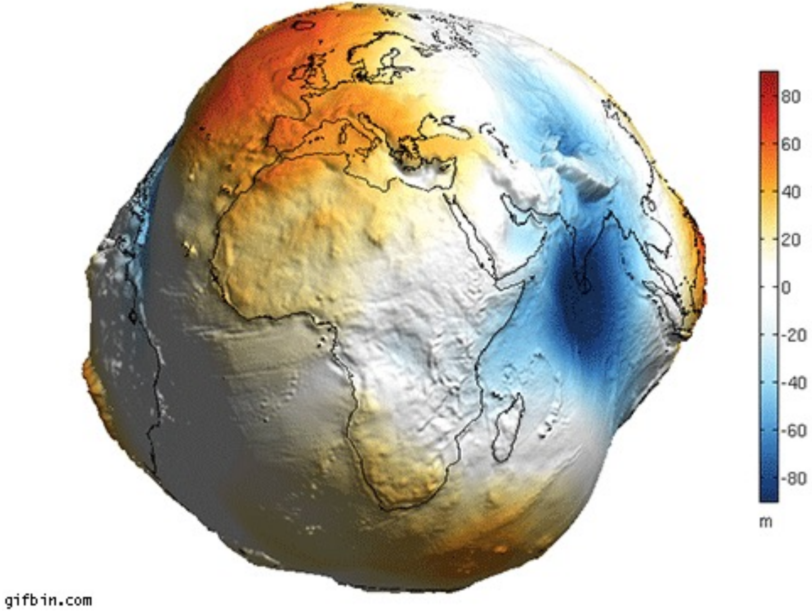
It is possible to reproduce the Earth's extreme P-T conditions

Laboratory experiments



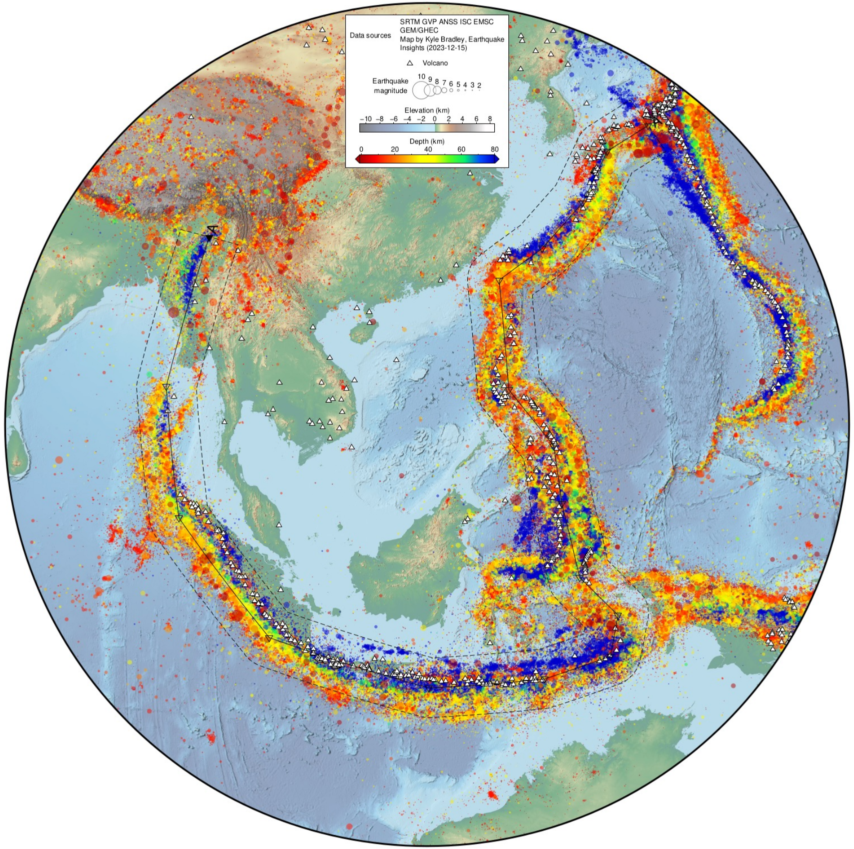
Predicting rock deformation and the interaction of processes taking place on scales ranging from microns to several hundred kilometres.

Geoid anomalies



Geoid anomalies are deviations of the Earth's geoid (the gravitational equipotential surface that corresponds to mean sea level) from an idealized hydrostatic ellipsoid, caused by lateral variations in Earth's internal mass distribution. These anomalies are primarily driven by density contrasts within the Earth's mantle, which can result from factors like mantle down/upwelling, and thermochemical instabilities.

Earthquakes

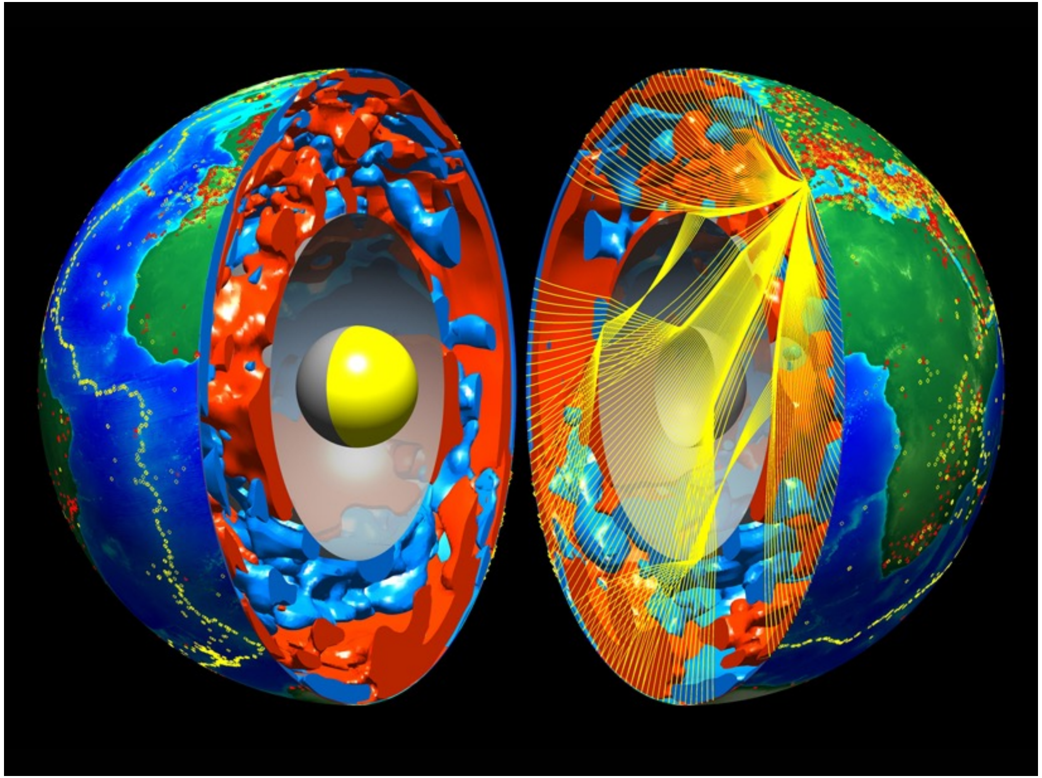


The Ring of Fire is a major zone of high seismic and volcanic activity that nearly encircles the Pacific Ocean, where approximately 90% of the world's earthquakes and 75% of its active volcanoes occur. This activity is the direct expression of powerful plate tectonics.

Seismic observations

Seismic waves travel at different speeds through different rocks. In a spherically symmetric Earth model, we can track how P-waves and S-waves bend, reflect, or disappear as they pass through layers of varying density and rigidity. By comparing predicted travel times and paths with real earthquake recordings, scientists infer the thickness, composition, and physical properties of Earth’s internal layers.

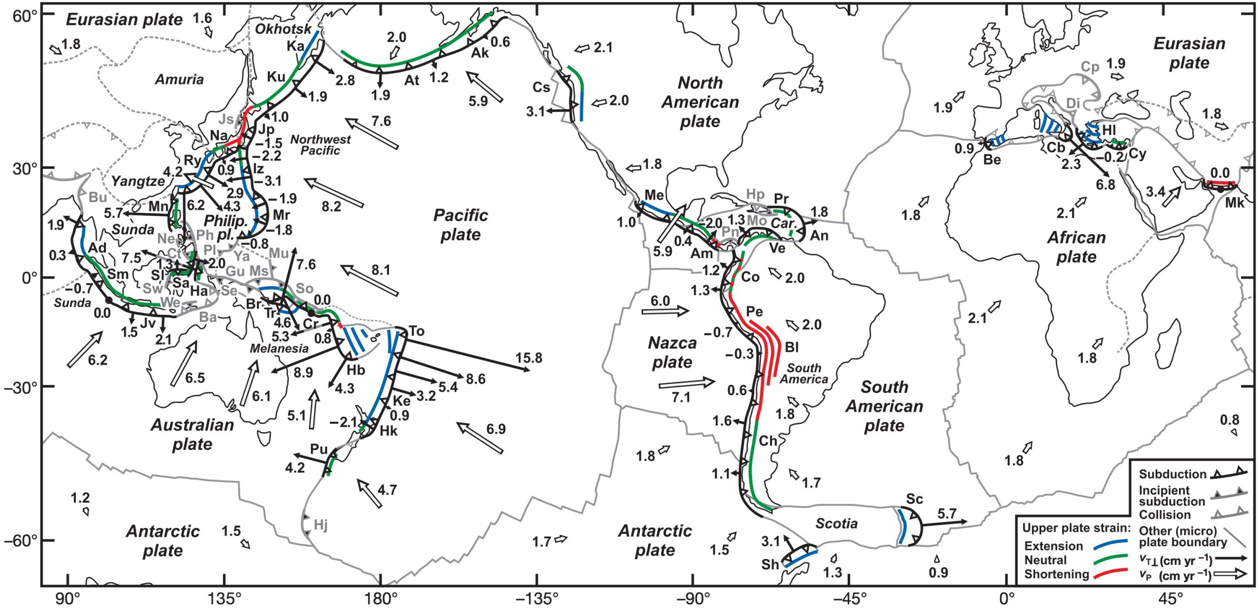
Seismic tomography



Seismic tomography is a technique that uses seismic waves from sources like earthquakes or explosions to create 3D images of the Earth's interior. By analysing how the waves' travel time and amplitude are affected by the materials they pass through, scientists can infer the properties of those materials, revealing features like variations in temperature and composition beneath the surface.

Satellite GPS tracking

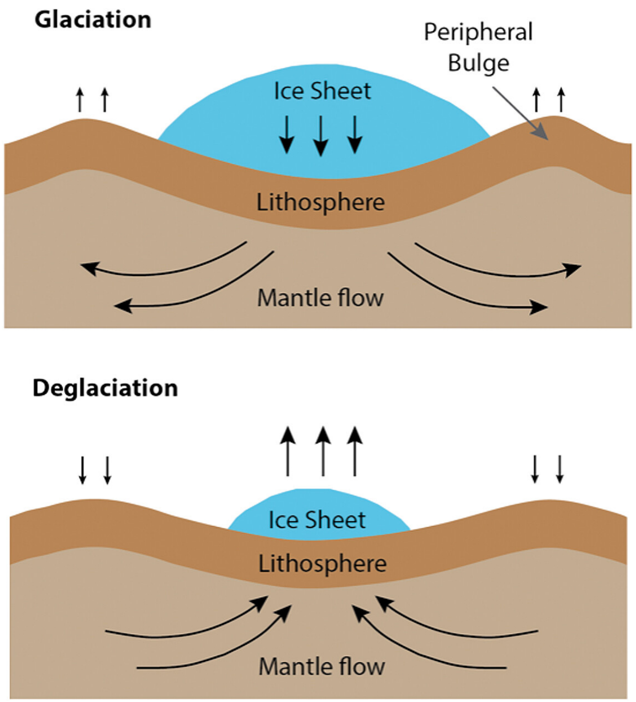
Every station on this map moves a few millimeters to centimeters per year, and the direction and speed of motion match the boundaries of tectonic plates.



These measurements are direct evidence that the lithosphere is broken into moving plates — not a theory inferred indirectly, but something we can observe in real time with millimetre precision.

Post-glacial rebound

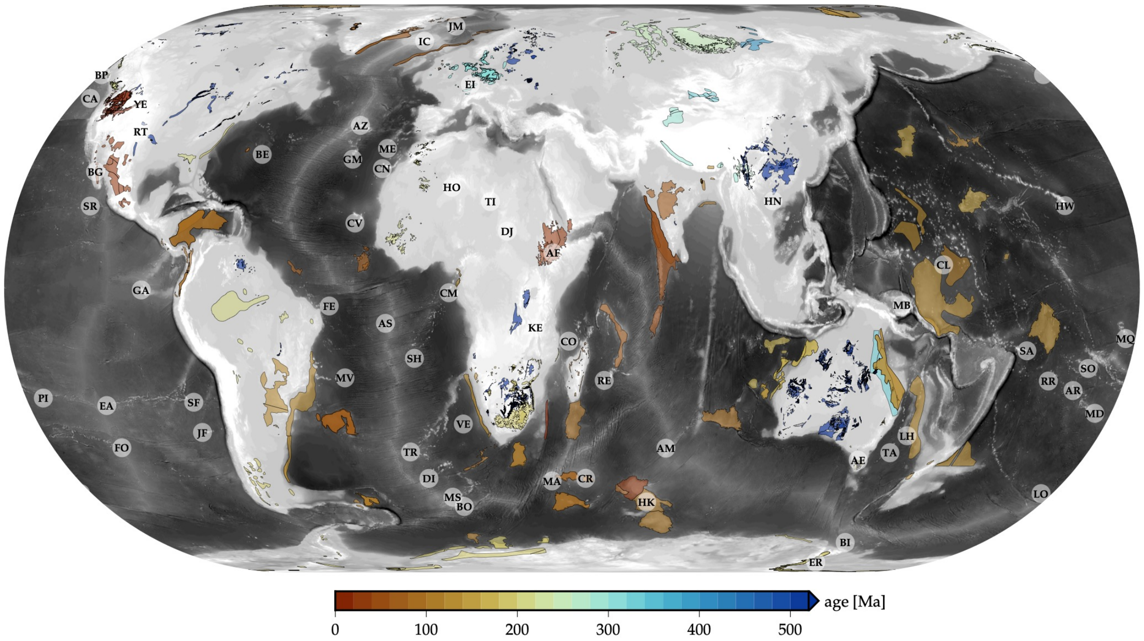
Post-glacial rebound is the rise of land masses that were depressed by the immense weight of ice sheets during the last ice age.



After the ice sheets melted, this weight was lifted, and the land slowly bounces back up, a process that continues today. Regions formerly covered by glaciers, like Canada and parts of Scandinavia, are still rising by over a centimetre a year.

Mantle Hot Spots

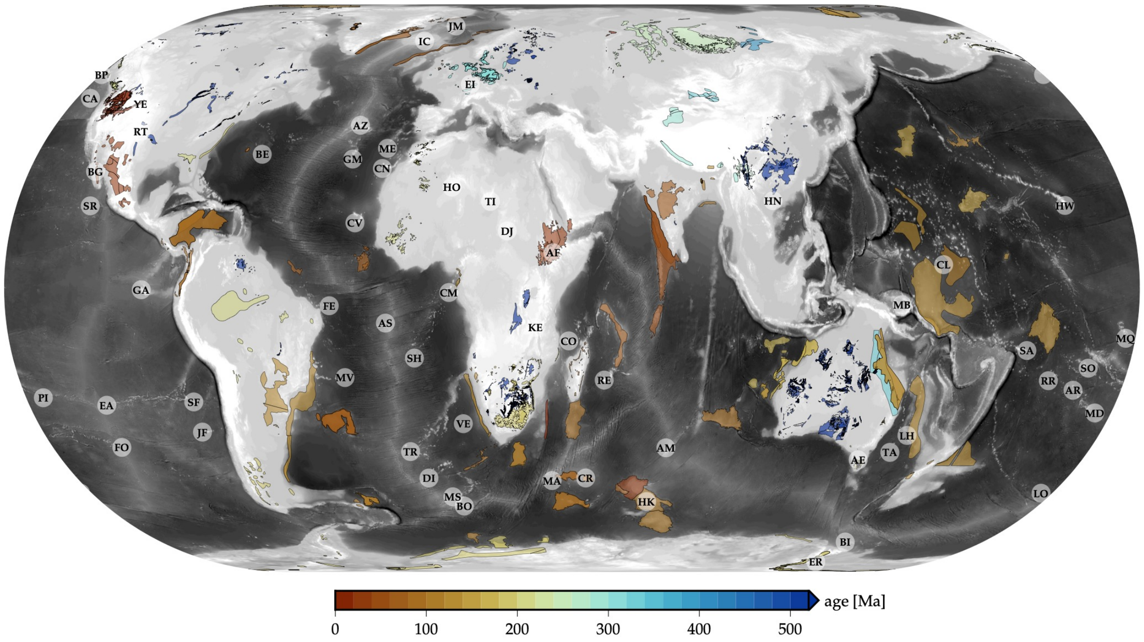
Mantle hotspots are volcanic regions fuelled by stationary plumes of superheated rock from deep within the Earth's mantle, with notable examples including Hawaii, Iceland, and Yellowstone.



As tectonic plates drift over these fixed points, chains of volcanoes can form over millions of years, with the active volcanism occurring at the "current" location and older, extinct volcanoes marking the plate's past positions.

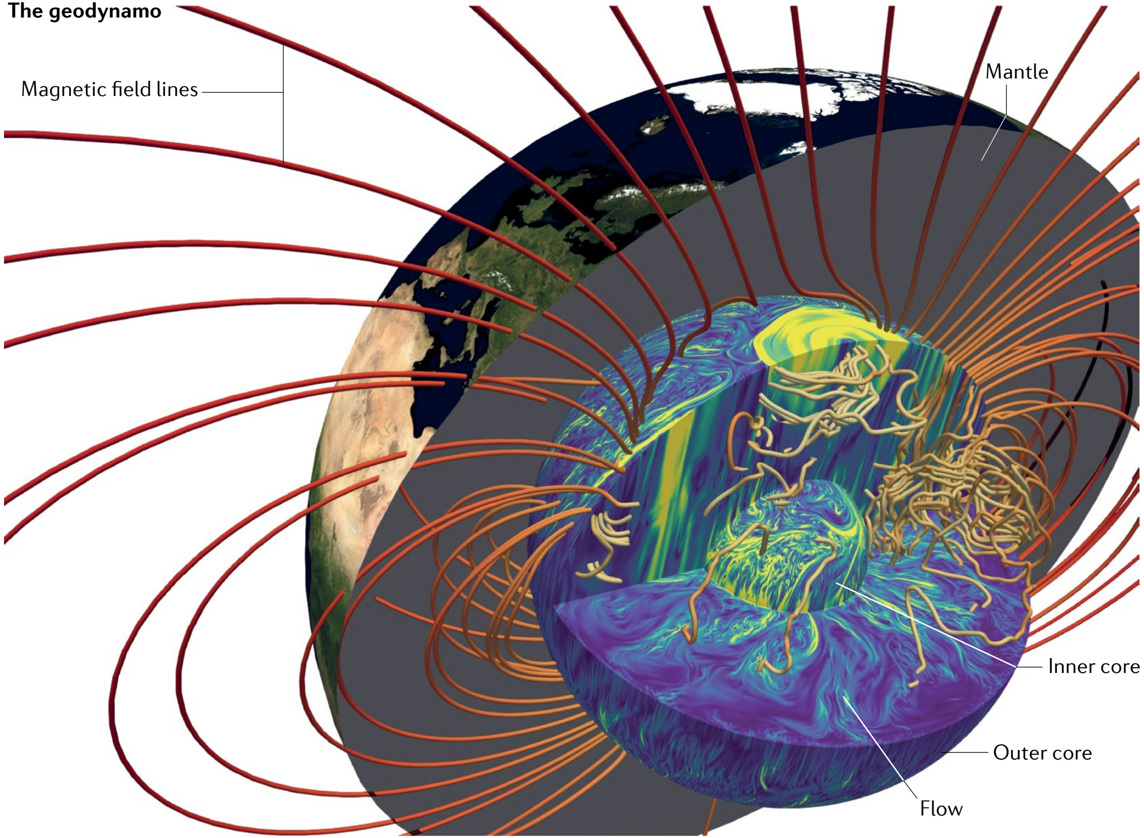
Large Igneous Provinces (LIP)

A large igneous province (LIP) is an extremely large accumulation of igneous rocks, including intrusive (sills, dikes) and extrusive (lava flows, tephra deposits), arising when magma travels through the crust towards the surface.



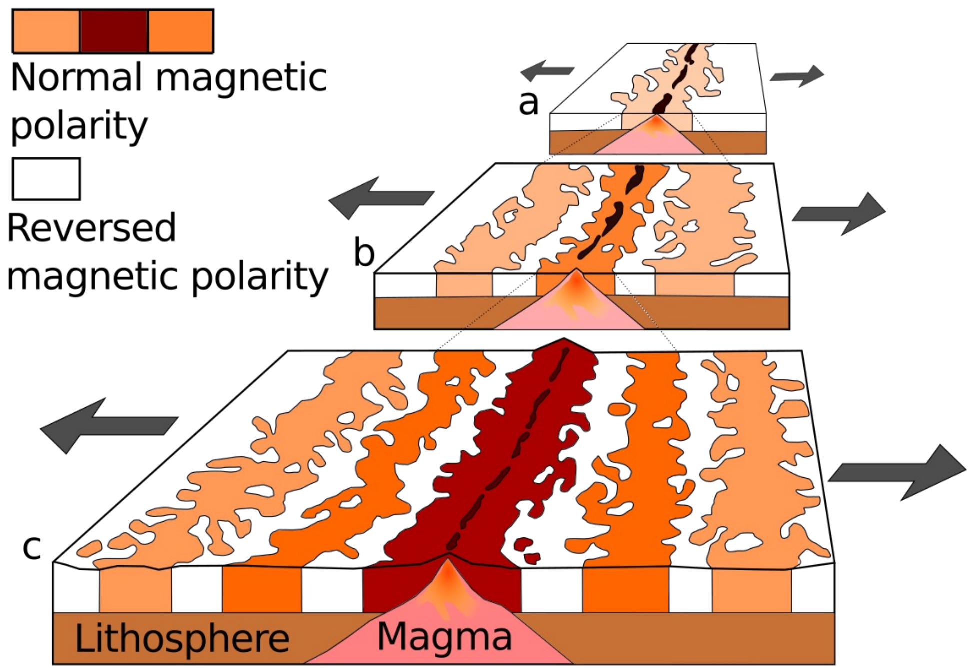
The intense volcanic activity associated with LIPs can cause significant environmental changes and is linked to mass extinction events. They are composed mainly of mafic rocks, which are rich in iron and magnesium, such as basalt.

Earth's magnetic field



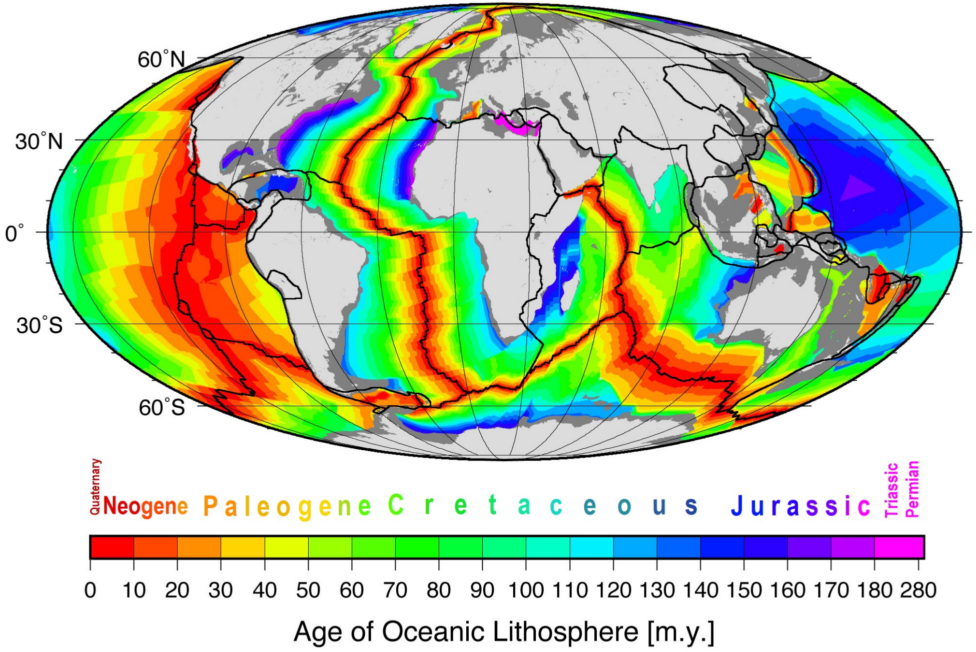
Earth's magnetic field is generated by the churning of molten iron in the outer core through a process called the geodynamo. Convection currents in the liquid outer core, driven by heat escaping the core, create electric currents. The Earth's rotation then organizes these currents into a self-sustaining magnetic field.

Earth's magnetic field



This field is recorded in the oceanic crust through the magnetization of volcanic rocks at mid-ocean ridges; as magma cools and solidifies, magnetic mineral crystals become locked in place, preserving the field's direction at that time. The resulting pattern of alternating magnetic stripes on the seafloor is evidence of seafloor spreading and the Earth's magnetic field reversals, where the north and south poles have periodically flipped.

Oceanic lithosphere age

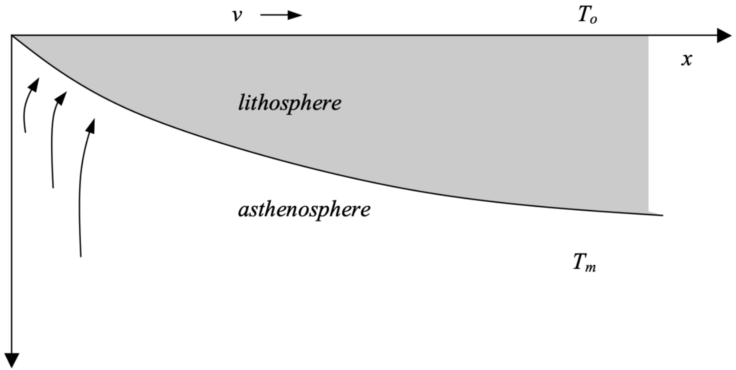


Oceanic lithosphere gets progressively older as it moves away from a mid-ocean ridge. This age increases with distance because new oceanic lithosphere is continuously created at the ridge, where molten rock rises and cools to form oceanic crust and the underlying mantle.

The age of the oceanic lithosphere varies from nearly zero at mid-ocean ridges to a maximum of about 180-200 million years

(Half-space) cooling of the oceanic lithosphere

Idealised model of how newly formed oceanic lithosphere cools as it moves away from a mid-ocean ridge.



$$\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial z^2}$$

$$T(z,0) = T_m \qquad \text{for } z > 0 \quad \text{(initially hot half-space)}$$

$$T(0,t) = T_0 \qquad \text{for } t > 0 \quad \text{(fixed cold surface)}$$

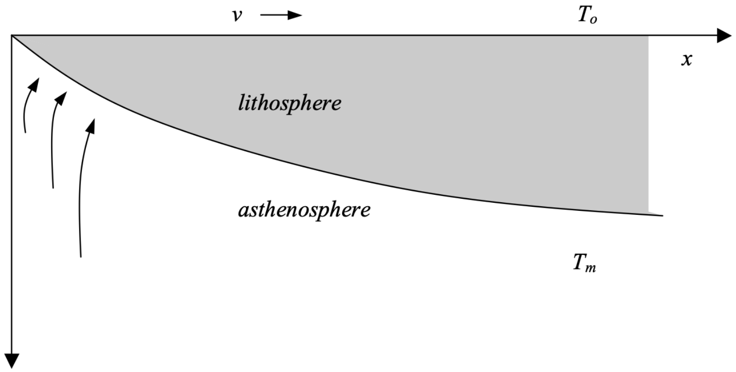
$$T(z,t) = T_0 + (T_m - T_0)\,\mathrm{erf}\left(\frac{z}{2\sqrt{\kappa t}}\right)$$

$$\boxed{T(z,t) = T_0 + \Delta T\ \mathrm{erf}\left(\frac{z}{2\sqrt{\kappa t}}\right)}$$

Idealised model of how newly formed oceanic lithosphere cools as it moves away from a mid-ocean ridge.

(Half-space) cooling of the oceanic lithosphere

Idealised model of how newly formed oceanic lithosphere cools as it moves away from a mid-ocean ridge.



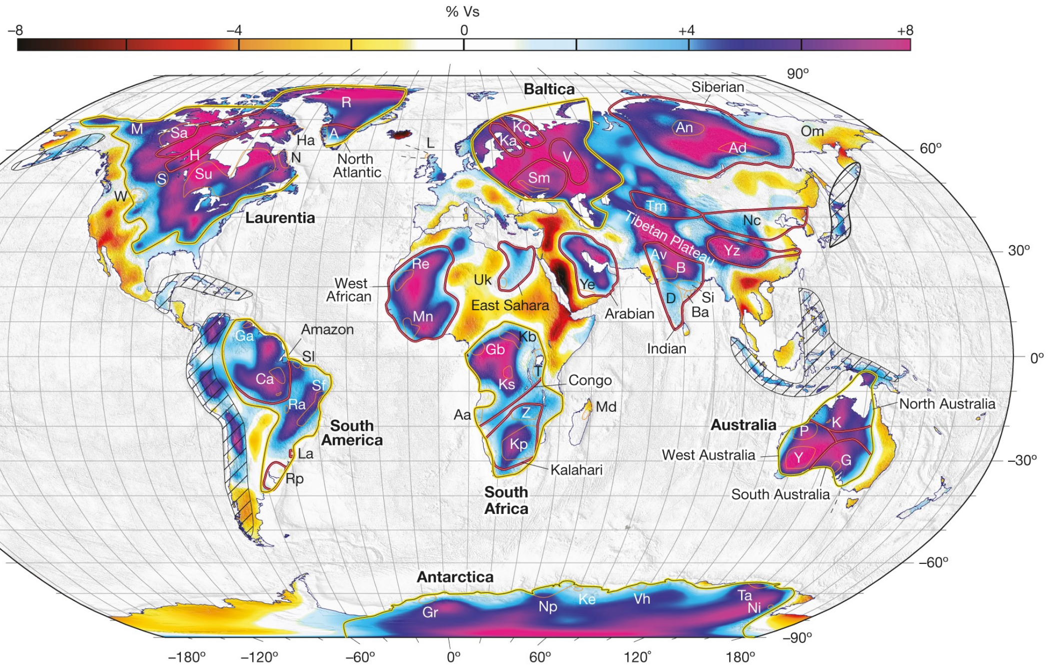
What it tells us

- As time (plate age) increases, the cold thermal boundary layer thickens like
- Cooling and contraction make the lithosphere denser and thicker, so the seafloor subsides with age.
- The vertical temperature gradient at the surface decreases, so heat flow drops with age.

In words: young oceans are hot, thin, shallow, and high heat-flow; old oceans are cold, thick, deep, and low heat-flow — and this simple conduction model captures those first-order trends.

Radiometric dating & cratons

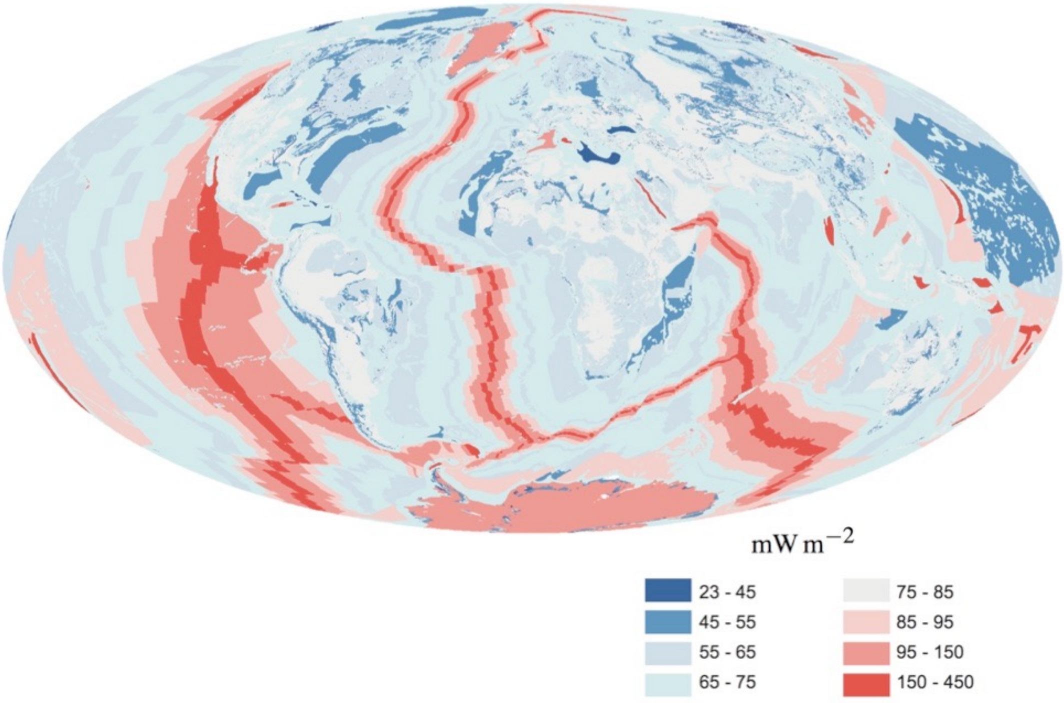
Defining cratonic regions with seismic imaging of continental mantle lithosphere.



Radiometric dating is the principal method used to determine the absolute ages of Earth's cratons and the ancient rocks they contain. The uranium-lead (U-Pb), samarium-neodymium (Sm-Nd), and rubidium-strontium (Rb-Sr) methods are particularly effective for dating these very old materials, which range from 2.5 to over 4.0 billion years old (Archean eon).

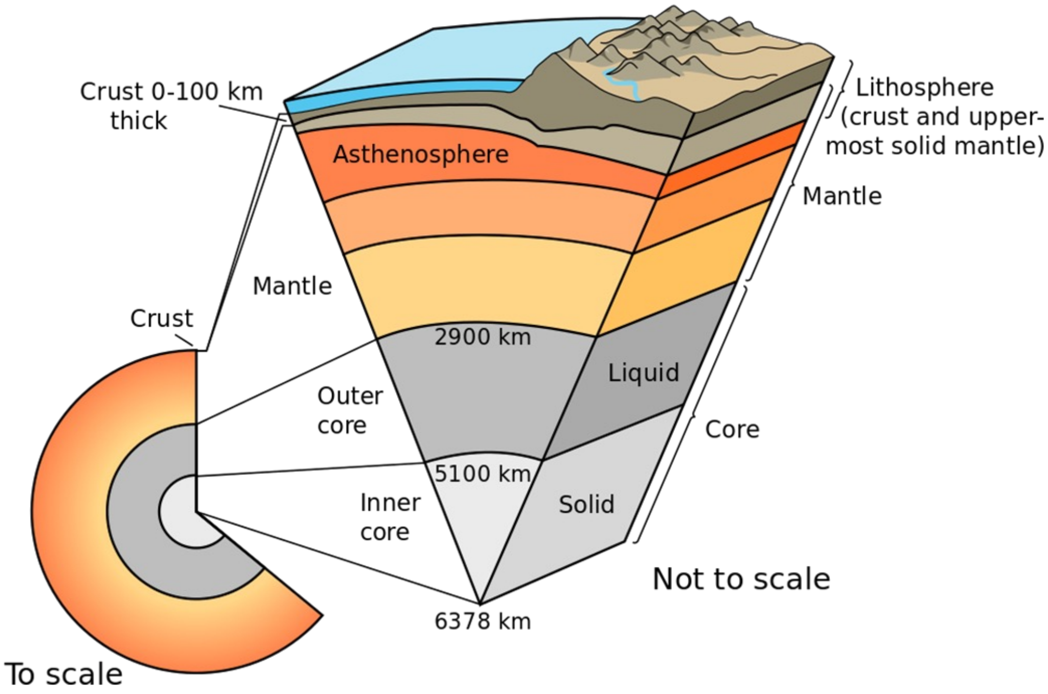
Global Heat Flow Map

Defining cratonic regions with seismic imaging of continental mantle lithosphere.



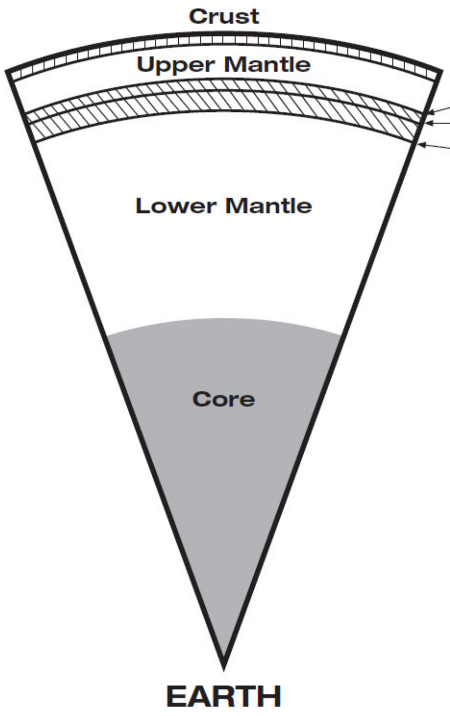
The global heat flow map illustrates the natural heat loss from the Earth's interior to its surface, with variations driven by tectonic activity.

Topography and internal structure of the Earth



Earth's topography and internal structure, from the thin outer crust down to the solid inner core. The image presents the layers to scale, emphasizing how extremely thin the crust is compared to the mantle and core.

Internal structure of the Earth



~410 km

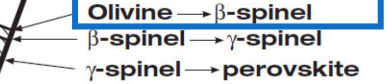
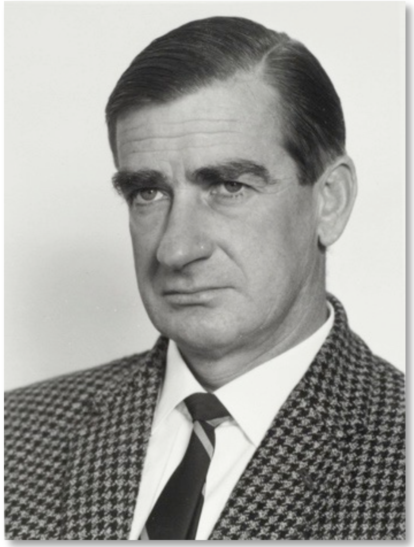


Table 1. Mineralogical Phases and Their End-Members. Each line gives the name, the crystallographic formula of an independent phase, and the names and chemical formulae of the end-members.

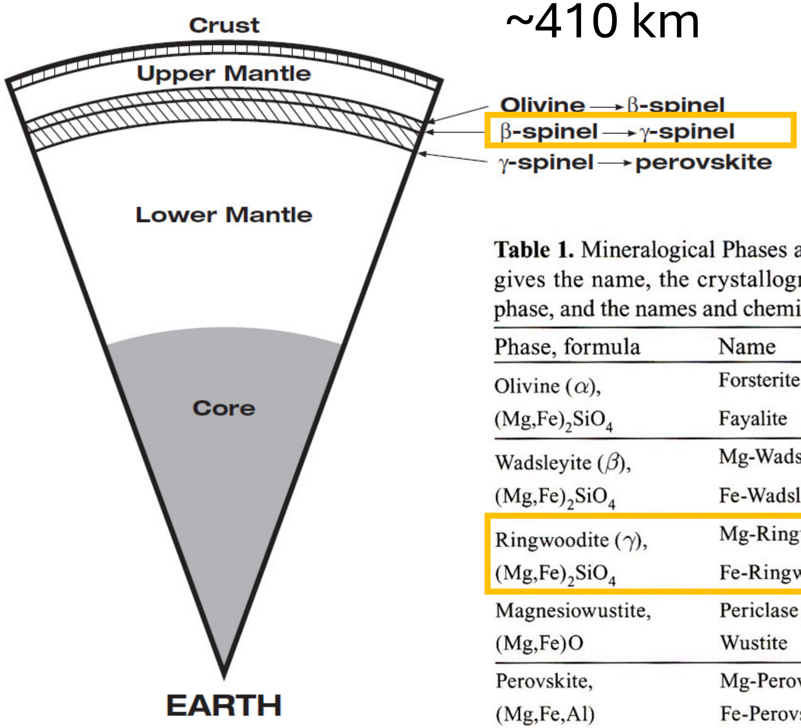
Phase, formula	Name	End-member
Olivine (α),	Forsterite	Mg_2SiO_4
$(Mg,Fe)_2SiO_4$	Fayalite	Fe_2SiO_4
Wadsleyite (β),	Mg-Wadsleyite	Mg_2SiO_4
$(Mg,Fe)_2SiO_4$	Fe-Wadsleyite	Fe_2SiO_4
Ringwoodite (γ),	Mg-Ringwoodite	Mg_2SiO_4
$(Mg,Fe)_2SiO_4$	Fe-Ringwoodite	Fe_2SiO_4
Magnesiowustite,	Periclase	MgO
(Mg,Fe)O	Wustite	FeO
Perovskite,	Mg-Perovskite	$MgSiO_3$
(Mg,Fe,Al)	Fe-Perovskite	$FeSiO_3$
$(Al,Si)O_3$	Al-Perovskite	Al_2O_3



Arthur David Wadsley (1918-1969)

Internal structure of the Earth

~410 km



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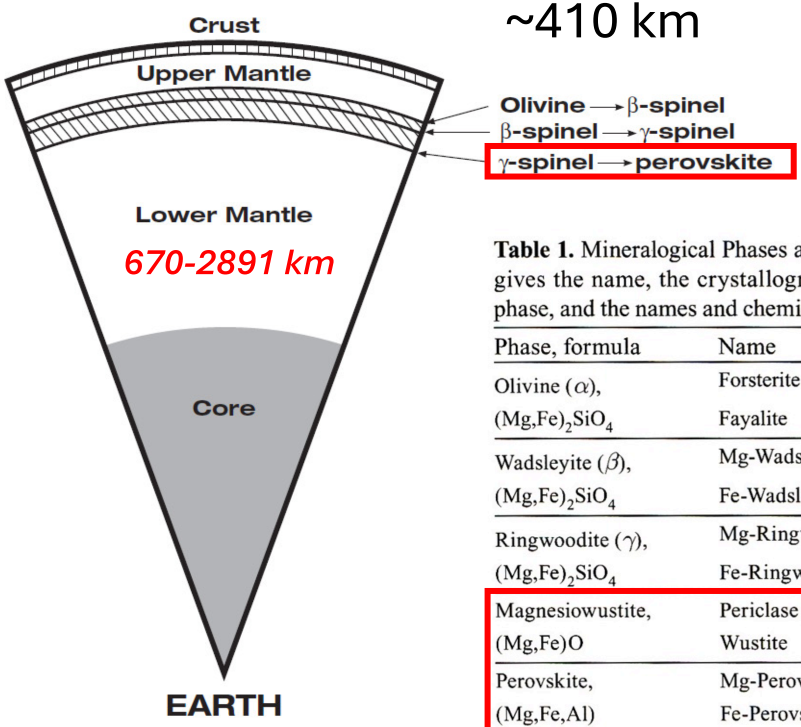
$(Mg,Fe)_2SiO_4$	Fe-Ringwoodite	Fe_2SiO_4
Magnesiowustite,	Periclase	MgO
(Mg,Fe)O	Wustite	FeO
Perovskite,	Mg-Perovskite	$MgSiO_3$
(Mg,Fe,Al)	Fe-Perovskite	$FeSiO_3$
$(Al,Si)O_3$	Al-Perovskite	Al_2O_3

Alfred Edward 'Ted' Ringwood (1930-1993)

Internal structure of the Earth

~410 km



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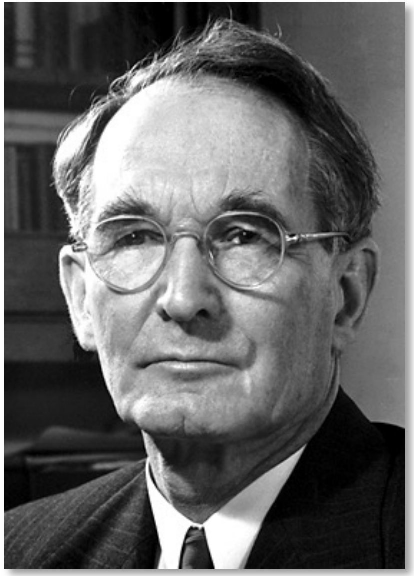
(Mg,Fe)O	Wustite	FeO
Perovskite,	Mg-Perovskite	$MgSiO_3$
(Mg,Fe,Al)	Fe-Perovskite	$FeSiO_3$
$(Al,Si)O_3$	Al-Perovskite	Al_2O_3

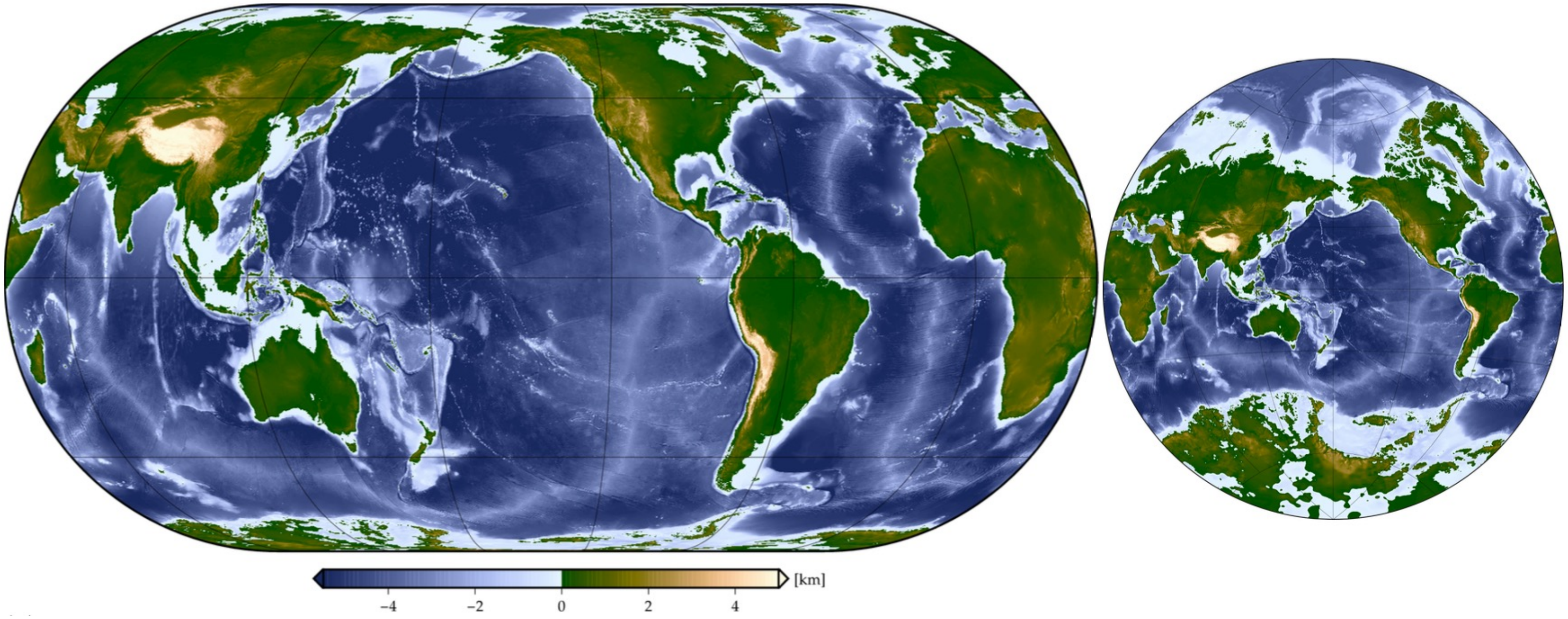


Percy Williams Bridgman (1882-1961)

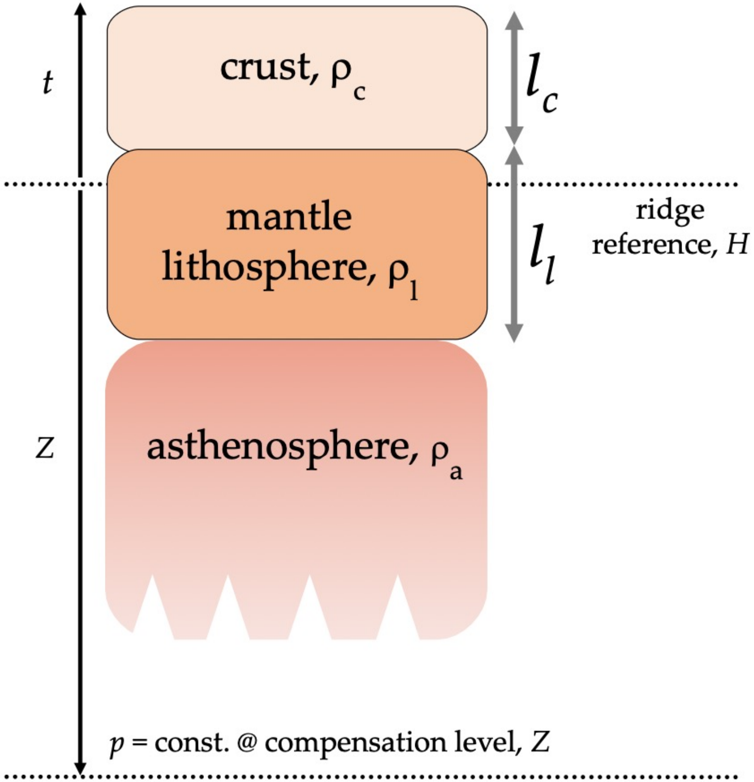
Nobel Prize in Physics 1946

Topography

Earth's topography is understood as the sum of two main components: **isostatic topography** (due to the weight and density of the crust) and **dynamic topography** (caused by mantle flow and convection).

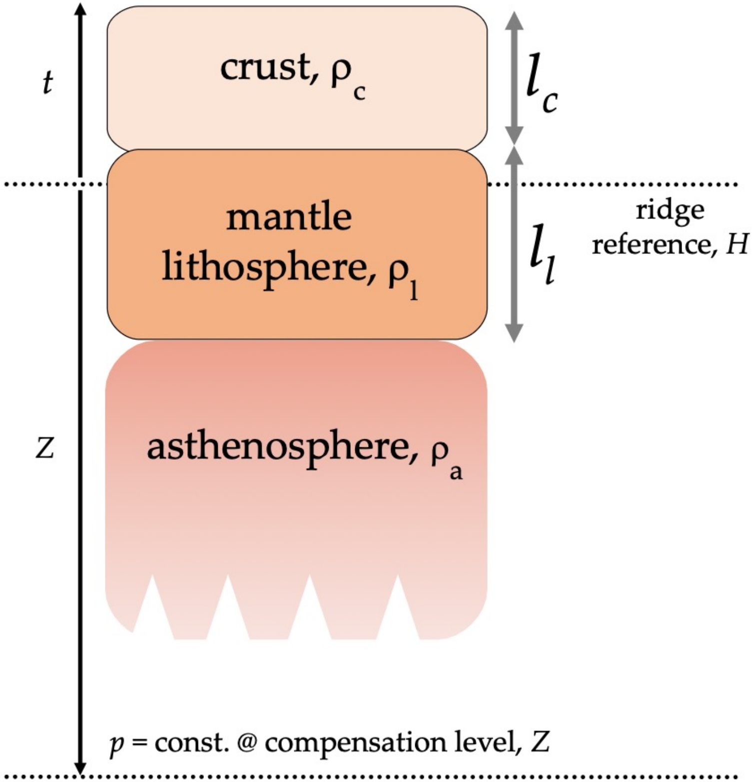


Isostasy



Isostasy is a geophysical principle describing the gravitational equilibrium of the Earth's lithosphere floating on the underlying asthenosphere, similar to how an iceberg floats in water. It explains that the lithosphere's elevation is determined by its thickness and density, with variations in mass (like mountains or ice sheets) being balanced by compensating mass changes deeper in the Earth.

Isostasy

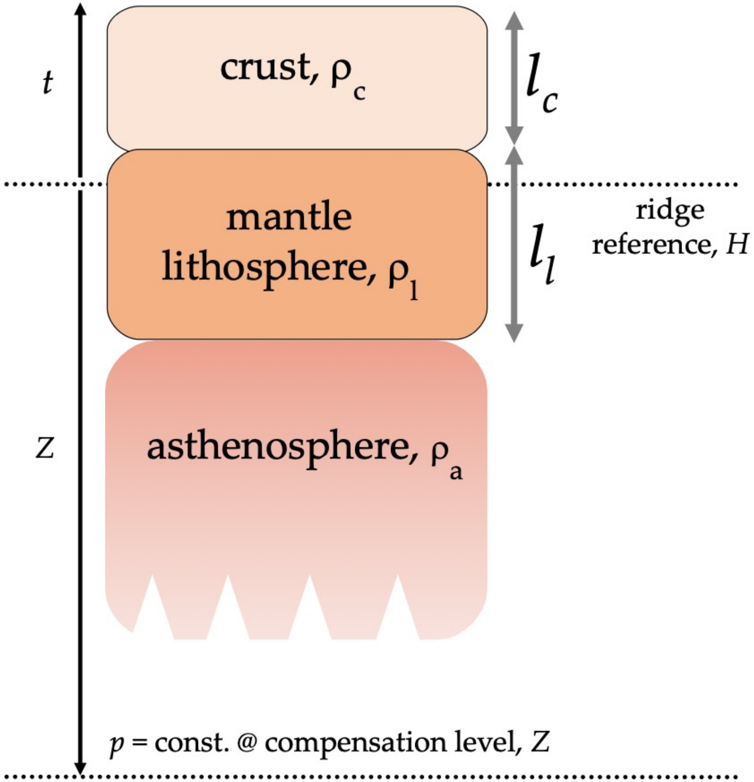


How can we link the assumption of force balance to topographic or structural observables?

When considering forces, it is often useful to start with Newton. His second law says that force, expressed as a vector pointing in some direction, F (units N, Newton), is mass m (units kg) times acceleration, g:

$$\boldsymbol{F} = m\boldsymbol{g}$$

Isostasy



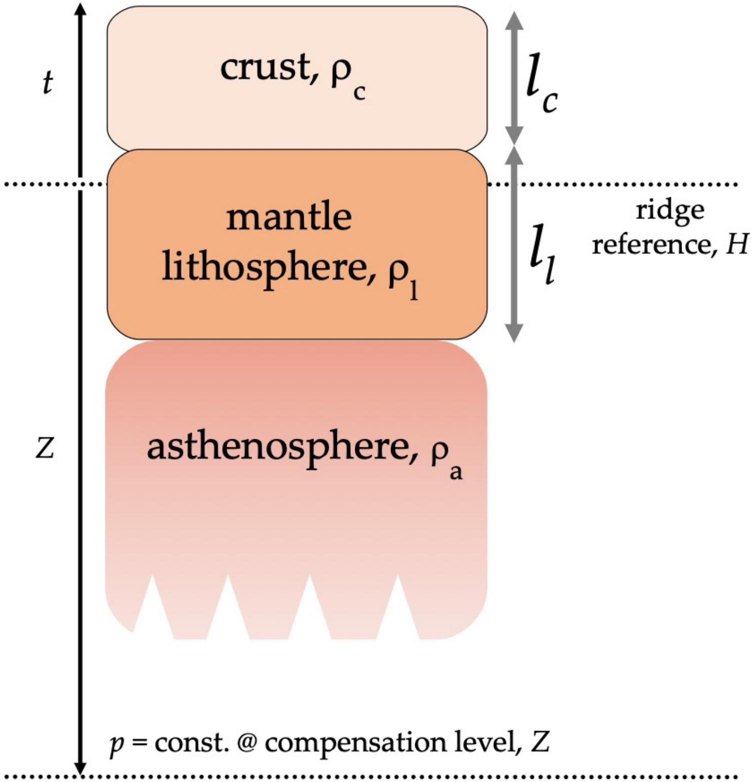
If that m object is our mantle column considered for the floating equilibrium, with area A and volume V on top of the compensation depth is:

$$m = \rho V$$

$$\rho = \frac{m}{V}$$

$$p_l = \rho g h = \int \mathrm{d}z \rho(z) g(z)$$

Isostasy



Airy isostasy: the "root for mountain" equation:

$$R = \frac{\rho_c}{\rho_m - \rho_c} T$$

$$R \approx \frac{2700}{3300 - 2700} T = \frac{2700}{600} T \approx 4.5T$$

R: roots
T: topography

So a 1 km high mountain implies ~4.5 km extra root.

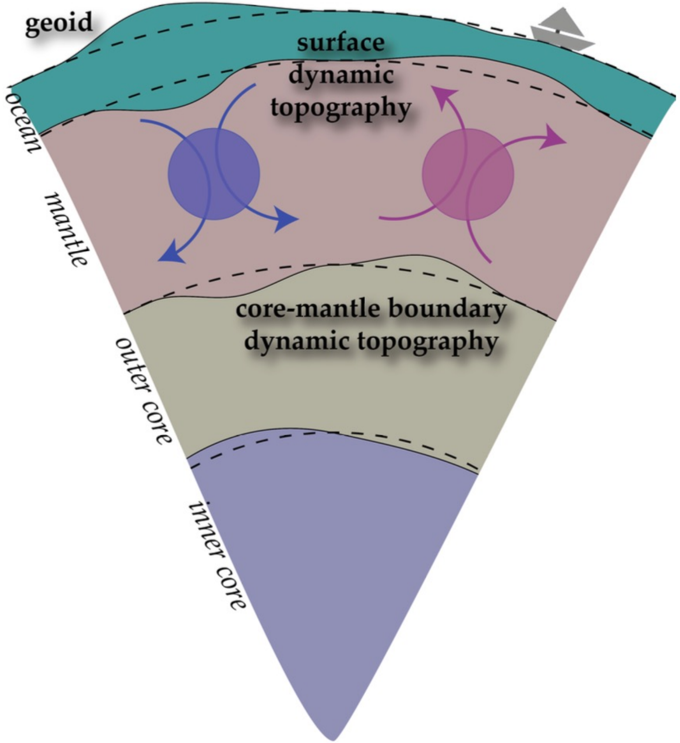
Gravitational potential (geopotential)

Newton's 1st law states that the gravitational force, F, exerted by a mass M, e.g., a planet, on a mass m, is given:

$$F = |\boldsymbol{F}| = G\frac{mM}{r^2}$$

Where r is the distance between the objects (their centers of mass, assumed as points), M is the object to the m object's center of mass, and G is the universal gravitational constant.

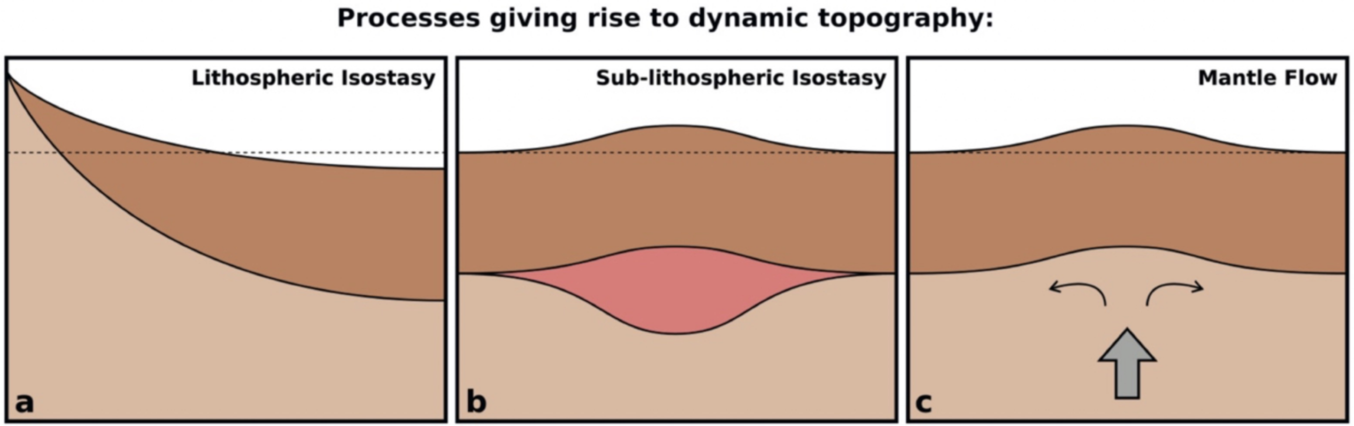
Gravitational potential (geopotential)



Cartoon illustrating the definition of the geopotential surface of the actual geoid and its deflection from a reference geoid of ellipsoidal form shown with dashed lines. Internal density anomalies, such as due to a dense and light anomaly, have a static and dynamic response on the geoid. Static, since the excess mass of a positive geoid anomaly means one has to move further away to experience the same gravitational pull. If the anomaly introduces flow, the resulting stresses will also deflect the surface and core-mantle boundary, and those ondulations lead to additional, dynamic effects on the geoid on timescales of ~Myr.

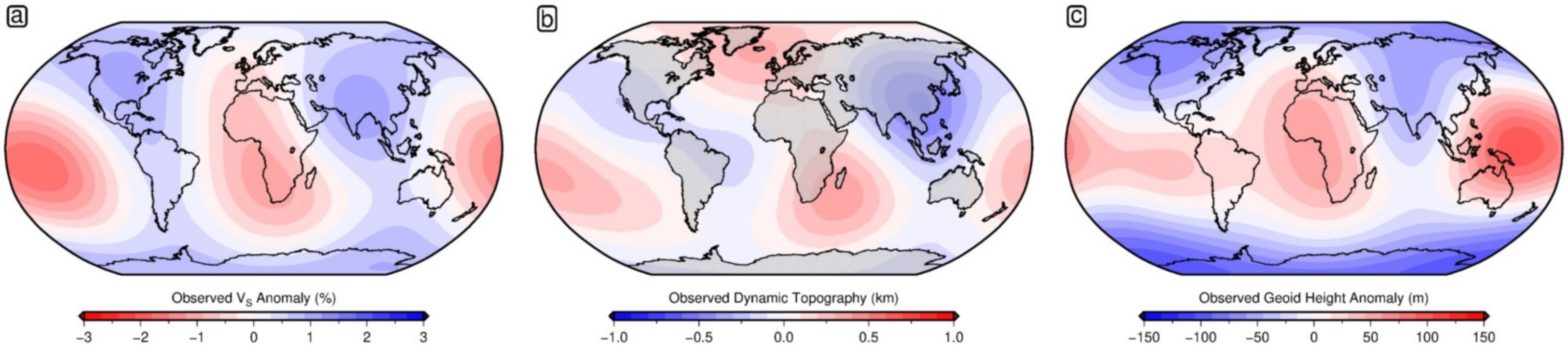
Dynamic topography:

Lithospheric isostasy + Sub-lithospheric isostasy + Mantle flow



Dynamic topography:

Lithospheric isostasy + Sub-lithospheric isostasy + Mantle flow



Long-wavelength correlations between deep mantle shear wave velocities and geodynamic observables. **a**) Vs anomalies. **b**) Same for observational estimates of dynamic topography. **c**) Same for observed non-hydrostatic geoid.

Internal structure, temperature, and composition of Earth

1-D structure of Earth as "seen" from seismology

RECAP:

Seismic waves are vibrations of the Earth where mechanical and kinematic energy gets transported away from a source, such as an earthquake or explosion.

(While more complicated in practice) we can think of this seismic wave by considering a ray path that is orthogonal to the wavefront. **That ray path will find the fastest path between source and receiver**.

If velocity increases with depth in the planet, the ray will thus not go straight from one side of the object to a recorder on the other side, but instead dive downward first and then be bent upward. This ***refraction*** is governed by ***Snell's law.***

A wave may also be **reflected** at a sharp contrast, such as a compositional layer, where the energy of transmission through an interface depends on the impedance, the product of wave speed and density. This provides constraints on the depth of the interface and the nature of the contrast.

Internal structure, temperature, and composition of Earth

1-D structure of Earth as "seen" from seismology

Waves in an elastic solid are compressional, P, and shear, S, waves exist. If we think of them as propagating through a planet as rays, we call them two types of body waves. Their respective wave speeds correspond to different types of solutions of the wave equation and depend on different mechanical (elastic) properties and density as:

$$v_P = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}} \quad \text{and} \quad v_S = \sqrt{\frac{\mu}{\rho}}$$

where μ, K, and ρ are the shear modulus, incompressibility, and density, respectively. Because K, μ > 0, → vp > vs, which means that the P wave arrives first, and motivates the names of primary and secondary wave.

Internal structure, temperature, and composition of Earth

1-D structure of Earth as "seen" from seismology

Based on the understanding of wave propagation, the analysis of refraction and reflection from a large amount of body wave records would then allow seismologist to infer a 1-D model of vp and vs for the Earth.

Properties on a log-scale for depth within the mantle happen in the upper~700 km, on which we focus here. Figure shows the Preliminary Reference Earth Model (PREM; Dziewónski and Anderson, 1981).