The Earth as a planet:
Interior and Surface layers

Bibliographic material:
Langmuir & Broecker (2012) How to build a habitable planet

Planets and Astrobiology (2023)

G. Vladilo

Earth internal structure

- Observational constraints
  - The main source of information to sample the deep internal structure of the Earth are seismic waves resulting from earthquakes, which are unpredictable
- Theoretical limitations
  - The physics of condensed matter, in solid and liquid form, of planetary interiors is more complex than the physics of (almost) perfect gases that describes large part of stellar interiors
  - At the temperature and pressure conditions typical of the planetary interiors the equations of state are uncertain since they are hardly testable in laboratory
- As a result, the interior of the Earth is less known than the surface of many astronomical sources
  - This situation is even more critical for other planets

Internal structure of the Earth: Observational techniques

Seismology

- Analysis of natural shock waves triggered by earthquakes
  - Information on the deepest layers and the planet core

Seismic exploration

- Analysis of artificially induced shock waves
  - Provides information on the surface layers
  - Search for commercially economic subsurface deposits of crude oil, natural gas, and minerals

Analysis of surface rocks originated in the internal layers

- Volcanic rocks provide information on geochemical processes taking place in the internal layers where they have been formed

Analysis of seismic waves

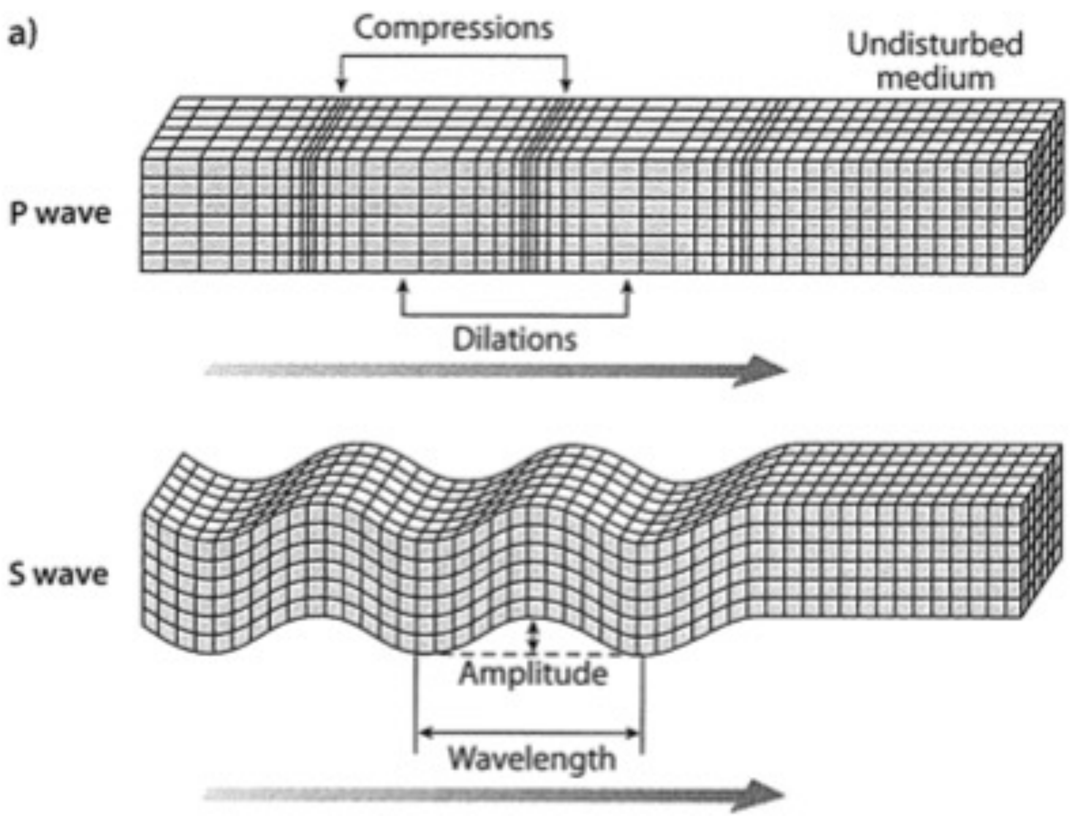
When a seismic wave travelling through the Earth encounters an interface between two materials with different acoustic impedances, some of the wave energy will reflect off the interface and some will refract through the interface.

The refraction index depends on the state of the matter (e.g. solid or liquid)

Analysis of seismic waves reveals the presence and location of discontinuities at the interface between layers with different refraction index and the possible presence of liquid layers

P and S waves

Compressional waves: matter displaces in the direction of the motion



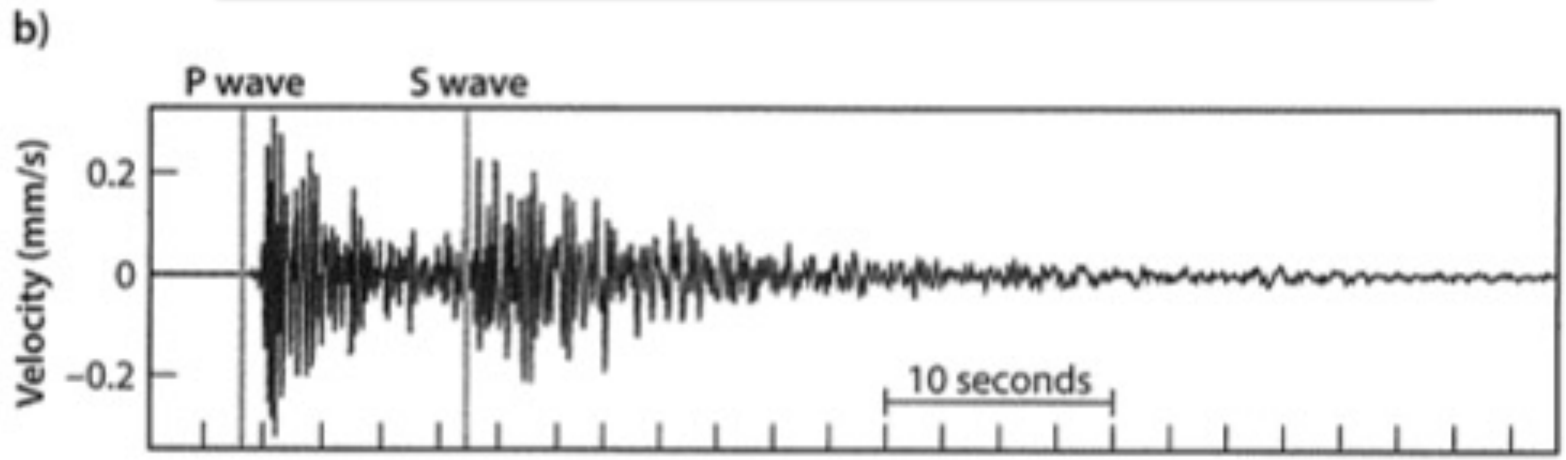
Shear waves: matter moves perpendicular to the direction of the motion

P and S waves

P and S waves have different velocities of propagation and different behaviour in the liquid phase

S waves are slower

S waves do not propagate in liquid phase

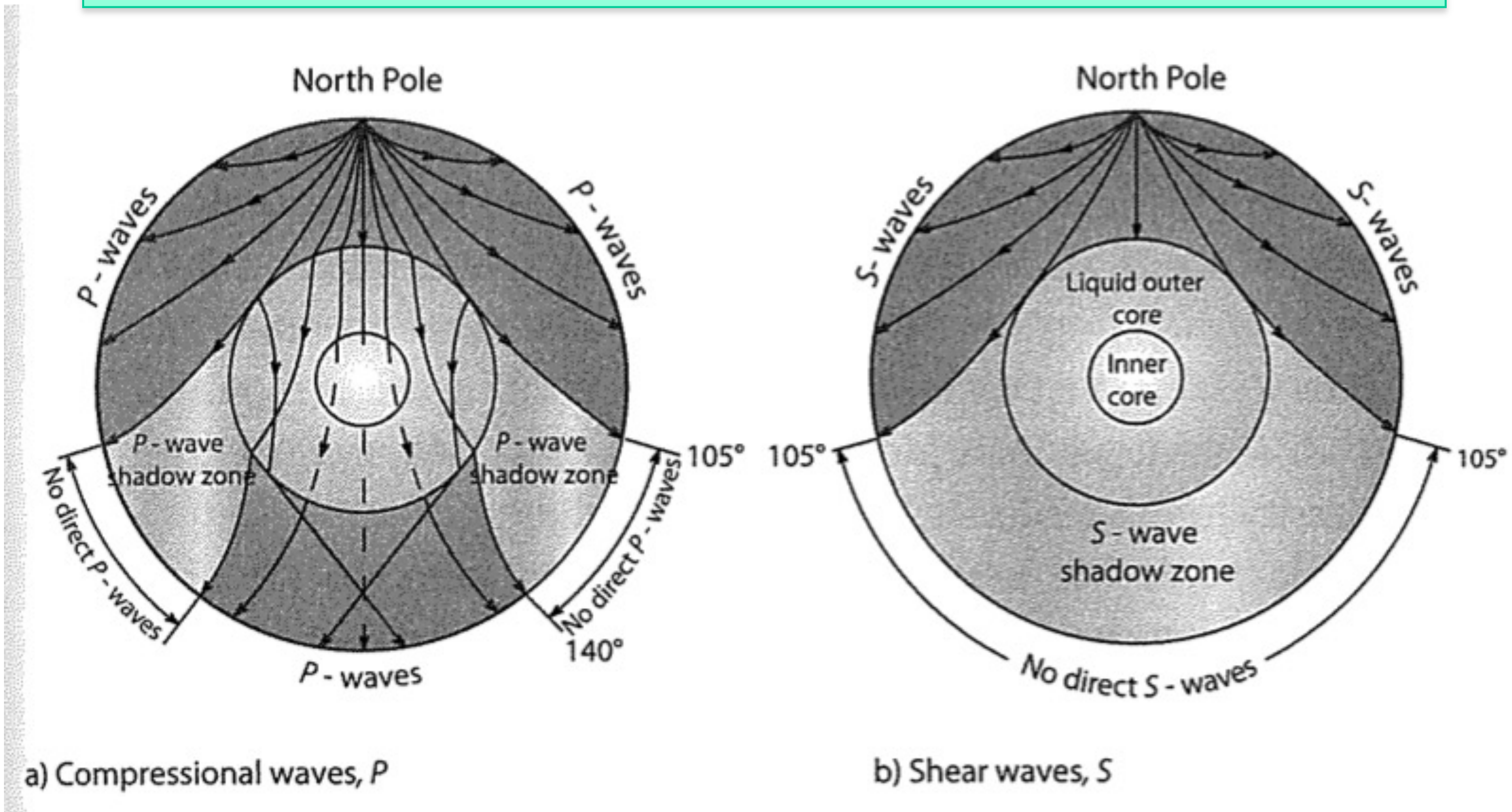


time

Paths of earthquake waves through Earth

The waves bend depending on the changes in the density of the material through which they pass

The regions where no direct waves arrive are referred to as *shadow zones*

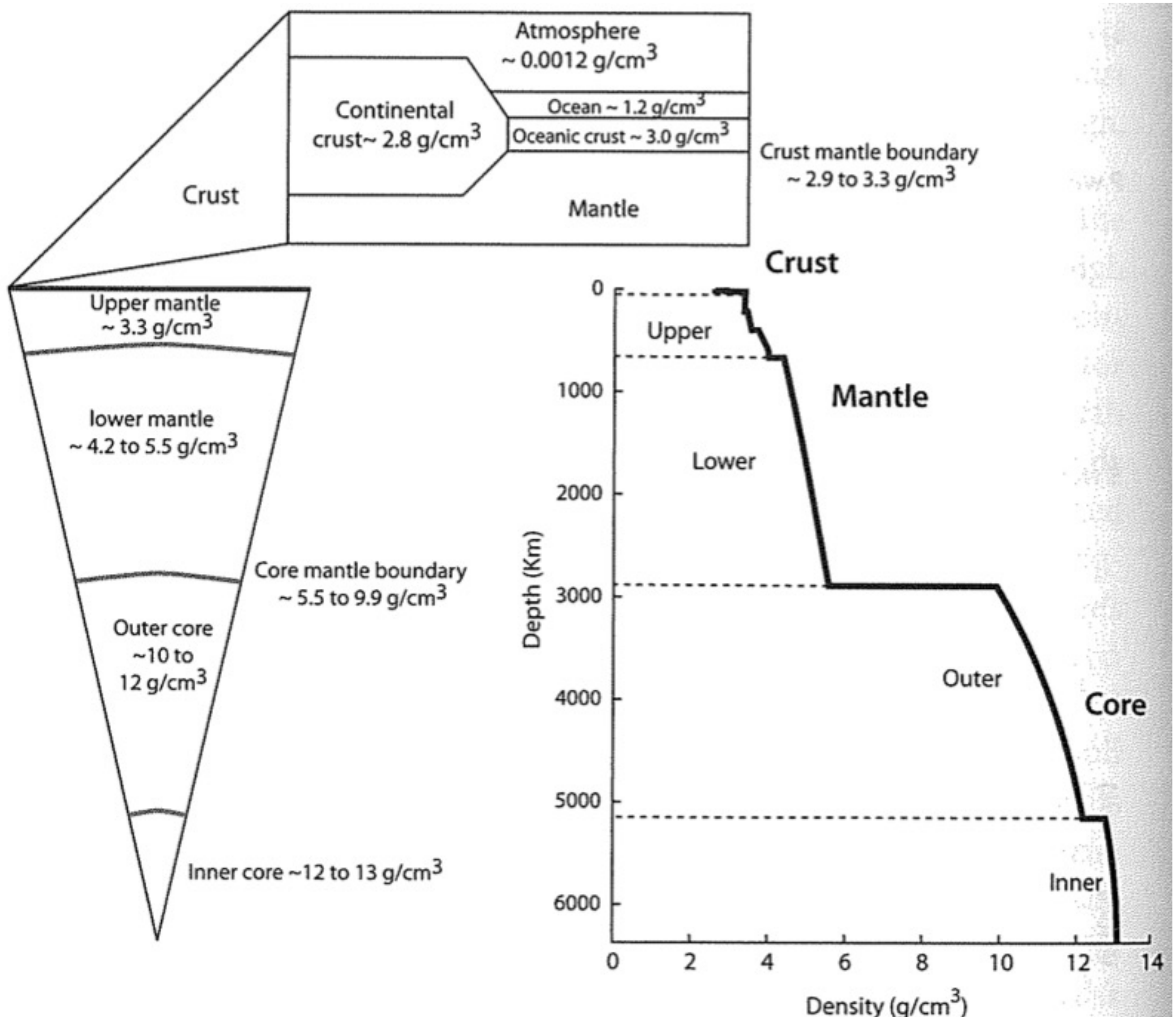


Earth internal density profile

Density profile through Earth determined by the analysis of seismic waves

Density increases progressively in each layer, largely due to compression

Abrupt changes in density occur where the material composition changes

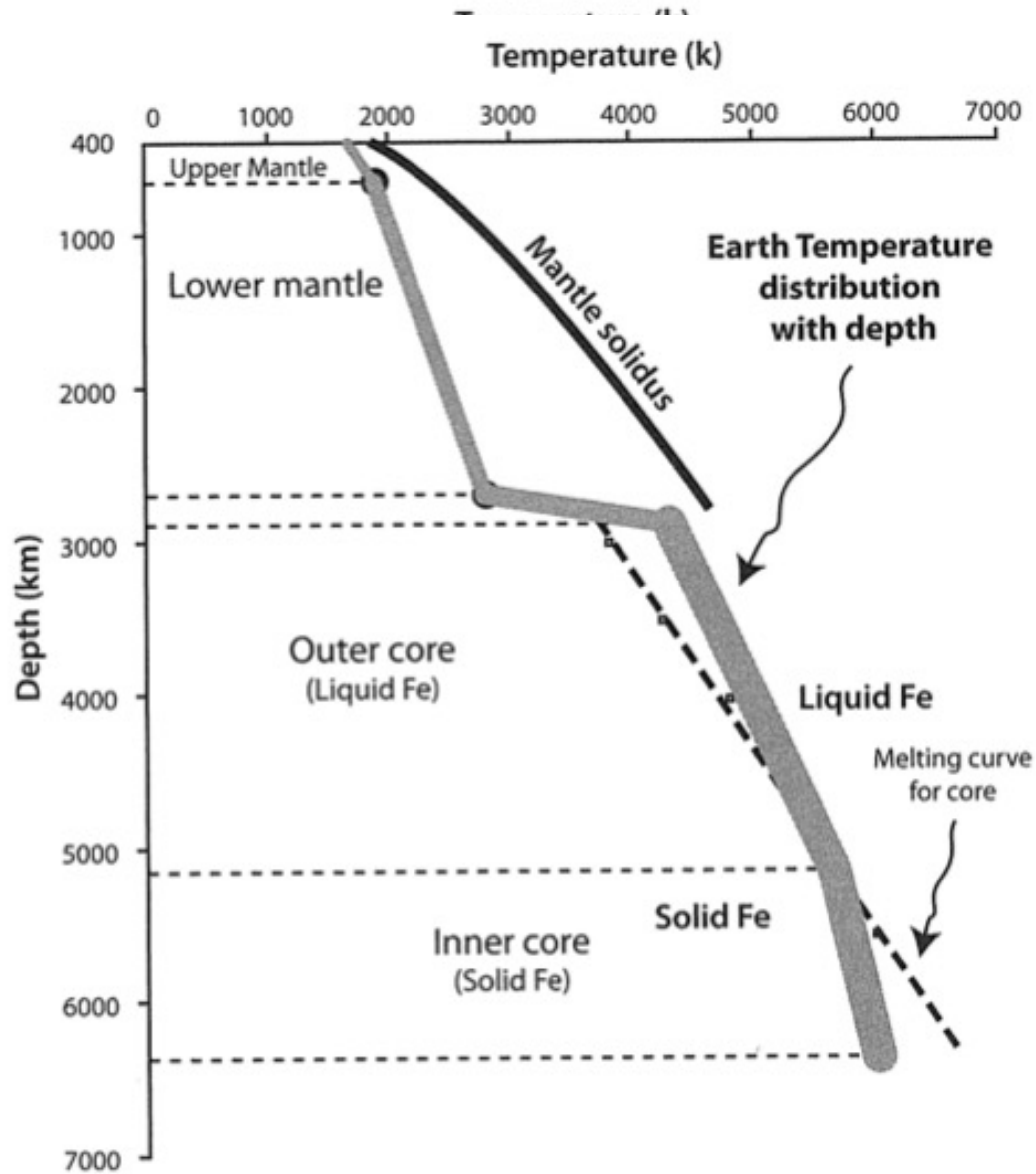


Earth internal temperature profile and state of matter

The state of matter depends on the different melting points of rock and metal and how they vary with pressure

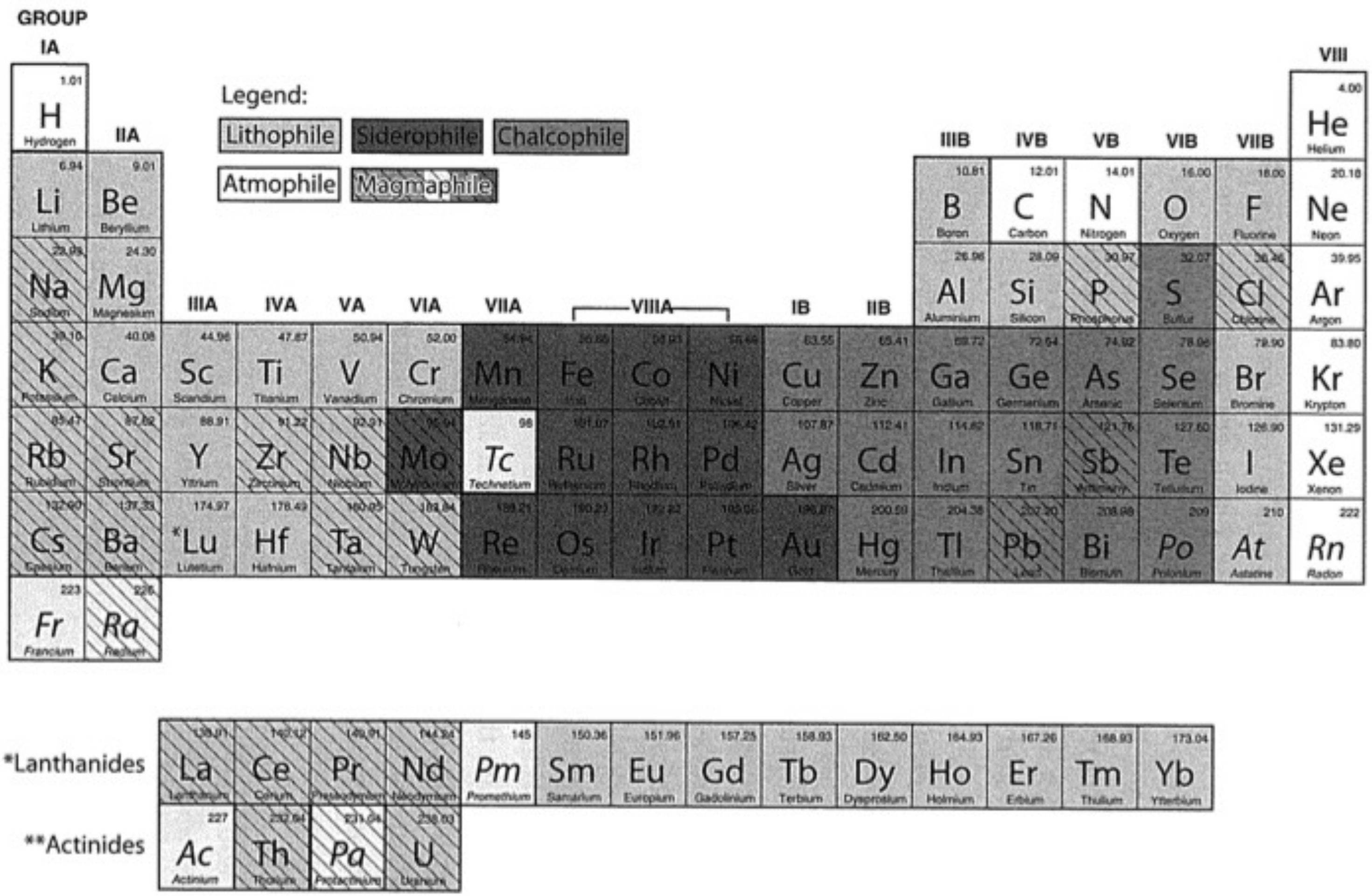
The outer core is liquid, while the mantle above it is solid, because the temperature of melting of Fe is lower than that of silicate at great depths, and there is a jump in temperature at the core/mantle boundary

The inner core is solid, while the outer core above it is liquid, because of the increase of melting temperature with depth



Chemical affinities of the elements

Elements are grouped according to their preferred host phases into:
lithofile (silicate loving), *siderophile* (iron loving), *chalcophile* (sulphur loving), and *atmophile* (gas loving)



Distribution of the elements among Earth's layers

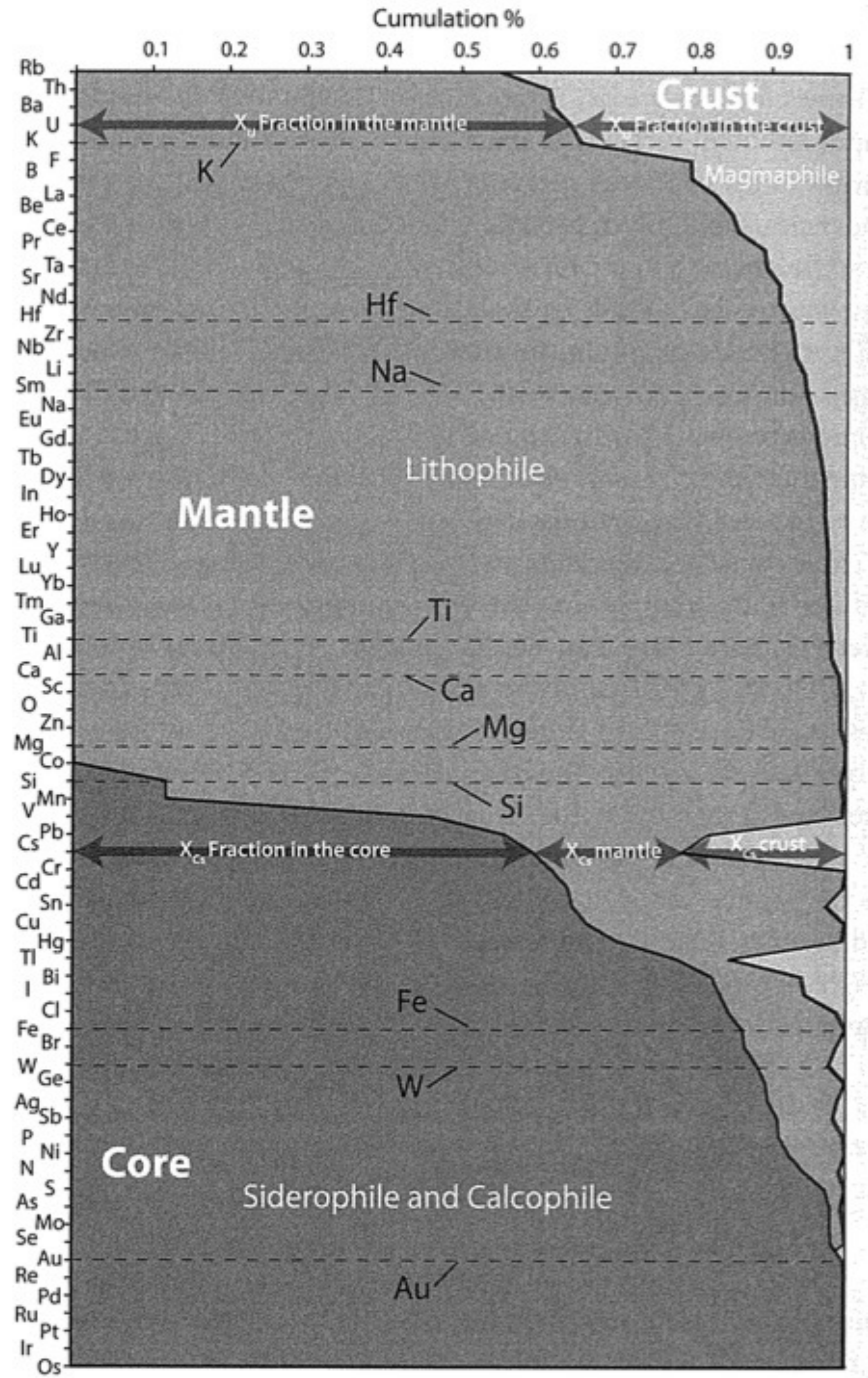
Vertical axis: list of 63 elements

Horizontal axis: proportions of the element in each layer normalized to 1

Chalcophile and siderophile elements have large proportions in the core

Lithofile elements are in Earth's silicate layers

Elements are <u>not</u> stratified according to their atomic weight (see, e.g., Th and U)



Lithosphere and astenosphere

The distinction between core, mantle and crust is based on compositional differences. However, for the same chemical composition, rheological properties, such as viscosity, can be completely different.

For instance, viscosity is strongly temperature dependent, decreasing when temperature increases.

Lithosphere:

Crust and rigid part of the upper mantle

Heat is transferred by conduction, quite inefficiently

Average thickness ~100 km unders oceans, ~150-200 km under continents

Asthenosphere:

Deeper and hotter layers of the mantle where peridotite has a ductile behaviour and where heat is dissipated by convection

Convection: the Rayleigh number

$$R_A = \frac{\alpha g \Delta T h^3}{\eta \kappa}$$

Rayleigh number:

dimensionless ratio between

the physical quantities that enhance convection

(α: coefficient of thermal expansion, g: gravitational acceleration, ΔT: temperature contrast, h: height of convection cells)

and those that inhibit convection

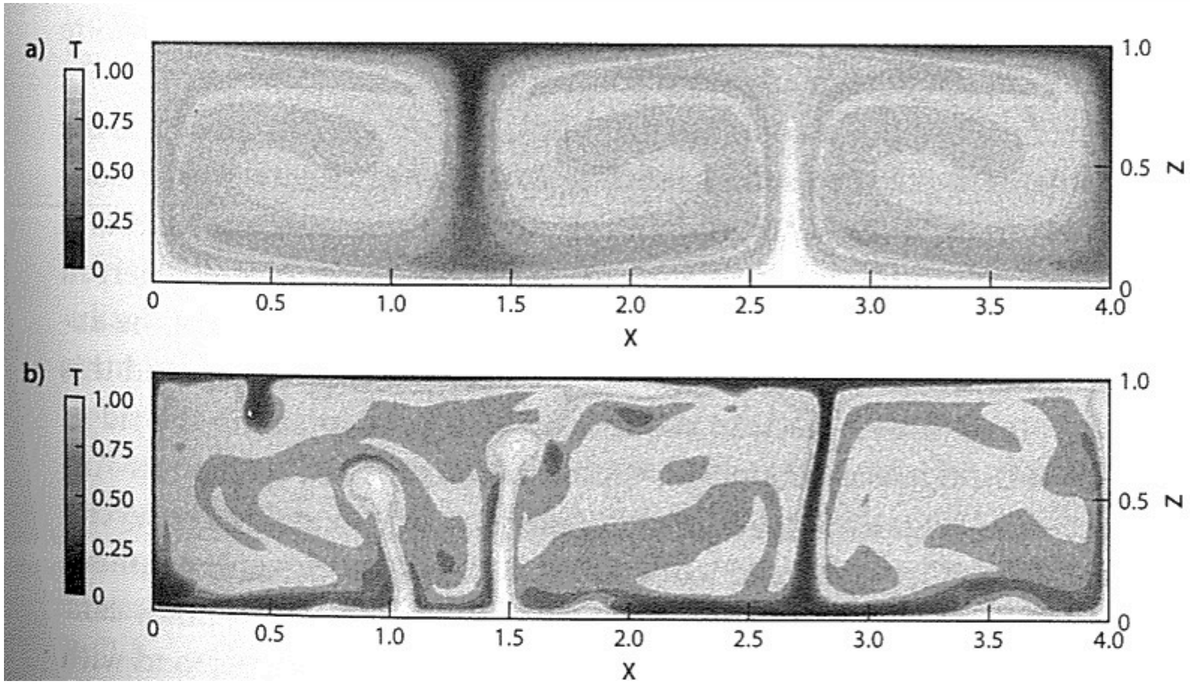
(η: viscosity, $\varkappa$: thermal conductivity)

When $R_A \approx 2000$ or larger convection is inevitable

Is the Earth mantle convecting?

The mantle viscosity is huge (10^{24} times times more viscous than water), but distances and temperature gradients are large and thermal diffusivity slow

As a result, the mantle has $R_A \approx 10^6$ or more, and convection must be present

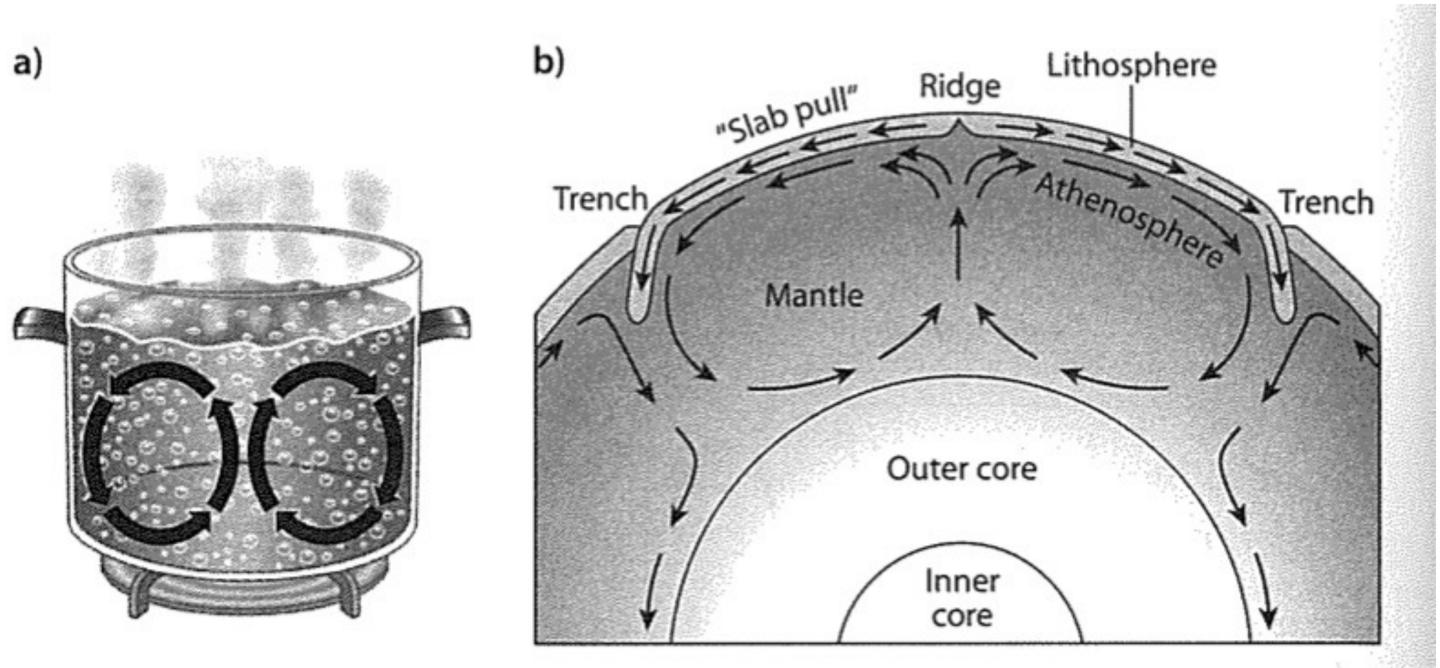


$R_A = 10^5$

$R_A = 10^7$

Simulations indicate that at very high values of R_A convection becomes less organized (not just simple cells) and more turbulent, with vigorous ascending and descending plumes

Convection cells & plate tectonics

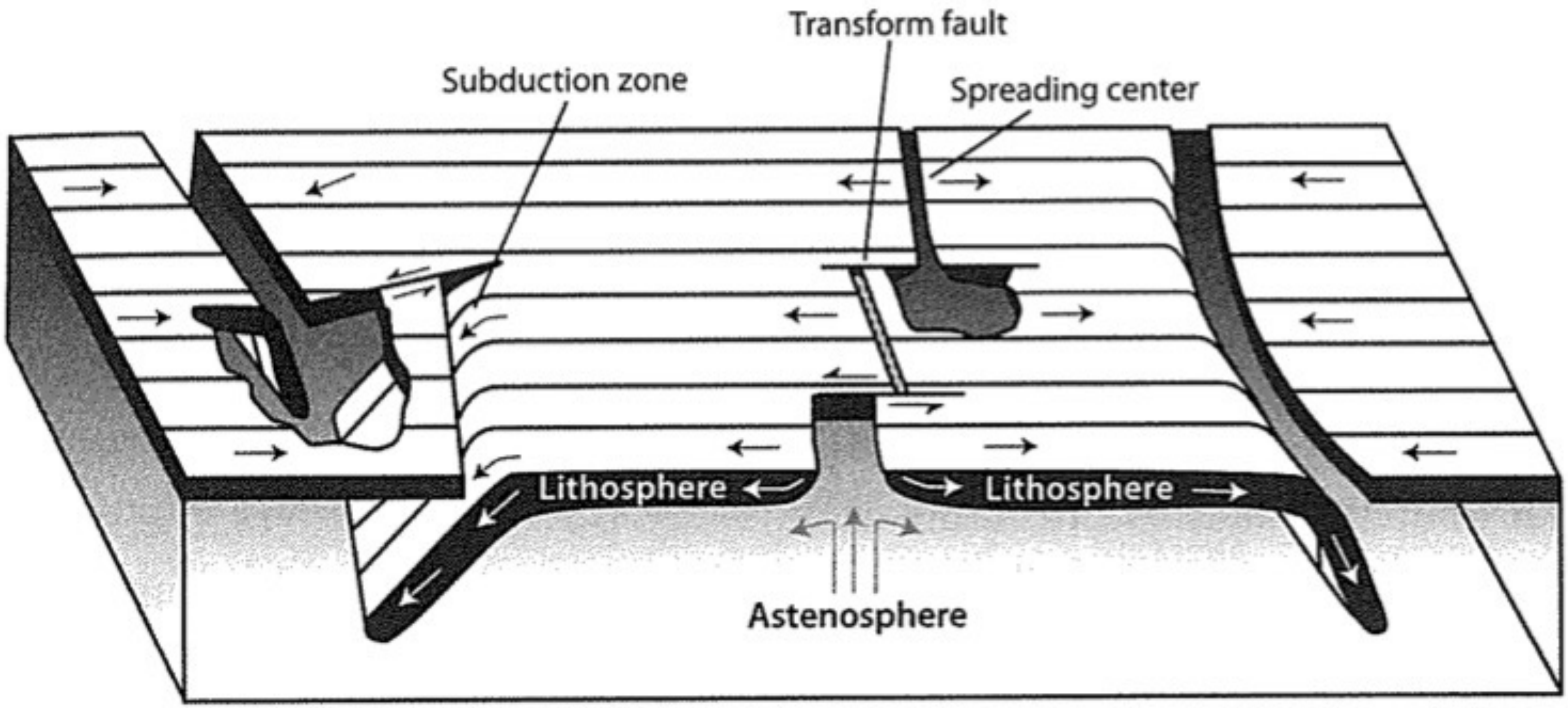


a) Simplest form of convection leads to circular convection cells

b) Convection in the asthenosphere is the mechanism that drives plate tectonics

Schematic view of a hypothetical relationship between subducting plates being associated with the downwelling limb of a convection cell and ridges being caused by convecting upwelling. The actual situation is much more complicated

Basic concept of plate tectonics

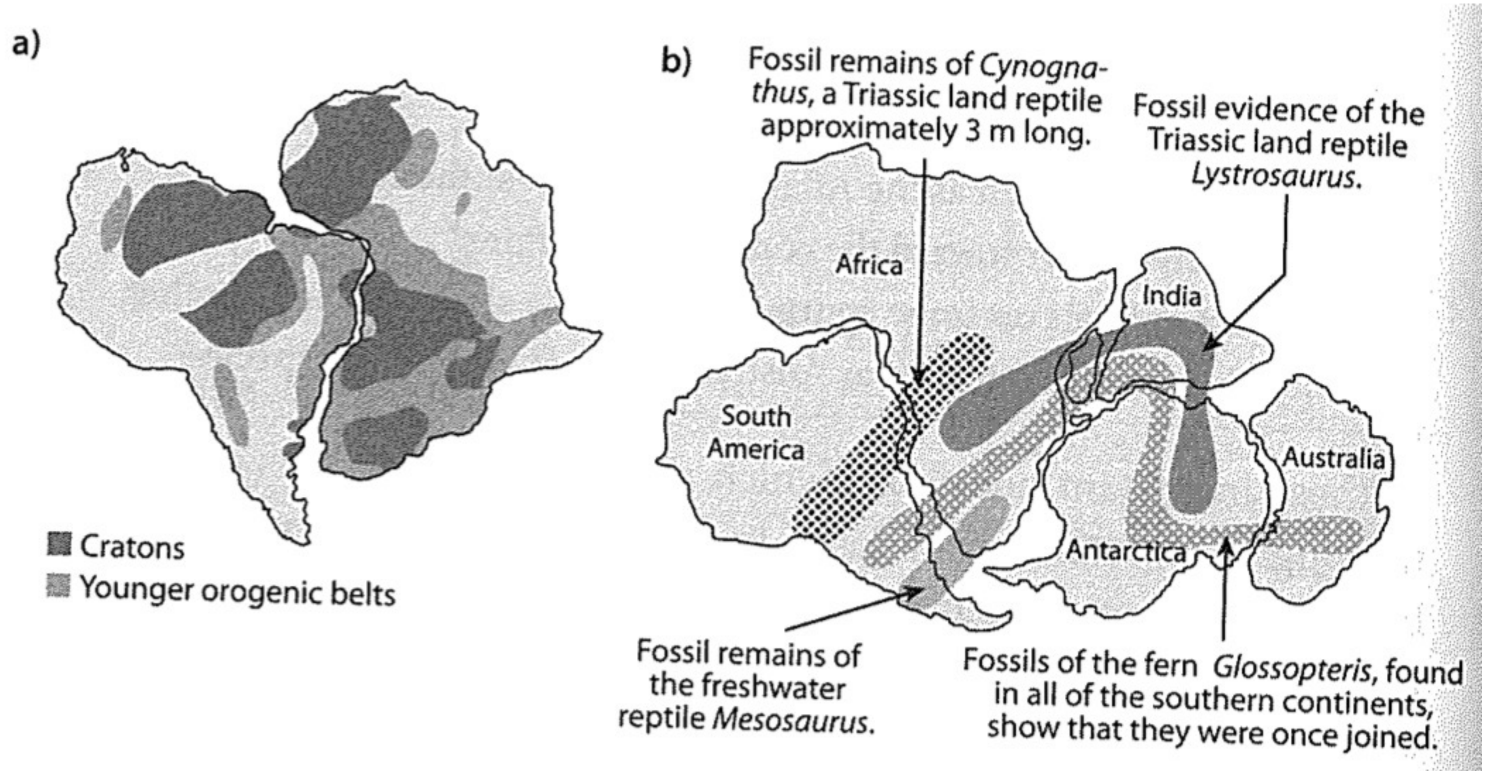


The earth's surface consists of rigid plates, defined by a lithosphere that is sufficiently brittle that it cracks and makes earthquakes. The underlying astenosphere flows and does not crack. The plates are created at spreading centers and consumed at trenches. They can also slide by one another at transform faults.

Adapted from Isacks, Oliver & Sykes (1968)

Plate tectonics

Early evidence



a) fit of continents and correspondence of rock formation proposed by Wegener

b) correspondence of fossils across continents that are currently separated

Plate tectonics: evidence for seafloor spreading

From the pattern of magnetic variation

Black: magnetic North Pole was in the Northern Hemisphere

White: magnetic North Pole was in the Southern Hemisphere

Ages can be determined from paleomagnetic studies carried out on land

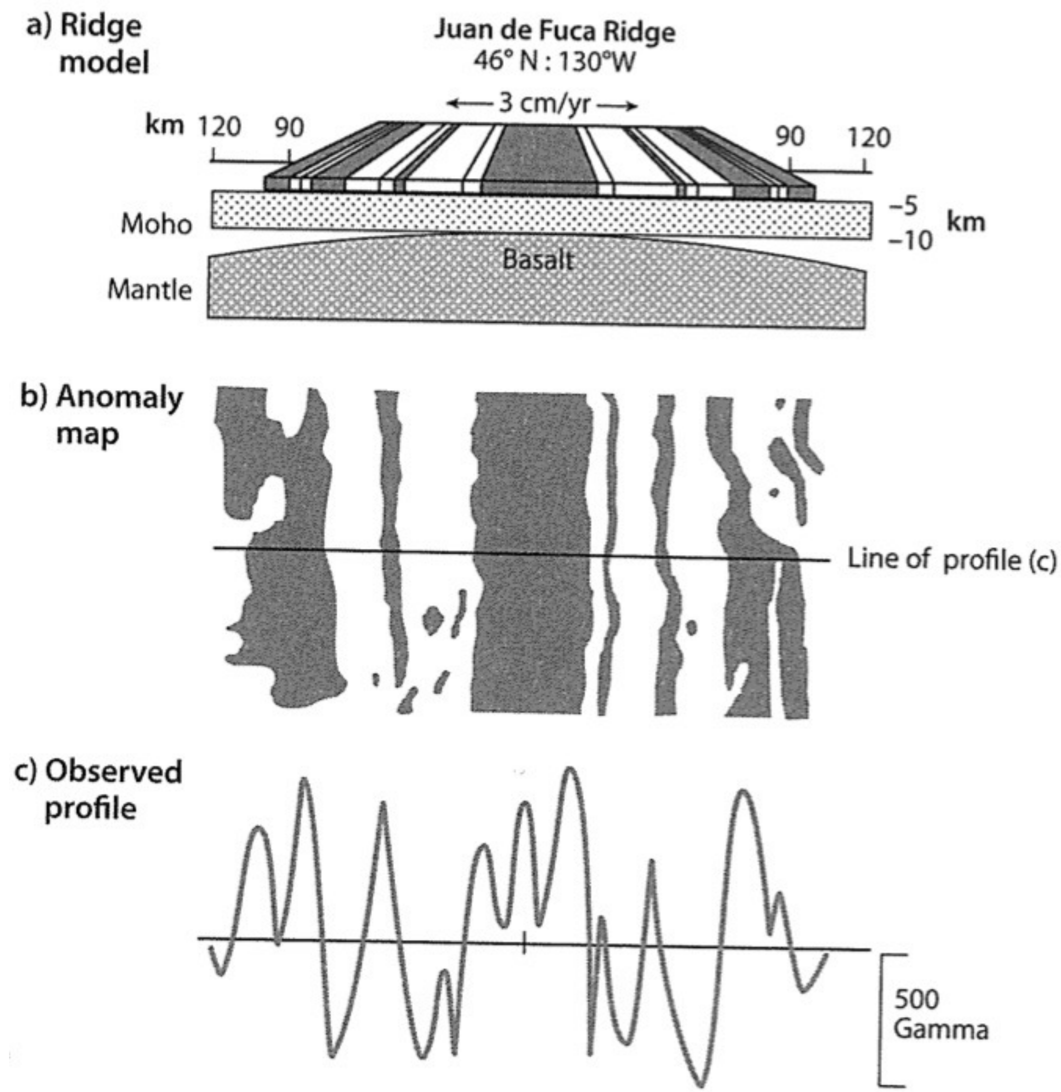
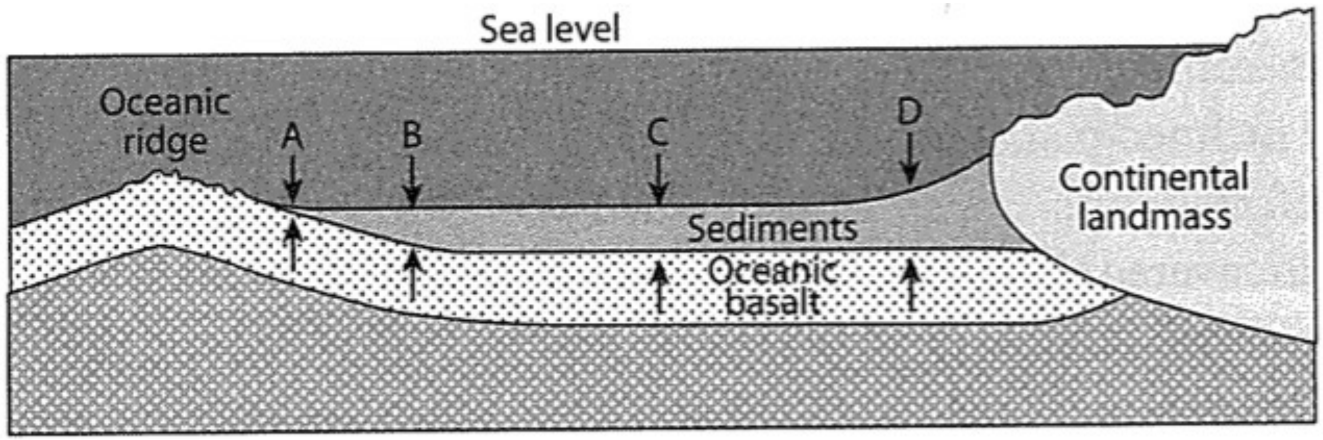


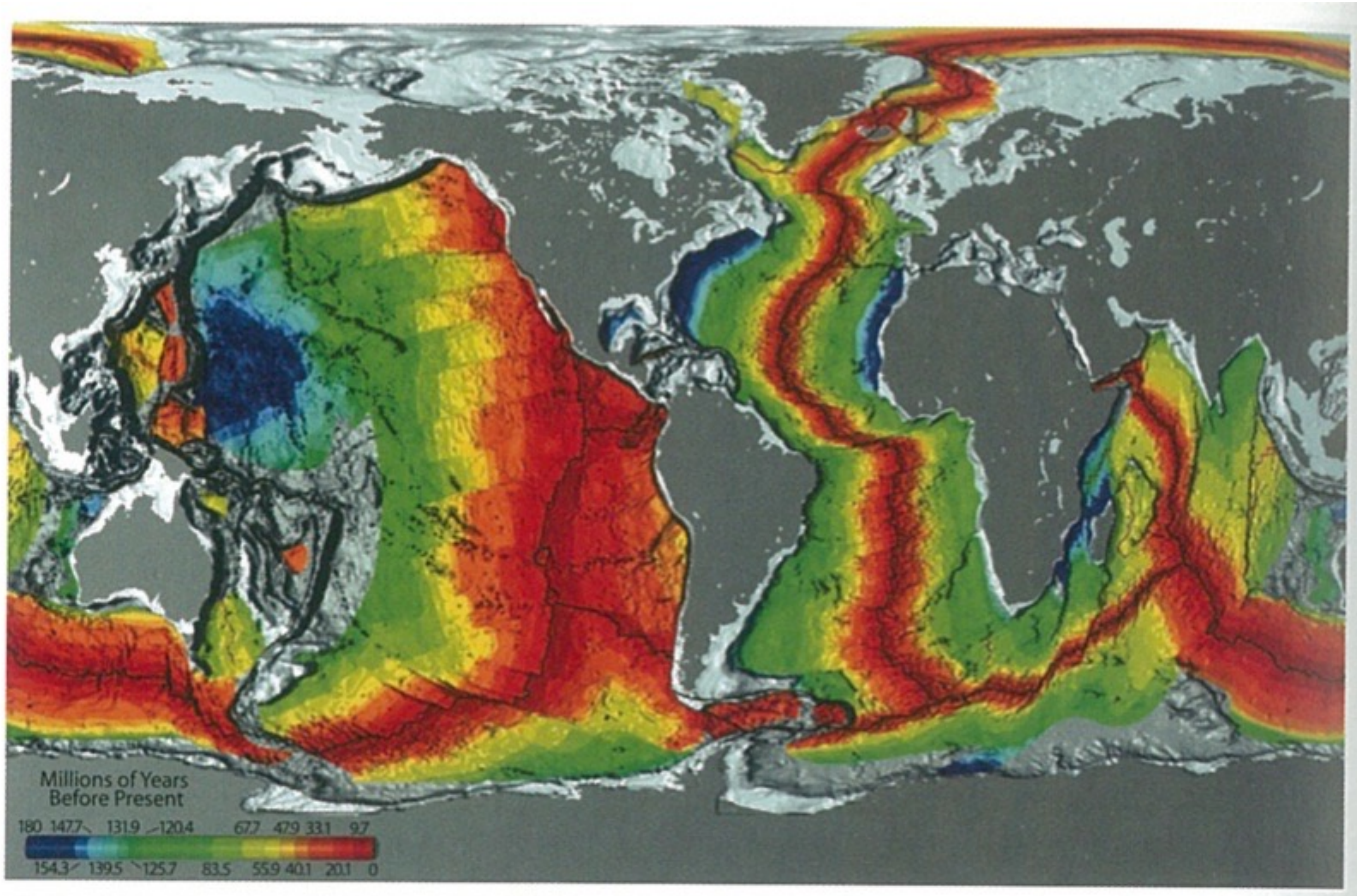
Plate tectonics: evidence for seafloor spreading



Location	Thickness	Sediment age: Surface	Sediment age: Bottom
A	1–5 m	recent	10^6 years
B	10–100 m	recent	10×10^6 years
C	500 m –1 km	recent	75×10^6 years
D	1–3 km	recent	130×10^6 years

The thickness of the sediment is correlated with the age of the oldest sediments overlying the igneous ocean

Plate tectonics: evidence for seafloor spreading



Age of the oceanic lithosphere

The broader bands in the Pacific as compared to the Atlantic indicate faster Pacific spreading rates

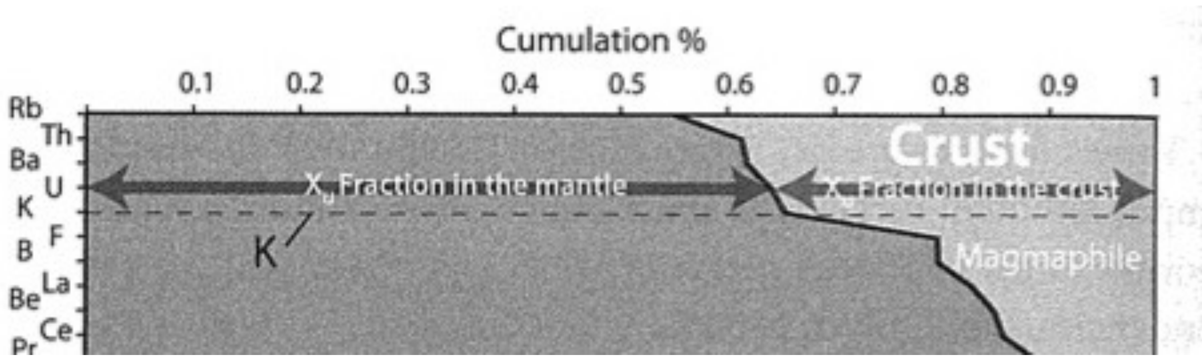
Energy for plate tectonics: internal heat

- The main source of internal heat is the radioactive decay of long-lived radioisotopes:

^{235}U (0.7 Gyr), ^{238}U (4.5 Gyr), ^{232}Th (14 Gyr), ^{40}K (1.25 Gyr)

These isotopes are mostly concentrated in the continental crust that produces about 20% of the heat of the Earth

They are less concentrate in the mantle, but due to its greater volume, it contributes about 55% of the heat budget



Budget and evolution of internal heat

Budget of internal heat

Radioactive decay. Crust: ~20%. Mantle: ~55%

Latent heat due to cristallization of the outer core: ~10%

Fossil heat of planetary accretion: ~15%

Effects on the climate

The internal heat has a negligible effect on the climate because the crust is a good thermal insulator

Currently the total energy released is ~ 42×10^{12} W

Corresponds to ~ $0.08\ W/m^2$ at the surface

Negligible with respect to the energy received by the Sun, which dominates the energy budget of the climate

In the primitive Earth

Higher fossil heat, higher abundance of radioisotopes, higher internal heat

As soon as the crust formed, most of the heat was retained in the interior