

# Course of Geothermics

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## **Course Outline:**

- 1. Thermal conditions of the early Earth and present-day Earth's structure**
2. Thermal parameters of the rocks
3. Thermal structure of the lithospheric continental areas (steady state)
4. Thermal structure of the lithospheric oceanic areas
5. Thermal structure of the lithosphere for transient conditions in various tectonic settings
6. Heat balance of the Earth
7. Thermal structure of the sedimentary basins
8. Thermal maturity of sediments
9. Mantle convection and hot spots
10. Magmatic processes and volcanoes
11. Heat transfer in hydrogeological settings
12. Geothermal Systems

## A practical definition

HEAT ( $Q$ , SI:[Joule]) is a form of Internal Energy of a material  
which is transferred through solid and fluid media by thermal interaction

TEMPERATURE ( $T$ , SI:[degC/K]) is a measurement of the Internal  
Energy of a system

# Temperature and age of the Earth

- The initial temperature distribution within the Earth is unknown, but most of scientist agree that the Early Earth (< 50 Myr after the formation of the solar system) was in molten conditions, which facilitated the gravitational separation of dense metallic material from lighter silicates.
- Before the discover of the radioactivity in 1896 by Becquerel, Kelvin considered the Earth to be an inert body cooling in space, due to its positive thermal gradient with depth.
- By assuming that the Earth began as a sphere initially at constant temperature and using an average gradient of 36.5C/km, Kelvin calculate the age of the Earth to be ~ 200 Myr if the initial  $T$  was 5540°C or only 98 Myr if the initial  $T$  was 3870°C with an error margin of 20-400 Myr, due to the uncertainty of the thermal diffusivity of the crustal rocks.
- With the discover of the radioactivity, the age of the Earth was estimated to be ~4.55 Gyr and Turcotte (1980) attributed 83% of the present surface heat flow to the decay of radioactive isotopes and 17% to the cooling of the Earth and estimated a cooling rate of the mantle of 36C°Gyr<sup>-1</sup>.



# Sources of heat energy on Earth

Energy released by the main sources within the Earth (in Joules)

| Source of energy                         | Energy released during the lifespan of the Earth, according to author |   |  |                              |   |                        |                            |
|--|---|---|--|------------------------------|---|------------------------|----------------------------|
|  | Monin (1977)  | Adushkin and Vityazev (2007) <sup>a</sup> | Orlyonok (1980, 2000)                                | Sorokhtin and Ushakov (2002) | Sorokhtin and Ushakov (2002) <sup>b</sup> | Pollack (1997)         | Hancock and Skinner (2000) |
| Accretion                                |   |   |  | $2.32 \times 10^{32}$        |   | $2.24 \times 10^{32}$  | $2.49 \times 10^{32}$      |
| Planet differentiation                   | $1.61 \times 10^{31}$   | $1.5 \times 10^{31}$                      | $1.5-5 \times 10^{31}$                               | $1.684 \times 10^{31}$       |   |                        |                            |
| Core separation                          |   |   |  | $1.403 \times 10^{31}$       |   | $1.493 \times 10^{31}$ | $1.61 \times 10^{31}$      |
| Bombard-ment                             |   | $2.0 \times 10^{32}$                      |  |                              |   |                        |                            |
| Short-lived isotopes                     |   | $10^{30}$                                 |  |                              |   |                        |                            |
| Long-lived isotopes                      | $0.9 \times 10^{31}$  | $4.0 \times 10^{30}$                      | $(0.6-1.2) \times 10^{31}$                           | $4.33 \times 10^{30}$        | $1.6 \times 10^{30}$                      |                        | $8.0 \times 10^{30c}$      |
| Elastic contraction                      |   | $10^{30}$                                 | $1.2 \times 10^{31}$                                 |                              |   |                        |                            |
| Tidal dissipation                        |   | $10^{30}$                                 | $3.6 \times 10^{30}$                                 | $4-5 \times 10^{30}$         | $2.04 \times 10^{30}$                     |                        | $2-3 \times 10^{30}$       |
| Chemical reactions and phase transitions |   | $10^{30}$                                 | $1.7 \times 10^{30}$                                 |                              |   |                        |                            |
| Solar radiation                          |   | $2.5 \times 10^{34}$                      | <b>(4000 &gt; than the heat flux from the Earth)</b> |                              |   |                        |                            |
| Collision with Mars-sized body           |   |   |  |                              |   | $4.48 \times 10^{31}$  |                            |

<sup>a</sup> Energy released during first 500 Ma of the Earth's evolution

<sup>b</sup> Energy released during first 600 Ma of the Earth's evolution

<sup>c</sup> Radiogenic heat

**Heat energy needed to melt the entire Earth  $\sim 3.2 \times 10^{38}$  J.**

- The main sources of heat energy on Earth are (1) the energy of solar radiation, (2) the release of gravitational energy during planetary accretion, (3) gravitational energy during differentiation, (4) the contraction of the planet and its separation into its core, mantle and crust, (5) radioactive energy by short- ( $^{26}\text{Al}$ ,  $^{36}\text{Cl}$ ,  $^{60}\text{Fe}$ ) and long-lived ( $^{235}\text{U}$ ,  $^{238}\text{U}$ ,  $^{232}\text{Th}$ ,  $^{40}\text{K}$ ) radioactive isotopes.
- Some sources generated heat energy in the past (accretion, overall differentiation of the planet, decay of short-lived radioactive isotopes), while some others are sources of perpetual and ongoing generation of heat energy (radiogenic heat from the decay of long-lived radioactive isotopes, ensuing differentiation, tidal energy, chemical reactions, etc.).
- The sources of heat loss include the constant radiation of heat by the Earth into outer space and escaping matter, such as hydrogen (heat capacity  $\sim 14.3 \text{ kJ kg}^{-1} \text{ K}^{-1}$ ), derived from decomposition of water from *UV* rays.

## Accretion of the Earth

- The accretion process of Earth brought together matter which was originally dispersed in the proto-solar nebula, releasing gravitational energy ( $E_g \sim 2.2 \times 10^{32} \text{ J}$ ).
- During accretion, the gravitational energy of impactors is first transformed into kinetic energy and then dissipated in the form of heat at the impact: (a) If all the energy is released at shallow depth and lost to space by radiation, accretion would raise the temperature of the Earth by  $< 70 \text{ K}$ . (b) If no energy is lost in the space and thus is used to heat the Earth, the temperature of the whole Earth is raised by:

$$\Delta T = \frac{-E_g}{MC_p} \sim 3.75 \times 10^4 \text{ K}$$

$M$  = mass of the Earth ( $5.974 \times 10^{24} \text{ kg}$ )

$C_p$  = specific heat capacity ( $\sim 10^3 \text{ J Kg}^{-1} \text{ K}^{-1}$ )

- The actual evolution occurred between the two end-members cases, involving partial dissipation of the impact energy within the planet and radiative heat transfer through the primordial atmosphere. The energy partition depended on the size of the impactors and time between the impacts: (1) with the increase of the sizes of impactors, the depth of energy release and time for energy transport to the surface increased as well (2) the increase of time between impacts enhanced the heat loss to the atmosphere.
- Almost all the gravitational energy in the formation of the core translated as heat energy and raised the Earth's temperature by about  $3,000 \text{ K}$ .
- During the Earth existence, the gravitational differentiation and decaying of long-lived radioactive elements has generated about  $2.5 \times 10^{31} \text{ J}$  of heat energy accumulated inside the planet.

# Thermal conditions during the early stages of the Earth's formation

- The uppermost layers of the Earth (up to a depth of ~1000 km) was heated to the melting point by the collision with large bodies between 4.5 and 3.8 Gyr.
- An impact initially deposits a large fraction of its kinetic energy in a region comparable in size to the projectile itself. The moving material generally opens a crater whose size and form depends on the relative importance of gravity and strength in the crater excavation.
- The major part of the kinetic energy of the impact is thus converted to heat in a roughly hemispherical region centered on the crater, which extends to a depth of only a few projectile diameters.
- The heat coming from short-lived isotopes could have created a surface temperature in the range 1200-1700 K.
- Due to these high temperatures, a magma-ocean covered the Earth from the Hadean to the beginning of the Archean (1-10 Myr to a few 100s Myr), with a surface temperature during its accretion likely in the range of 1,200–1,700 K.
- Felsic rocks were molten and could solidify when the temperature dropped below 1300 K.
- The survival time of the magma ocean depends on both the atmosphere and whether or not an insulating lid can develop. In the absence of these two effects, the lifetimes are very short, of order  $10^3$  years, while in presence of them the lifetime may be much longer, of order  $10^8$  years.

Estimates of the Earth's surface temperature in the early and middle Precambrian

| Time (Ga)                        | Surface temperature (K) | References                                 |
|----------------------------------|-------------------------|--|
| 4.4                              | < ~ 473                 | Valley et al. (2002)                       |
| 3.5–3.2                          | 343 ± 15                | Lowe and Tice (2004)                       |
| After 2.9                        | <333                    | Lowe and Tice (2004)                       |
| During the pre-Archean           | 573 ± 100               | Valley et al. (2006)                       |
| Late Archean–early proterozoic   | 30 K less than now      | Eyles and Young (1994)                     |
| 3.5–3.2                          | 328–358 (ocean water)   | Knauth (2005), Knauth and Lowe (2003)      |
| Most geological time             | 5 K higher than now     | Kuhn et al. (1989)                         |
| Archean hydrosphere              | 343                     | Lambert (1982)                             |
| ~0.2 after the Earth's formation | ~ 373                   | Mackenzie (1998)                           |
| 4.3                              | 373                     | Morse and Mackenzie (1998)                 |
| 3.8                              | 343                     | Morse and Mackenzie (1998)                 |
| 4.2                              | 373                     | Mojzsis et al. (2001), Sleep et al. (2001) |
| Hadean                           | 90 % of surface <0      | Mukhin and Pimenov (2002)                  |



## Physical conditions during the early stages of the Earth's formation

- During formation of the magma-ocean, melts formed magmatic layers in ascending order of their density and iron content (uppermost layers were felsic and lowermost mafic).
- The density jumps between the different chemical layers was only about 30-100 kg/m<sup>3</sup>.
- 2-3% of difference in density was sufficient to differentiate the magma-layers (no mixing, considering also the difference in composition).
- Difference in density between the current uppermost (3300 kgm<sup>-3</sup>) and lowermost mantle (5500 kgm<sup>-3</sup>) supports the hypothesis of the formation of different layers without interaction.

Iron content and density of the most common rock-forming minerals

| Minerals       | Density range, kg/cm <sup>3</sup> | Comments   |
|----------------|-----------------------------------|--|
| K-feldspars    | 2,520–2,560                       | On average albite is ~2.76 % denser than K-feldspars; anorthite is ~5.75 % denser than albite                          |
| Plagioclases   | 2,610–2,760                       |  |
| Quartz         | 2,600–2,650                       | –  |
| Micas          | 2,700–3,170                       | Fe-rich mica is ~10.4 % (for biotite) and ~13.2 % (for annite) denser than Mg-rich micas                               |
| Clinopyroxene  | 3,200–3,900                       | On average Fe-enriched clinopyroxenes are ~4.4–7.6 % denser than Mg-enriched   |
| Orthopyroxenes | 3,100–4,020                       | On average Fe-rich orthopyroxene is ~23.4 % denser than Mg-rich orthopyroxene  |
| Amphiboles     | 2,900–3,500                       | On average Fe-enriched amphiboles are ~6.25 % denser than Mg-enriched  |
| Olivine        | 3,200–4,390+                      | The density of fayalite is ~34.4 % higher than the density of forsterite   |
| Garnets        | 3,420–4,310                       | The density of almandine is ~19.4 % higher than the density of pyrope and ~22.9 % higher than the density of grossular |

# Physical conditions during the early stages of the Earth's formation

- Among the mafic and ultramafic magma-layers, the upper portions were formed by lither *Mg*-rich and the lower portions by *Fe*-rich magmas.
- When solidification of the magma ocean started the source of formation of magma increased.
- Nowadays, most of the basic and ultrabasic magmas should have formed under the lithosphere and the depth of the magma forming layers should increase permanently.

Density of molten forsterite, fayalite and olivine Fo<sub>93</sub>

| Mineral          | Temperature, K | Density, kg/m <sup>3</sup> | References                  |
|------------------|----------------|----------------------------|-----------------------------|
| Forsterite       | 2,163          | 2,970                      | Coombs and Gardner (2004)   |
| Fayalite         | 1,573          | 3,757                      | Shiraishi et al. (1978)     |
|                  | 1,673          | 3,725                      | Shiraishi et al. (1978)     |
|                  | 3,000          | 3,529                      | de Koker et al. (2008)      |
|                  | 2,163          | 3,810                      | Lange (1997)                |
|                  |                | 3,893                      | Lange and Carmichael (1987) |
|                  | 1,773          | 3,747                      | Knittle (1995)              |
|                  | 1,573          | 3,750                      | Chen et al. (2002)          |
|                  | 1,300          | ~3,875                     | Ghiorso (2004)              |
|                  | 1,500          | ~3,861                     | Ghiorso (2004)              |
|                  | 1,600          | 3,850                      | Ghiorso (2004)              |
|                  | 1,973          | 3,593                      | Courtial et al. (1997)      |
|                  | 2,023          | 3,586                      | Courtial et al. (1997)      |
|                  | 2,073          | 3,587                      | Courtial et al. (1997)      |
|                  | 2,123          | 3,560                      | Courtial et al. (1997)      |
| Fo <sub>93</sub> |                | 2,865                      | Walker et al. (1988)        |



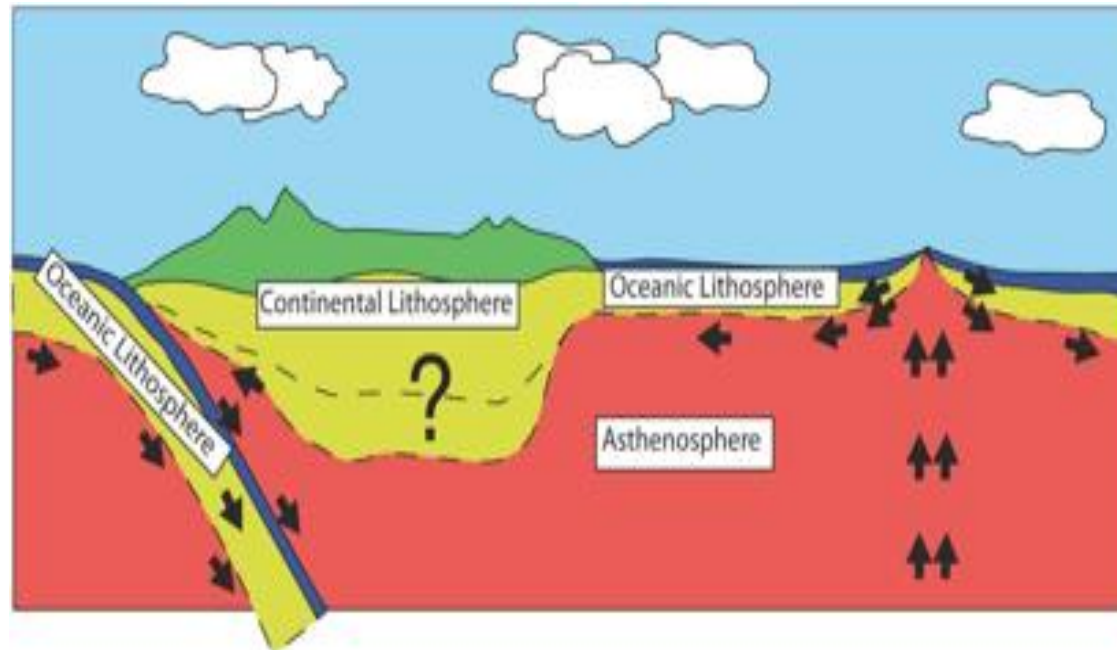
## Upper Mantle Composition vs Age

- The iron content in magmas increases systematically with decrease in their age and is minimal for the Archean rocks and maximal for rocks from the Cenozoic to the present.
- Cenozoic or younger continental basalts on average are almost all ferrobasalts ( $Fe = 12\%$ ).
- Oceanic basalts have a lower  $Fe$  content (8-12 %), indicating that these basalts formed at lower depth (shallower asthenosphere).
- Solidification of the magma-ocean very likely started with the formation of forsterite layer at a depth of about 100–120 km in areas of the current-day continental lithosphere.

|  | Archons (mean<br>garnet SCLM) | Protons (mean garnet<br>SCLM + massifs<br>+ xenoliths) | Tectons (mean<br>garnet SCLM) | Tectons (mean<br>Spinel peridotite) | Primitive Mantle,<br>McDonough and<br>Sun (1995) |
|--|-------------------------------|--|-------------------------------|-------------------------------------|--|
| SiO <sub>2</sub>                               | 45.7                          | 44.6   | 44.5                          | 44.4                                | 45.0   |
| TiO <sub>2</sub>                               | 0.04                          | 0.07   | 0.14                          | 0.09                                | 0.20   |
| Al <sub>2</sub> O <sub>3</sub>                 | 0.99                          | 1.9  | 3.5                           | 2.6                                 | 4.5  |
| Cr <sub>2</sub> O <sub>3</sub>                 | 0.28                          | 0.40   | 0.40                          | 0.40                                | 0.38   |
| FeO  | 6.4                           | 7.9  | 8.0                           | 8.2                                 | 8.1  |
| MnO  | 0.11                          | 0.12   | 0.13                          | 0.13                                | 0.14   |
| MgO  | 45.5                          | 42.6   | 39.8                          | 41.1                                | 37.8   |
| CaO  | 0.59                          | 1.70   | 3.1                           | 2.5                                 | 3.6  |
| Na <sub>2</sub> O                              | 0.07                          | 0.12   | 0.24                          | 0.18                                | 0.36   |
| NiO  | 0.30                          | 0.26   | 0.26                          | 0.27                                | 0.25   |
| Zn   | 34                            | 52   | 55                            | 53                                  | 55   |
| V  | 20                            | 48   | 70                            | 59                                  | 82   |
| Co   | 93                            | 107  | 110                           | 110                                 | 105  |
| Sc   | 7                             | 10   | 14                            | 12                                  | 16   |
| Mg#  | 92.7                          | 90.6   | 89.9                          | 89.9                                | 89.3   |
| Mg/Si  | 1.49                          | 1.43   | 1.33                          | 1.38                                | 1.25   |
| Ca/Al  | 0.55                          | 0.80   | 0.82                          | 0.85                                | 0.73   |
| Cr/Cr+Al                                       | 0.16                          | 0.12   | 0.07                          | 0.09                                | 0.05   |
| Fe/Al  | 4.66                          | 3.02   | 1.66                          | 2.23                                | 1.30   |
| Olivine/orthopyroxene/<br>clinopyroxene/garnet | 69/25/2/4                     | 70/17/6/7  | 60/17/11/12                   | 66/17/9/8                           | 57/13/12/18                                      |
| Density, g/cc                                  | 3.31                          | 3.34   | 3.37                          | 3.36                                | 3.39   |
| Vp, km/s (room temperature)                    | 8.34                          | 8.32   | 8.30                          | 8.30                                | 8.33   |
| Vp, 100 km, 700 °C                             | 8.18                          | 8.05   | 7.85                          | 7.85                                |  |
| Vs, Km/s (room temperature)                    | 4.88                          | 4.84   | 4.82                          | 4.82                                | 4.81   |
| Vs, 100 km, 700 °C                             | 4.71                          | 4.6  | 4.48                          | 4.48                                |  |

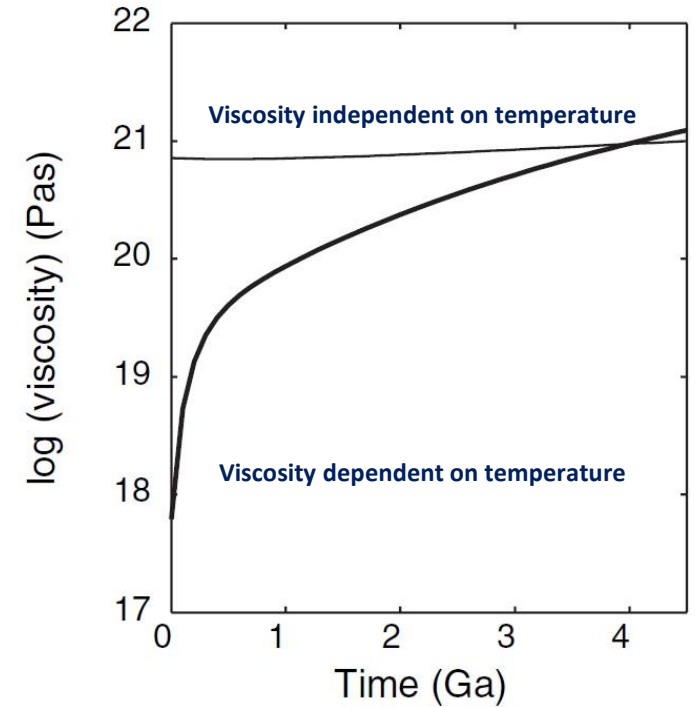
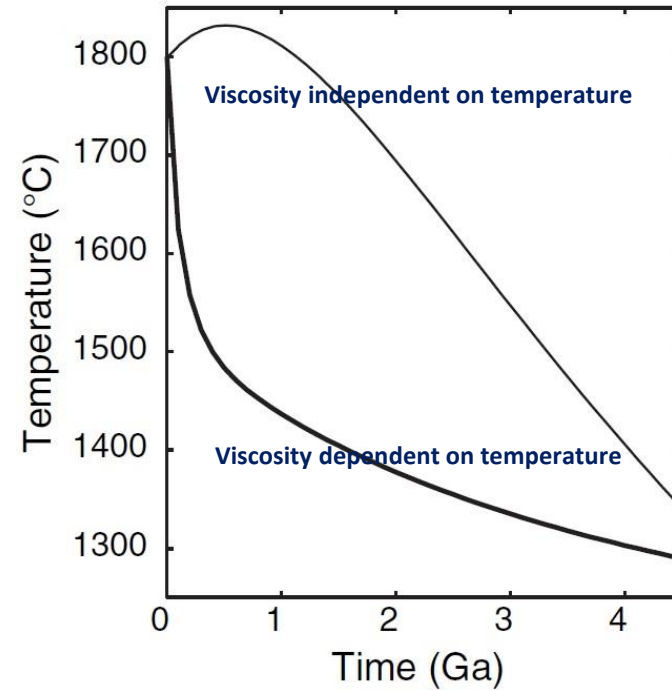
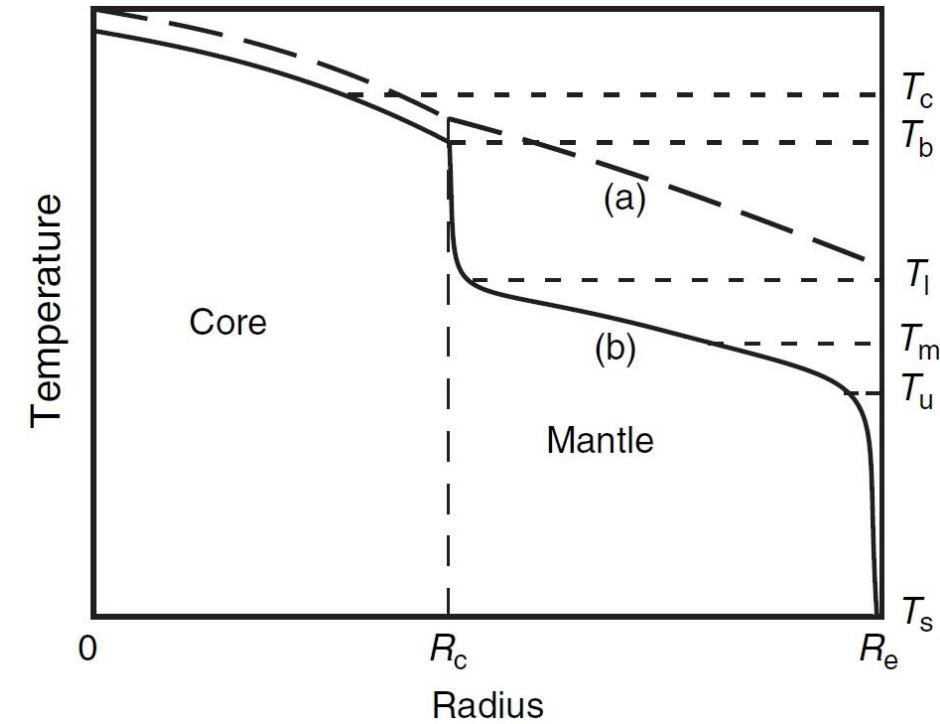
## Thermal conditions of early lithosphere formation

- The cooling of the magma ocean was likely slow because numerous layers would only allow for separate convection within each layer.
- The cooling of the magma-ocean started with the formation of the forsterite layer (which has the highest melting point: 2163 and 2307 at 0.1 MPa and 3 GPa, respectively) at a depth of about 100 km (depth of xenoliths), still present under the cratons.
- The cooling effect of the thick early Earth's atmosphere caused solidification of the near surface magmatic layers, which would have increased the geothermal gradient, and consequently the surface heat flow, enhancing the rate of cooling of the near surface magmatic layers.
- Solid forsterite, having a low heat conduction coefficient, likely blocked the transfer of heat from the upper mantle below the forsterite layer to the surface, slowing down the cooling of the upper mantle below the forsterite layer and causing the bottom part of the present continental lithosphere to form with a significant delay.



Present-day lithosphere conditions

# Initial Earth's thermal conditions

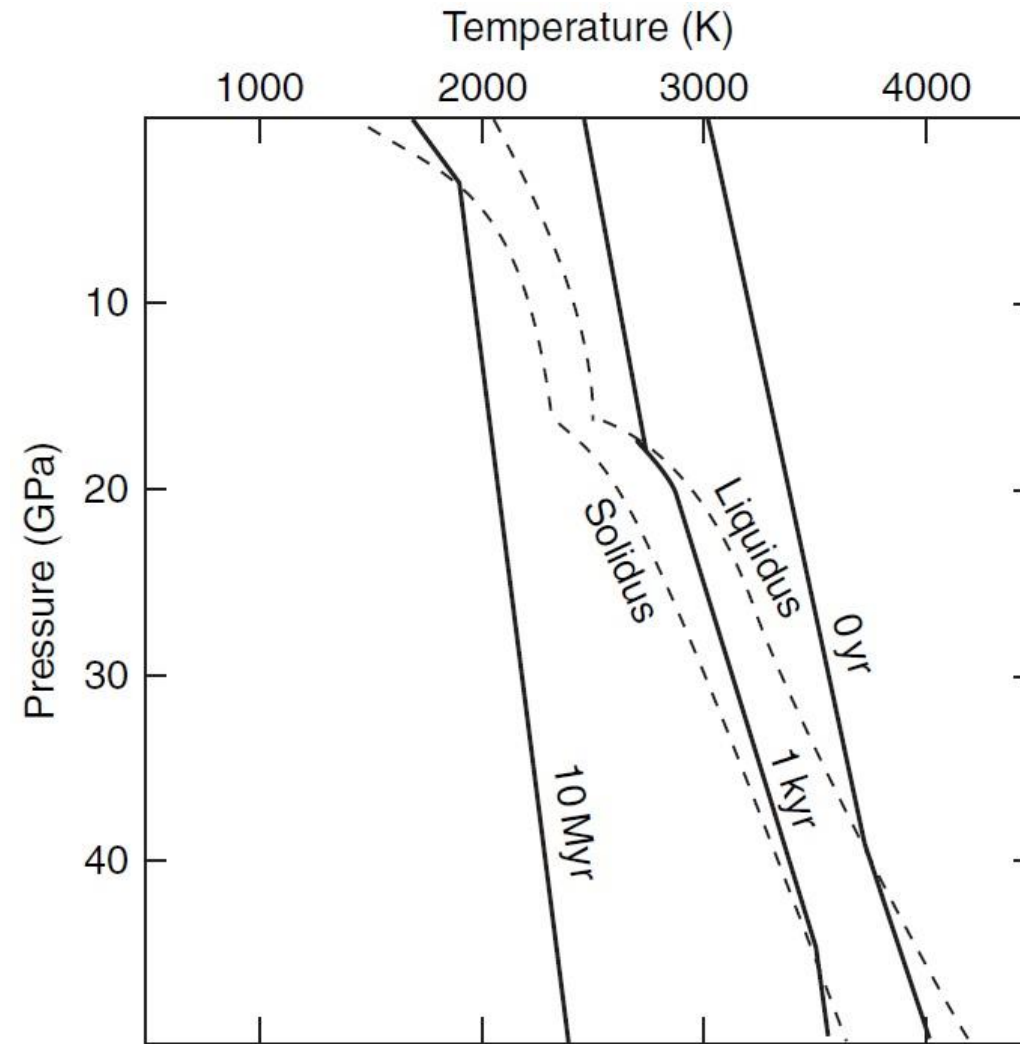


(a) Initial state. (b) Present state.  $T_c$ , mean core T;  $T_b$ , core–mantle boundary T;  $T_l$ , lower-mantle T;  $T_m$ , mean mantle T;  $T_u$ , upper-mantle temperature;  $T_s$ , surface T.

Davies, 2007, Treatise of Geophysics, vol. 9

- The peak temperature during the Earth's formation is difficult to estimate, since it was presumably determined by a competition between heat deposition by large impacts and heat removal by the effect of further impacts, by conduction near the surface, by mantle convection, and by rapid cooling of surface melt (magma ocean).
- At the beginning the viscosity is much lower than at present, and this reduces the resistance to mantle convection, which can therefore remove heat very rapidly. This high heat loss causes the temperature to drop rapidly, but then the viscosity rises rapidly and reduces the heat loss.
- This early transient stage continues until the heat loss approaches the heat generation, at which point the initially large imbalance between them becomes small and thus the rate of decline of temperature slows.

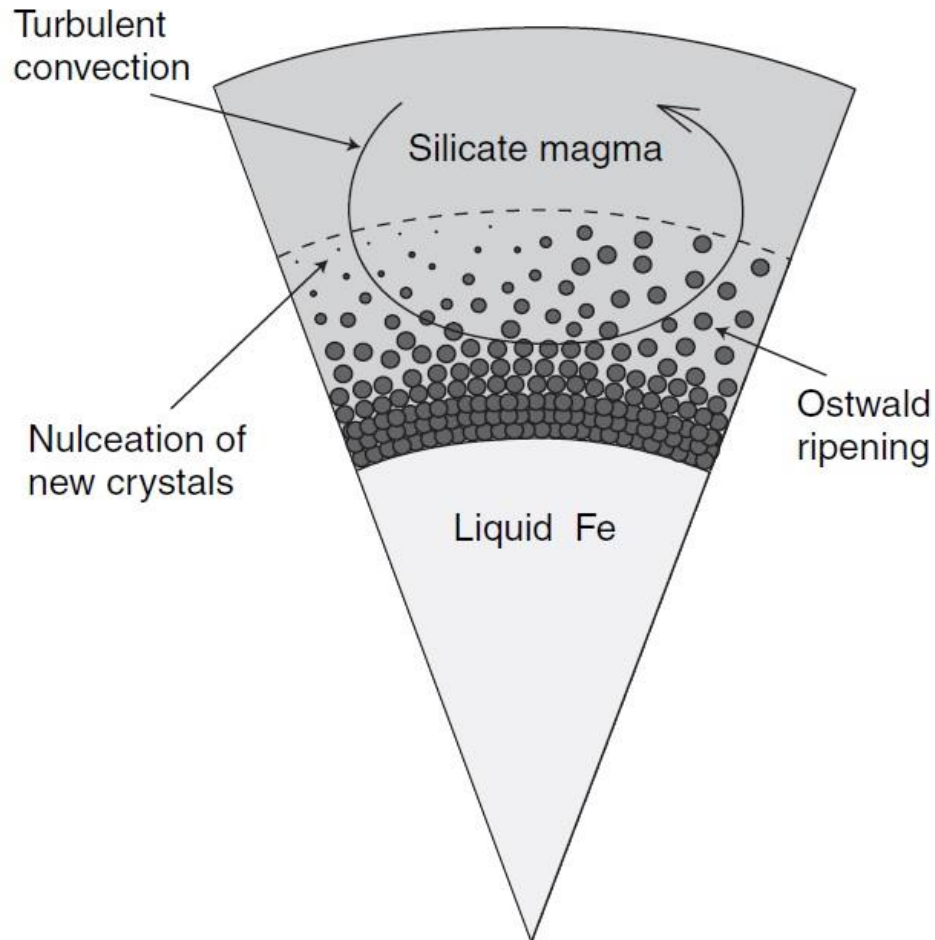
# Initial Earth's thermal conditions



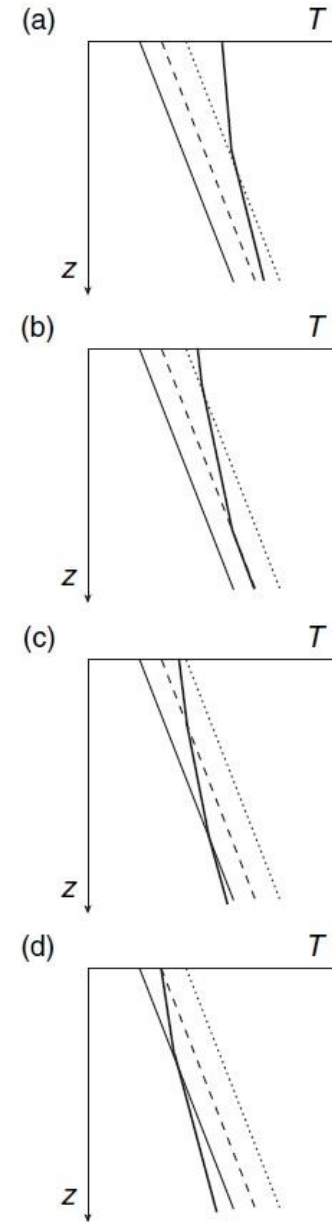
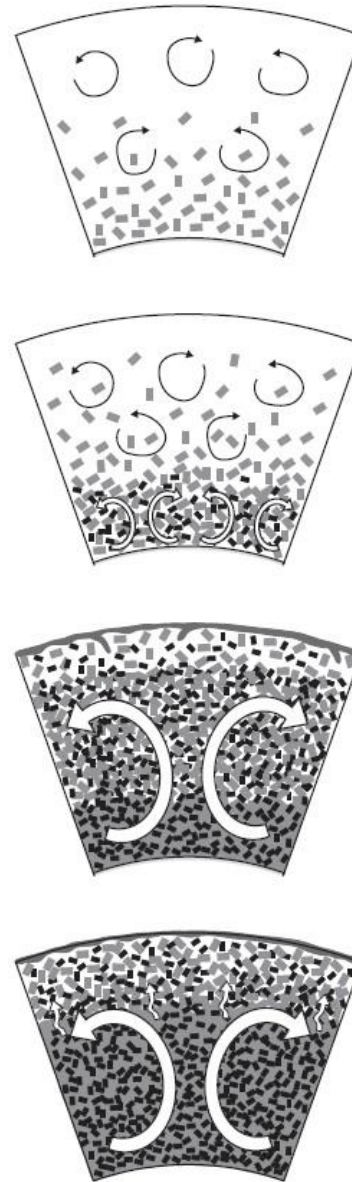
Jaupart and Labrosse, 2007, Treatise of Geophysics, vol. 7

- At about 10 Myr, the solid content in the partially molten upper mantle layer reaches the threshold value of 60%, which marks the cessation of liquid behavior.
- After that time, convection is in the subsolidus regime controlled by solid behavior which still prevails today.

# Crystallization of the magma ocean



Solomatov, 2007, Treatise of Geophysics, vol. 9



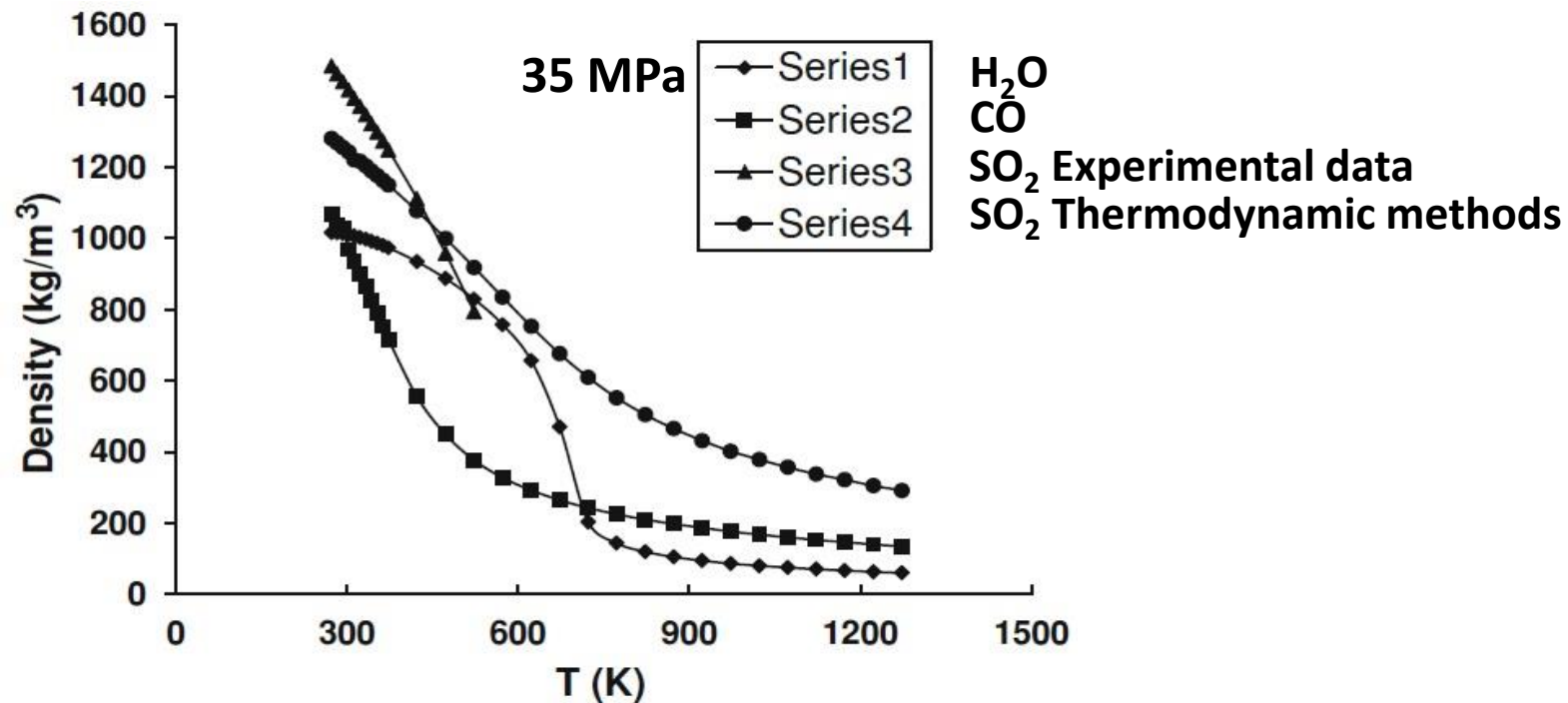
- (a) The lower part of the magma ocean is below liquidus (dotted line), convection is controlled by melt viscosity and  $T$  (heavy solid line) is adiabatic;
- (b) High viscosity, gravitationally unstable region with the maximum packing crystal fraction forms near the bottom of the magma ocean (dashed line);
- (c) Cooling proceeds via solid state convection which is still fast at this stage.  $T$  in the high viscosity region below solidus (solid line) can be superadiabatic;
- (d) The rate of cooling and crystallization of the remaining melt is controlled by solid-state convection and melt percolation. Convection becomes much slower, the heat flux drops, and a thick crust forms at the surface.

- The velocity controls the cooling rate of fluid parcels: the faster the cooling rate, the further the system is driven into the metastable state, the higher the nucleation rate and the more crystals are nucleated (faster cooling produces smaller crystals).



## Early Earth's Atmosphere

- During accretion, a magma-ocean with a surface temperature of  $\geq 1300$  K was formed, overlain by a thick, dense ( $\geq 35$  MPa) early terrestrial atmosphere composed of supercritical fluids with its main layers (sulfur-layer, carbon-layer, and water-layer) having different density.
- The early Earth's atmosphere at a pressure of  $\sim 35$  MPa was composed by the sulfur-layer (mostly  $\text{SO}_2$ ) with a density of  $\sim 292$  kg/m<sup>3</sup> and a thickness of 2.4 km, the carbon-layer (mostly CO) with a density of  $\sim 314.5$  kg/m<sup>3</sup> and a thickness of 1.3 km, and the water layer with a density of 60.35 kg/m<sup>3</sup> and a thickness of 43.8 km.



Density of water decreases drastically to 14.4% at  $T=773$  K and more slowly to a maximum of  $\sim 6\%$  of the initial value.



# Early Earth's Atmosphere

- The solidified forsterite layer would have separated the magma-ocean into two parts with the lower *Fe*-rich magmas and the upper *Fe*-poor magmas below and above the forsterite layer, respectively.
- The felsic magma layer with the lowest melting point and cooled by the early Earth's atmosphere started to solidify first within the upper part of the magma-ocean.
- At *T* between 1253 K and 673 K,  $2\text{CO}=\text{CO}_2+\text{C}$  (graphite formation). With the cooling also transfer of  $\text{SO}_2$  to  $\text{SO}_3$  occurred, likely forming individual sub-layers:  $\text{SO}_3$  10% at 1273 K and 100% at 673 K.
- Between 673 K and 550 K,  $\text{H}_2\text{O}$  and  $\text{SO}_3$  layers came in contact forming  $\text{H}_2\text{SO}_4$  (it starts the leaching of the Earth's surface).

| T and P       | CO-CO <sub>2</sub> (ρ and Th.)       | SO <sub>2</sub> -SO <sub>3</sub> (ρ and Th.) | H <sub>2</sub> O (ρ and Th.)          |
|---------------|--------------------------------------|--|---------------------------------------|
| 1273 K 35 MPa | ~314.5 kg/m <sup>3</sup> ~1.3 km (B) | ~292 kg/m <sup>3</sup> 2.4 km (M)            | ~60.35 kg/m <sup>3</sup> 43.8 km (T)  |
| 1173 K 35 MPa | ~341 kg/m <sup>3</sup> ~1.2 km (B)   | ~322 kg/m <sup>3</sup> ~2.2 km (M)           | ~75.3 kg/m <sup>3</sup> ~39.5 km (T)  |
| 823 K 35 MPa  | ~210 kg/m <sup>3</sup> ~1.0 km (M)   | ~505 kg/m <sup>3</sup> ~1.4 km (B)           | ~119.9 kg/m <sup>3</sup> ~22.1 km (T) |
| 673 K 35 MPa  | ~265 kg/m <sup>3</sup> ~0.6 km (T)   | ~676 kg/m <sup>3</sup> ~1.1 km (B)           | ~470.1 kg/m <sup>3</sup> ~5.6 km (M)  |
| 573 K 35 MPa  | ~327.9 kg/m <sup>3</sup> ~0.8 km (T) | ~835 kg/m <sup>3</sup> ~0.9 km (B)           | ~758.1 kg/m <sup>3</sup> ~3.5 km (M)  |
| 523 K 35 MPa  | ~377.3 kg/m <sup>3</sup> ~0.5 km (T) | ~794.4 kg/m <sup>3</sup> ~0.9 km (M)         | ~829.7 kg/m <sup>3</sup> ~3.2 km (B)  |

*T*=top, *M*=middle, *B*=bottom

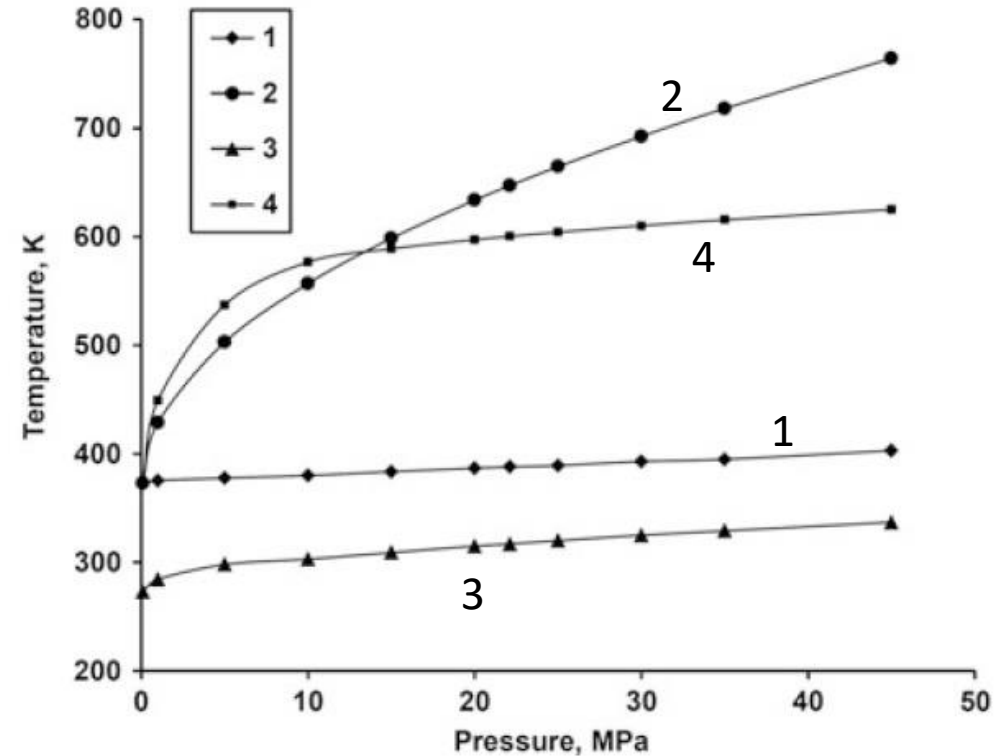
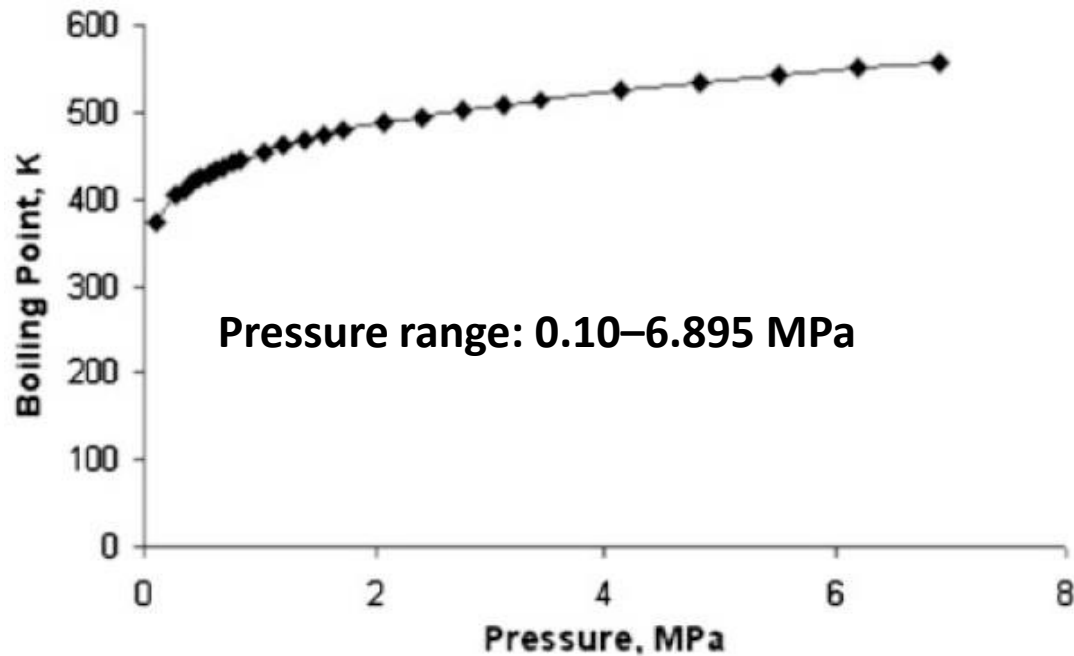
## Age of crust formation and weathering

- The existence of ferric iron oxides formation (banded iron formation – BIF), leading to magnetite generation, starts when the temperature surface drops below 723-843 K (10 MPa-0.1 MPa), between 3.85 and 3.50 Gyr, and continues up to ~473-523 K at the corresponding age of 1.8 Gyr.



- Oxidation processes started after 2.3 Gyr (when free oxygen was available) and thus didn't play a role in the deposition of BIFs during early Archean.
- Massive weathering of rocks started with the formation of  $\text{H}_2\text{SO}_4$  at temperature  $< 700$  K, when the  $\text{H}_2\text{O}$  and  $\text{SO}_3$  layer became in contact and the sulfuric acid was liquid (its boiling point  $< 700$  K at pressure  $> 35$  MPa and at high concentration).
- Many elements are resistant to high concentration of sulfuric acid (e.g., Hf for concentrations up to 80%, Zr up to 70-75%, Pb up to 90%, Fe up to 75%,  $\text{SiO}_2$  is insoluble).
- Dissolution of the oxides of albite ( $\text{Na}_2\text{O}$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{SiO}_2$ ) raises significantly (from 6.4 ppm to 318 ppm) with increase in  $T$  (373-623 K) and  $P$  (0.3-35 MPa).
- Hydrothermal alteration under acid conditions occurred ~3.4 Gyr and lasted till 3.2 Gyr: no crystallization of hydrothermal barite in veins, as a product of acid alteration between 3.2 and 1.8 Gyr (re-distribution of the sulfur-layer of the atmosphere with formation of sulfides and barites by 3.2 Gyr, before the water layer accesses to the surface).
- From 2.8 to 2.7 Gyr there was an intense magmatic activity (komatiite magmas), which may have caused the decomposition of sulfides which came in contact.
- The cooling of the Earth's surface became more efficient with the formation of a water-ocean, which depended on a  $P$  and  $T$  conditions.

# Boiling Point of Water with P and T variations



**(1)** P–T conditions for a constant density of water at  $958.36 \text{ kgm}^{-3}$ ; **(2)** interpolation-extrapolation model of the variable boiling point of water with increases in pressure using as initial and boundary conditions the boiling point of water at  $373.16 \text{ K}$  at  $0.1 \text{ MPa}$  and the critical boiling point of water  $T = 647.36 \text{ K}$  at  $P = 22.12 \text{ MPa}$ ; **(3)** P–T conditions of constant density of water at  $1000 \text{ kgm}^{-3}$ ; **(4)** extrapolation model of the variable boiling point of water with increases in  $P$  using data from Speight (2005).

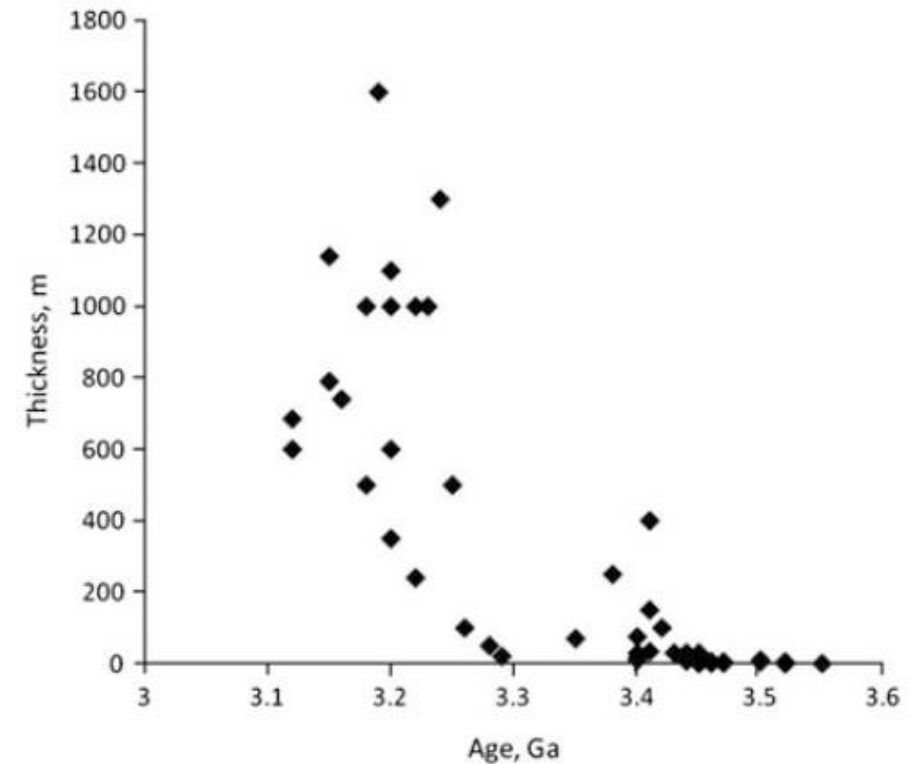
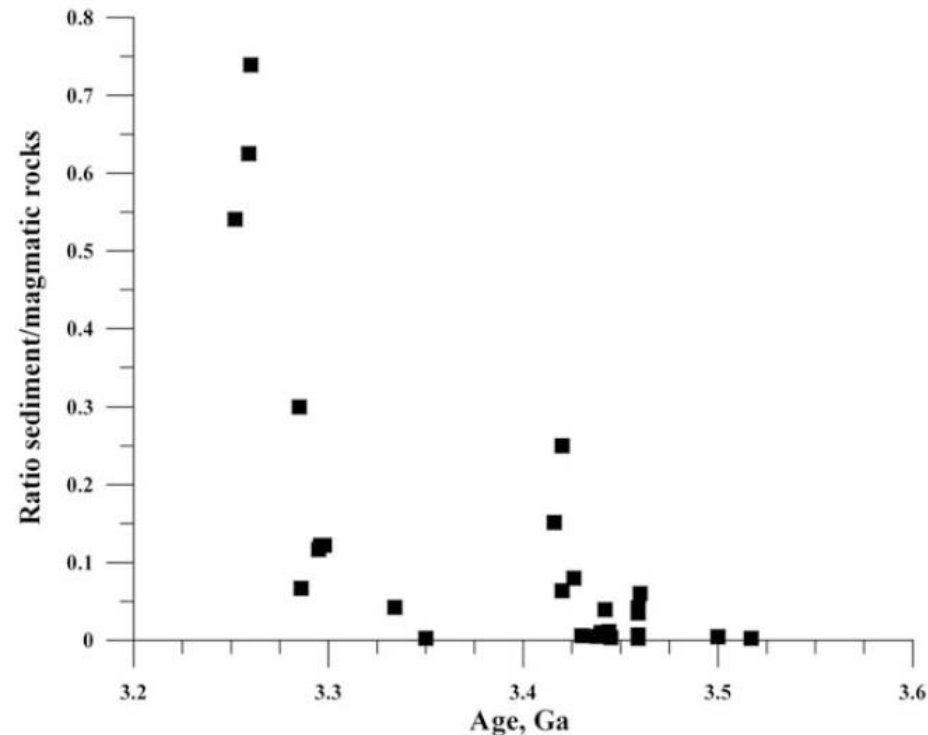
$$T_B - T_{B0} = A\sqrt{(P - P_0)}$$

$T_B$  and  $T_{B0}$  = boiling points of water at pressure  $P$  and at pressure  $P_0$   
 $A$  = constant defined by initial and boundary conditions

- Formation of liquid water from vapor under a  $P$  of  $\sim 35 \text{ MPa}$ ,  $T$  of the Earth's surface and the atmosphere had to be below  $615.5\text{--}717.9 \text{ K}$ .

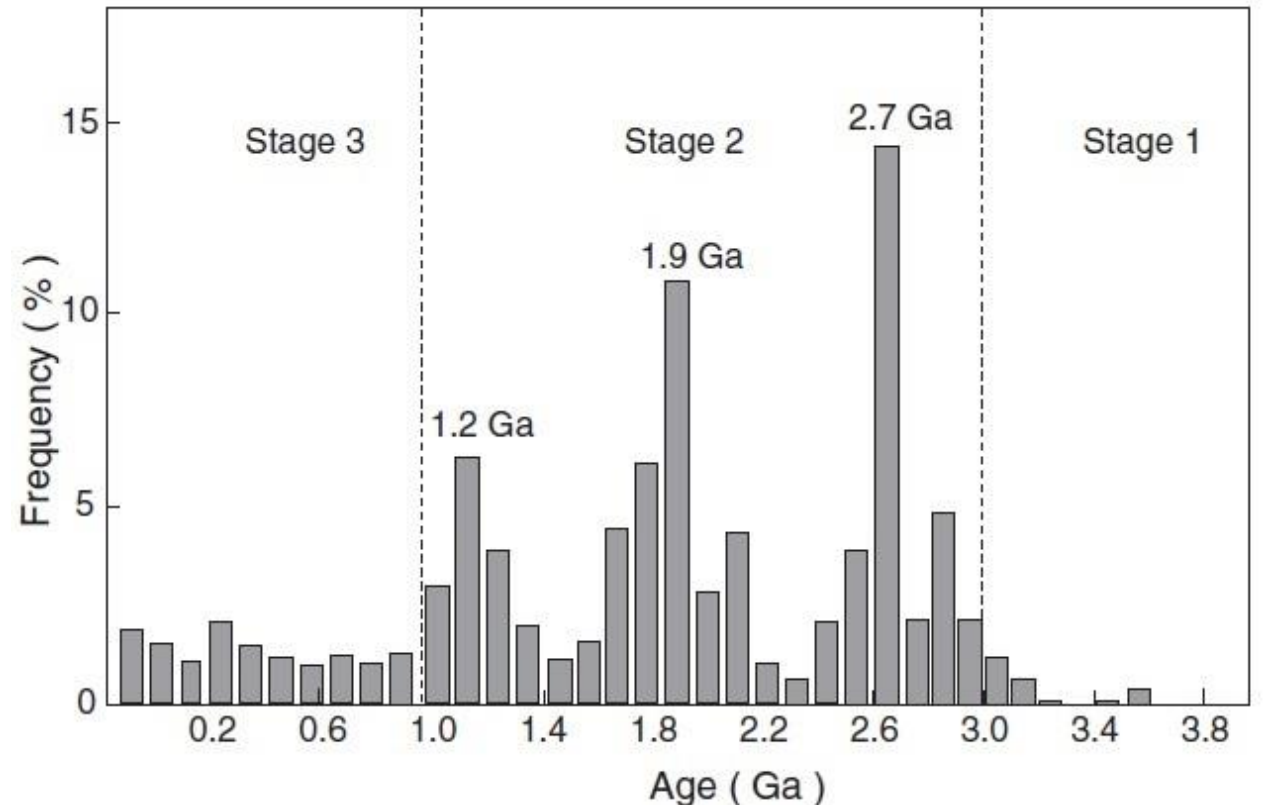
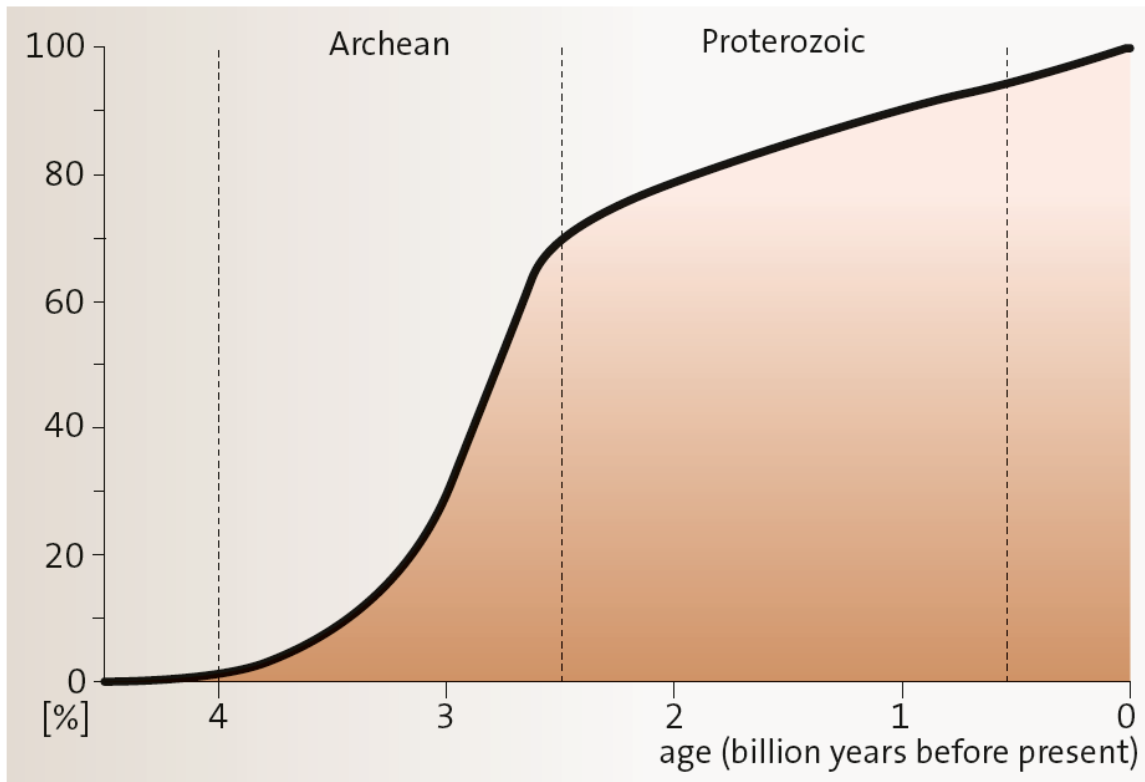
## Water-ocean layer: when did it form?

- Markers of the existence of a water-ocean are the thick deposits of sediments (carbonates and evaporates) and ophiolites.
- Carbonates are rare prior to ~2.9 Gyr and are not of sedimentary origin (metasomatic, 3.71-3.85 Gyr). They started to increase at the end of Early Archean, likely because of the absence of a water-ocean layer before this time or of the scarce solubility of  $\text{CO}_2$  in the hot water.
- Carbonates form in a range of  $T$  of the ocean between 473-673 K, reached in the early Archean: Serpentinized komatiite of age ~3.4-3.25 Gyr have been found.
- Significant amount of sediments started to form at 3.26 Gyr (at the end of the Early Archean). Before this time, absence of carbonates and evaporites, but presence of barites formations (between 3.46-3.55 and 3.2 Gyr): water- and sulfur-layer in contact.



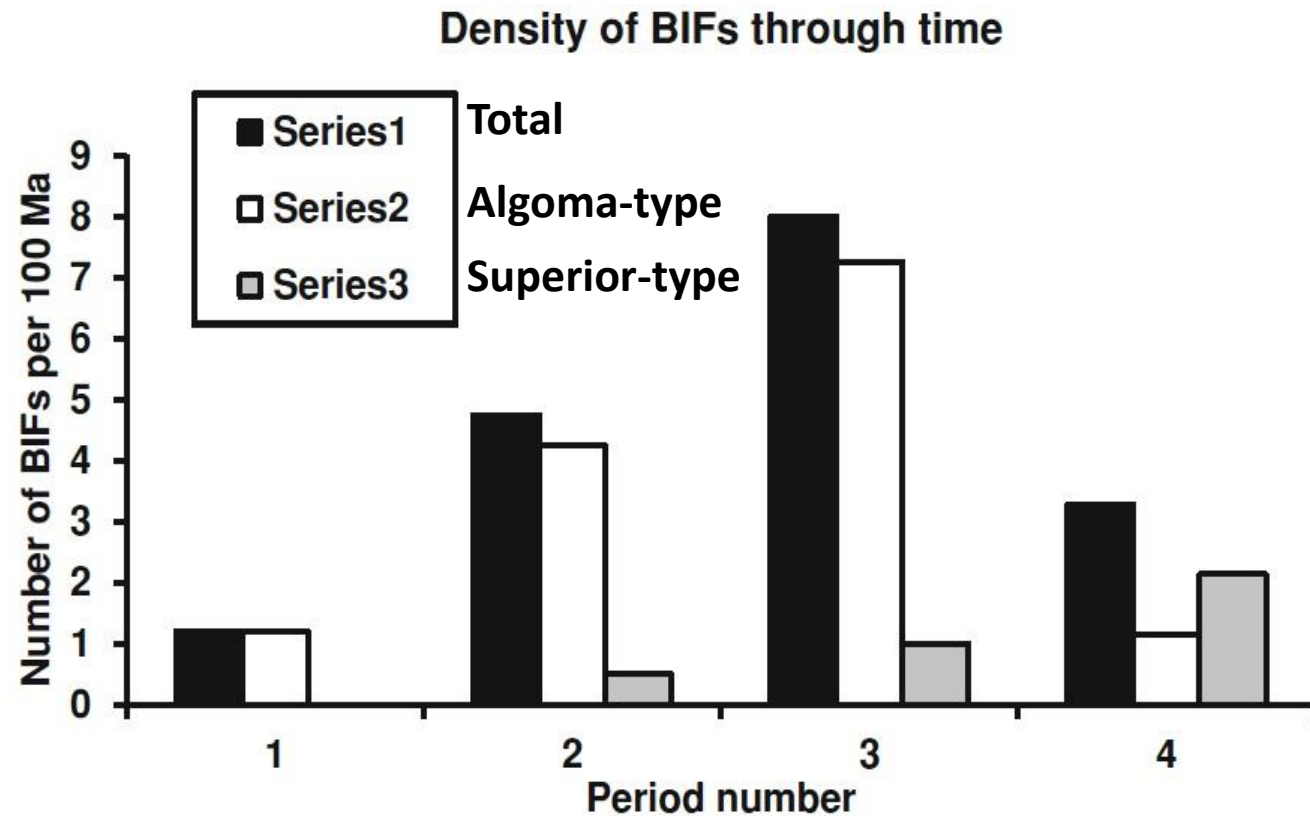
# Crustal Growth

- Enormous crustal growth occurred in the second half of the Archean era (before only small, unstable continents), between 3.2 and 2.5 Gyr. This is due to the considerably more efficient production of rocks constituting continental crust above subduction zones since ca. 3.2 Gyr.
- Measurements of Nb/Th and Nb/U ratios could define the net production rate of continental crust since 3.8 Gyr (the different ratios potentially provide information on the extent of the chemical depletion and the amount of continental crust that was present on Earth at different times).
- These results and on those of isotopic age determinations suggest that crust production was episodic with rapid net growth at 2.7, 1.9, and 1.2 Gyr (with pulses of  $\leq 100$  Myr) and slower growth afterwards.
- Previous studies suggested that: 39% of the continental crust formed in the Archean, 31% in the Early Proterozoic, 12% in the Middle–Late Proterozoic, and 18% in the Phanerozoic.



# Markers of lithospheric thermal conditions

- Processes as the deposition of BIFs, and the formation of pyrite deposits are markers of anoxic atmospheric environments, while the formation of paleosols and red beds take place in oxygen-rich environments.
- Transformation of ferric iron to ferrous iron (TFFI) occurs with an increase of temperatures from low to high values and viceversa, since ferrous iron is stable at HP and HT and ferric iron is stable at LP and LT.



1 Early Archean, 2 Middle Archean, 3 Late Archean, and 4 Early Proterozoic

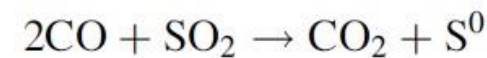


## Ferrous and Ferric Iron distribution in Precambrian BIFs

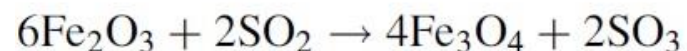
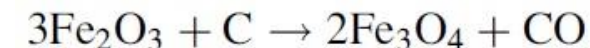
- The coefficient of stability of iron(II) oxide ( $v = \text{FeO}/(\text{FeO} + \text{Fe}_2\text{O}_3)$ ) is in the range of 0.44–0.55 and 0.51–0.66, for the Archean and Early Proterozoic BIFs, respectively, likely due to the reduction in temperatures to the zone of iron(II) stability or the rapid cooling of forming deposits.
- The excess of iron(II) oxide in the Precambrian metamorphic rocks may be related to the formation and stability of hematite, which can occur only in the presence of both water and oxygen.

| Rocks                           | Fe <sub>2</sub> O <sub>3</sub> | FeO   | FeO/(Fe <sub>2</sub> O <sub>3</sub> +FeO) |
|---------------------------------|--------------------------------|-------|---|
| Archean:                        |                                |       |   |
| Yilgam Block                    | 18.98                          | 23.65 | 0.55                                      |
| Montana                         | 26.91                          | 17.51 | 0.44                                      |
| Proterozoic:                    |                                |       |   |
| Hammersley Basin                |                                |       |   |
| Marra Mamba                     | 12.93                          | 25.49 | 0.66                                      |
| Dalles Gorge Member             | 18.40                          | 23.88 | 0.56                                      |
| Joffre Member                   | 20.16                          | 22.53 | 0.53                                      |
| Labrador Trough                 |                                |       |   |
| Unmet.                          | 19.96                          | 21.69 | 0.52                                      |
| Met.                            | 16.87                          | 23.68 | 0.58                                      |
| Biwabik                         | 20.28                          | 21.43 | 0.51                                      |
| Ukrainian Shield <sup>a</sup> : |                                |       |   |
| Pervomayskiy area:              |                                |       |   |
| Quartzite pyroxene-magnetite    | 24.32                          | 29.55 | 0.55                                      |
| Quartz-pyroxene schists         | 1.91                           | 50.9  | 0.96                                      |
| Quartz-pyroxene schists         | 2.93                           | 40.45 | 0.93                                      |
| Quartz-garnet-pyroxene schist   | 1.16                           | 16.3  | 0.94                                      |
| Quartz-garnet-pyroxene schist   | 1.84                           | 28.64 | 0.94                                      |
| Biotite-cilimanite schist       | 1.16                           | 4.93  | 0.81                                      |
| Petrovskiy area:                |                                |       |   |
| Quartz-biotite-amphibol schists | 1.12                           | 37.67 | 0.97                                      |
| Quartz-biotite-amphibol schists | 3.83                           | 27.1  | 0.88                                      |
| Garnet-biotite-quartz schists   | 2.02                           | 11.62 | 0.85                                      |
| Garnet-biotite-quartz schists   | 3.33                           | 14.31 | 0.81                                      |

- The interaction between the CO-layer and the SO<sub>2</sub>-layer caused several chemical reactions resulting in the formation of such important reducing agents as elemental carbon and sulfur at *T* of 873-973K:



- C, CO<sub>2</sub>, S, and SO<sub>2</sub> caused the reduction of hematite to magnetite at *T* of 723-843K and fast cooling during Earth's evolution could preserve iron(II):



## **Paleosols and Red beds during Precambrian age**

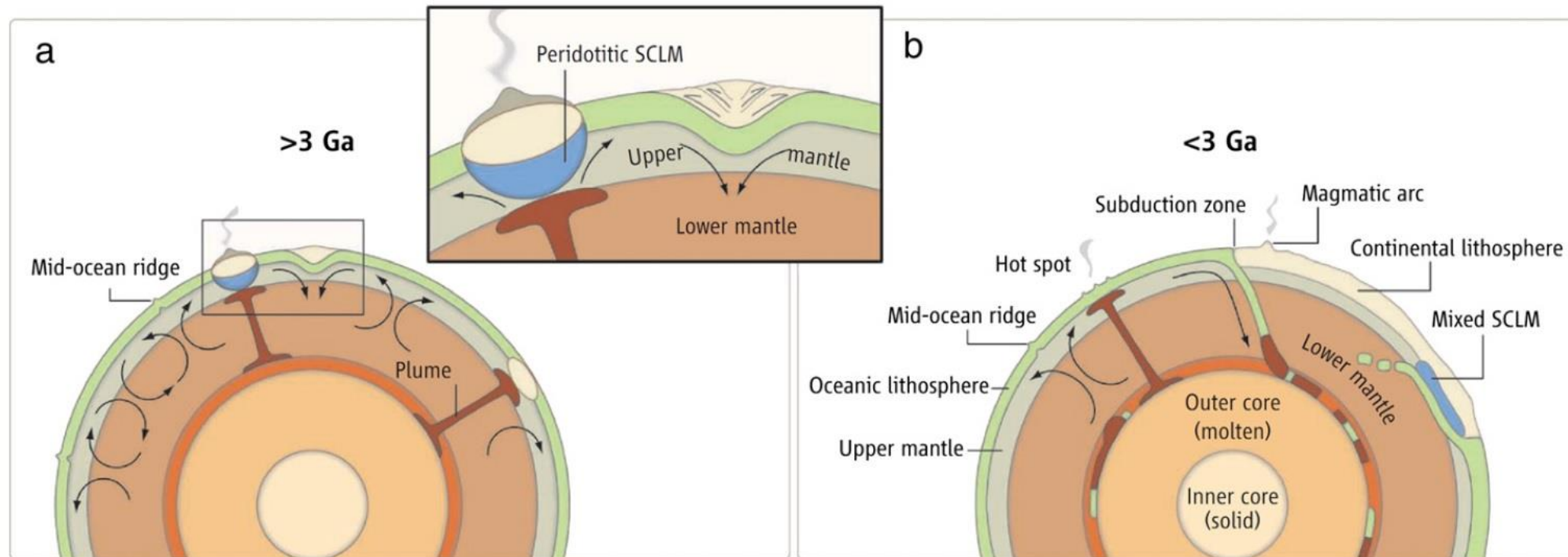
**Chemical profiles of the paleosols are useful to mark the the transformation of the Earth's atmosphere from an anoxic to an oxic environment:**

- If there was enough oxygen in the atmosphere, ferrous iron(II) would have oxidized to ferric iron(III) during weathering and the iron (III) within the paleosol would not be soluble or mobile, since only iron(II)-compounds are soluble in water.
- Pre-2.44 Ga paleosols suffered significant iron loss during weathering (anoxic environment), whereas the iron loss was negligible during their formation of the 2.2–2.0 Gyr and after (oxic environment).

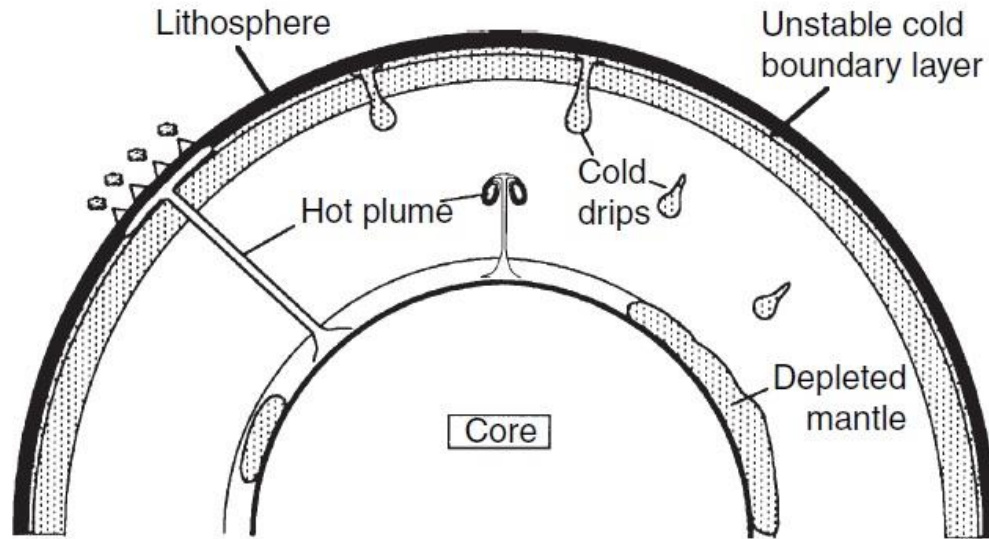
**Red beds, detrital sedimentary rocks rich in reddish-brown ferric oxide, were absent before 2.0-2.2 Gyr (anoxic environment, no direct contact between oxygen and surface).**

# Precambrian Geodynamics

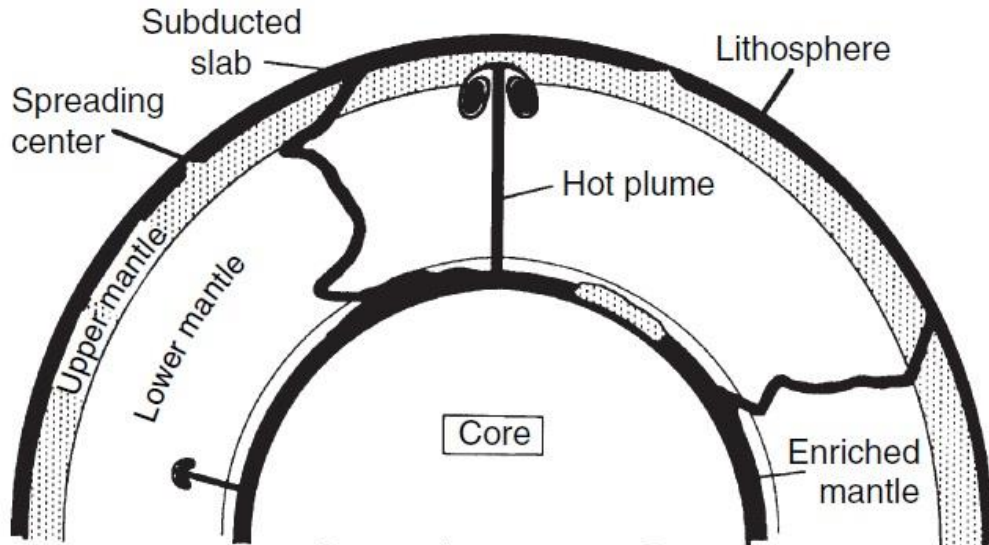
- Archean geodynamics was dominated by plume tectonics and the development of hot accretionary orogens with low topography.
- Due to the hot mantle temperature, slab break-off was more frequent in the Precambrian time and limited occurrence of ultrahigh-pressure (UHP) rocks. Mantle downwellings and slab break-off processes are likely to have played a key role in assembling and stabilizing the hot orogens.
- Both oceanic and continental lithospheres were rheologically weak due to the high temperatures.
- Numerical models suggest that the long-term stability of cratons sustaining multiple supercontinent cycles can be achieved if their viscosity and yield strength are sufficiently high and weak mobile belts are present along the boundaries of the cratons.
- Stable cratons facilitate subduction initiation of very young seafloor during continental growth and dispersal.
- Wide spread development of modern-style (cold) collision on Earth started during Neoproterozoic at 600–800 Myr. Cold collision created favorable conditions for the generation of UHP metamorphic complexes, which become widespread in Phanerozoic orogens.



# Precambrian Geodynamics



Pre-Archaean 4.0–4.5 Ga



Post-Archaean 0–2.0 Ga

- During the pre-Archean or Hadean (4.5–4 Ga), the mafic crust was too buoyant to founder, and only the underlying mantle part of the thermal boundary layer (already cold) foundered.
- The post-Archean change in chemistry is attributed to the replacement of the early depleted D'' layer by enriched subducted mafic crust.
- The higher temperatures of the plume during the Archean, may be due to the fact that the earlier phase the D'' layer covered only part of the core, leaving hot core directly in contact with mantle elsewhere and thus generating very hot plumes.



## Metamorphic rocks of Precambrian

- The age of metamorphic rocks helps define the time period in the Earth's evolution when such thermal conditions took place at the specific depth in the regions where these rocks are located.
- Among metamorphic rocks, **greenschist rocks (MP and MT)** were the earliest to appear followed by **granulites (MP-HP and HT)** and **amphibolites (MP and MT-HT)**, while the oldest **eclogites (HP-UHP and HT)** appear only in the Early Proterozoic and **blueschists (MP-HP and LT)** only in the middle-late Proterozoic.

Thermodynamic conditions of some metamorphic processes (adapted from Pilchin and Eppelbaum 2009)

| Type of metamorphism                         | Average temperature, K | Average pressure, MPa | Average depth of lithostatic pressure, km | Average geothermal gradient (K/km) for present surface conditions | Average geothermal gradient (K/km) for surface temperature ~573 K |
|--|------------------------|-----------------------|---|---|---|
| Blueschists<br>( <i>n</i> = 265)             | 677                    | 1,000                 | ~35                                       | 11.5  | 2.97  |
| Eclogites<br>( <i>n</i> = 556)               | 856                    | 1,900                 | ~64                                       | 9.1   | 4.42  |
| Amphibolites<br>( <i>n</i> = 353)            | 925                    | 770                   | ~26–27                                    | 24.1  | 17.41   |
| Granulites <sup>a</sup><br>( <i>n</i> = 601) | 1,075                  | 820                   | ~28                                       | 28.6  | 17.93   |
| Greenschist<br>( <i>n</i> = 188)             | 681                    | 420                   | 14–15                                     | 27  | 8.28  |

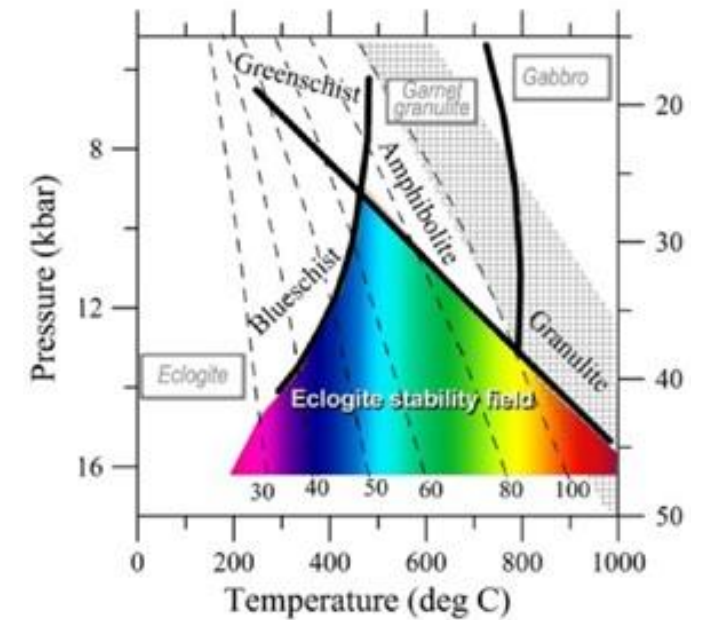
<sup>a</sup> Granulites of the Archean and Early Proterozoic

## Metamorphic rocks of Precambrian

- Greenschists, granulites and amphibolites could be formed under lithostatic pressure, but metamorphic rocks such as eclogites and blueschists (characteristic of regions subjected to great horizontal displacement) require the presence of overpressure, not possible during the early stages of the Earth evolution.
- Amphibolites appeared after granulites, since their formation require lower temperatures and differently from granulites, require basic magmas, which did not form in the uppermost layers of the magma-ocean and water penetration through the very hot rocks of the young Archean crust at depths of 23-30 km.
- For eclogite metamorphism, the magma-ocean must have been solidified at a depth of 64 km, but for the formation of greenschists, granulites and amphibolites it only needed to be solidified at 14–15 km, 28 km and 26–27 km thick, respectively.

| Thermodynamic conditions for the formation of eclogites with different origins |              |                |                         |   |                                   |
|--|--------------|----------------|-------------------------|---|-----------------------------------|
| Eclogites formed at temperatures K, (n)  | Average T, K | Average P, GPa | Average $P/T^a$ , MPa/C | Average depth of lithostatic pressure, km | Average geothermal gradient, K/km |
| $T < 843$ , (n = 279)  | 762          | 1.51           | 3.10                    | 50  | 9.8                               |
| $843 < T < 993$<br>(n = 216)   | 910          | 2.13           | 3.34                    | 70  | 9.1                               |
| $T > 993$ (n = 61)   | 1075.3       | 2.77           | 3.46                    | 90  | 8.7                               |

<sup>a</sup> Average value  $P/T$  was calculated as the average of the  $P/T$  ratios

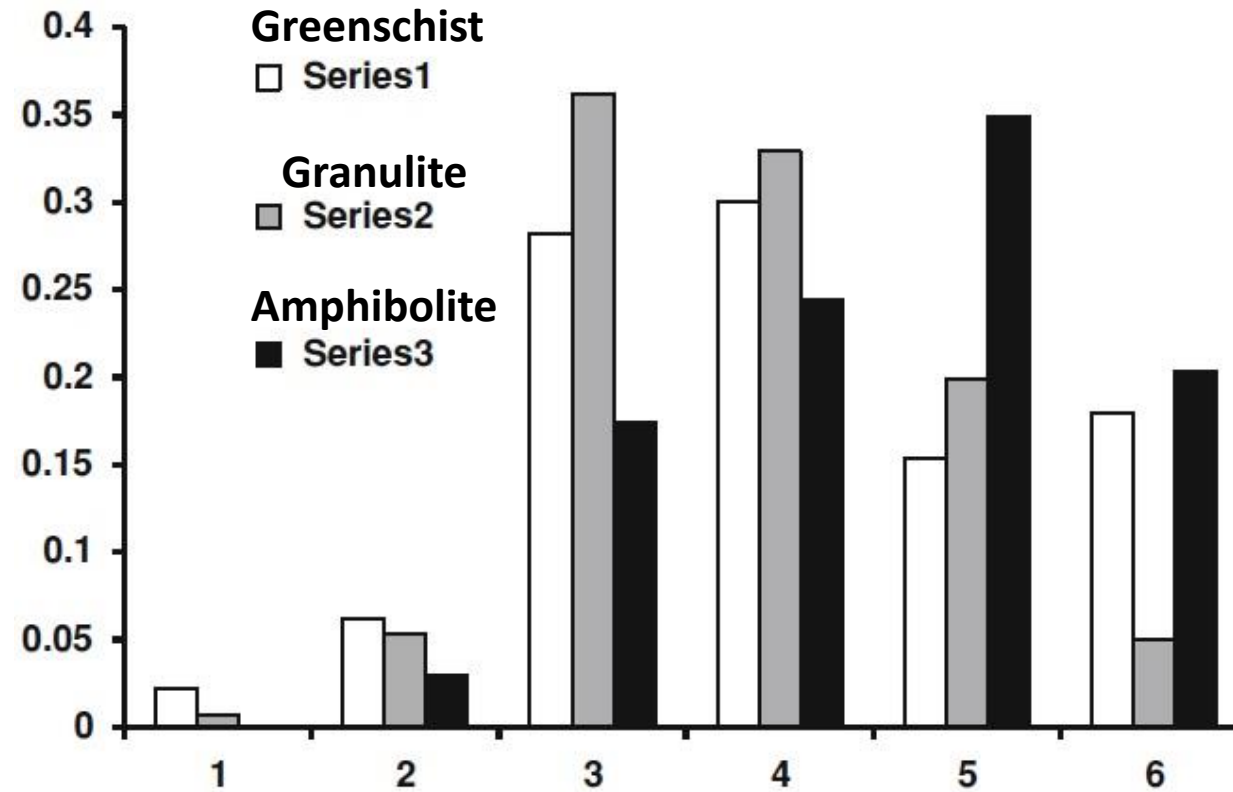


Artemieva and Meissner, 2012, Tectonophysics 530-531

The eclogites are divided in: eclogites of low moderate temperatures ( $T < 843$  K), which require the transformation of ferrous iron oxide to ferric iron oxide, eclogites of moderate temperatures ( $843 < T < 993$  K) and eclogites of high temperatures ( $T > 993$  K).



## Metamorphic rocks of Precambrian



(1) Early Archean (2) Middle Archean (3) Late Archean (4) Early Proterozoic (5) Middle Proterozoic (6) Late Proterozoic

Greenschist metamorphic facies, requiring low to moderate  $T$  and  $P$ , always had favorable conditions within the crust, while the abundance of granulite facies rocks declined constantly with the cooling of the uppermost layers, since  $T \sim 1073$  K at depths of  $\sim 28$  km became increasingly unrealistic.

# Thermodynamic conditions of metamorphic processes

**Presence of external forces, which can control changes in volume (e.g., prevent it from expanding), stress within the volume increases to extremely high values.**

$\alpha$ =thermal expansion coefficient

$\beta$ = compressibility coefficient

$$\alpha = \frac{(\partial V / \partial T)_P}{V_0} \quad \beta = \frac{(\partial V / \partial P)_T}{V_0} \quad P = P_0 + \frac{\alpha}{\beta}(T - T_0) - \frac{1}{\beta} \frac{\Delta V}{V_0}$$

The second term on the right side of the Eq. characterizes the dependence of pressure on the temperature of the rock. For  $T > T_0$  it will be an increase of pressure compared to the lithostatic or hydrostatic value, whereas  $T < T_0$  will lead to pressures below the lithostatic or hydrostatic value.

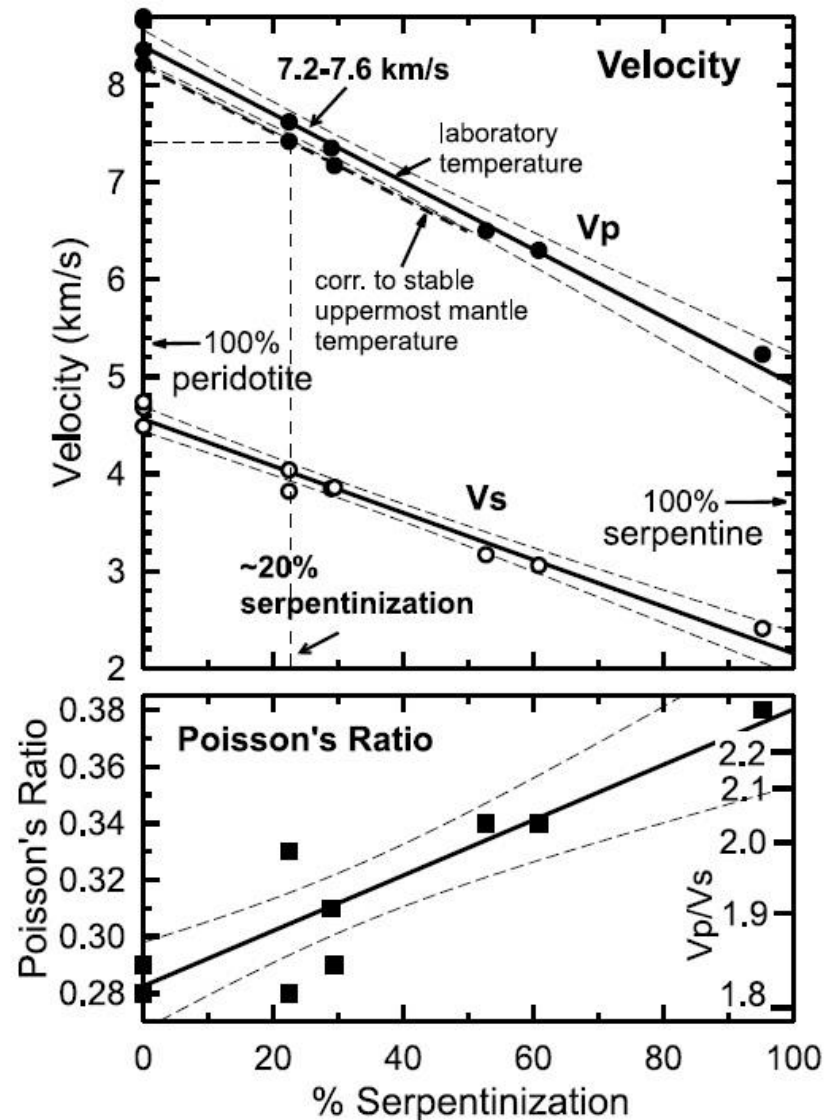
The third term on the right side of the equation represents pressure unloading (when  $\Delta V > 0$ ).

- We can notice that an increase of volume would lead to a decrease in pressure only in the case where the actual increase of volume was equal or greater than the change in volume caused by the process, but in all other cases it would lead to an increase in pressure.
- Since  $\beta$  for solid crustal rocks  $\sim 10^{-5}$  1/MPa, an increase in volume of only 1 % can cause composite unloading of pressure of about 1000 MPa, but if there was not any change in volume, the pressure would increase by about 1000 MPa.

**There are several processes that lead to the formation of significant overpressure capable of causing tectonic processes: (1) heating of underground water; (2) heating of great volumes of rocks; (3) melting of rocks; (4) rising of melt to the Earth's surface; (5) decompaction of crustal and upper mantle rocks.**

# Serpentinization

Serpentinite: low  $V_p$  and  $V_s$  velocity, low density, and high  $V_p/V_s$  ratio and Poisson's ratio

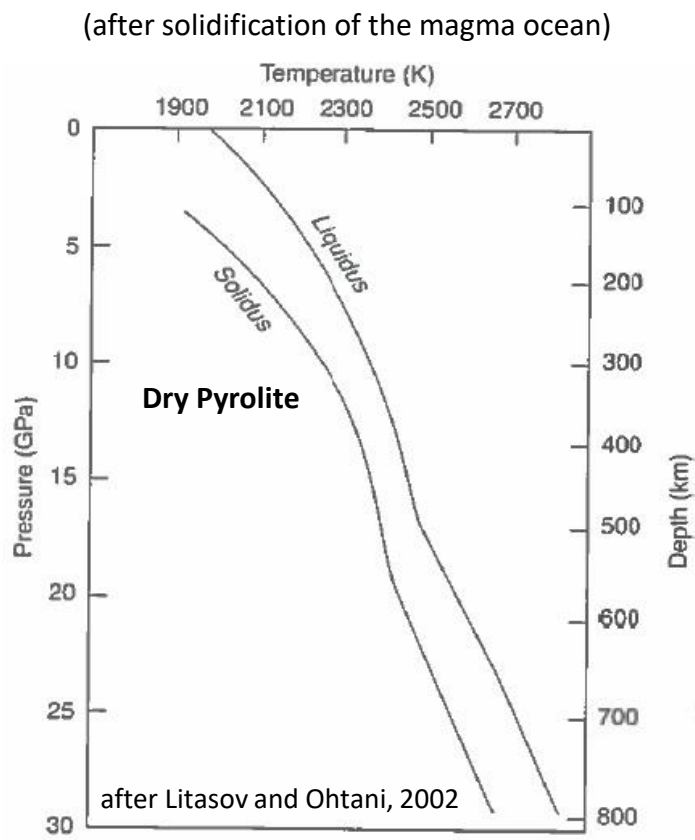
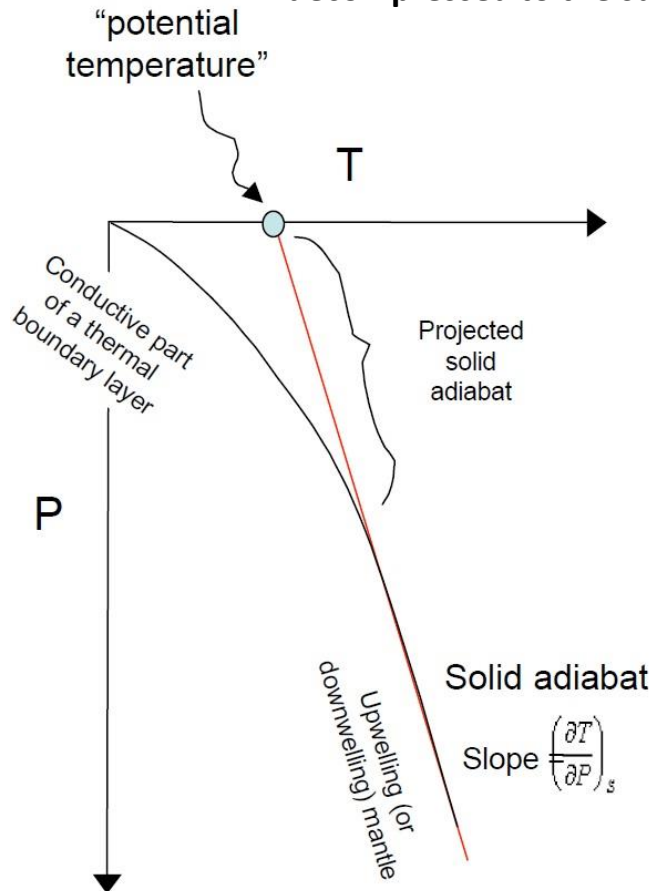


- Serpentinization occurs in a  $T$  range of 473-773 K (shallow depths, during obduction processes or in the oceanic regions) and can cause an increase in volume up to 40 %.
- Serpentinites are the key component of ophiolite association and all peridotite plates obducted onto the surface are partially serpentinized.
- An increase of 15–25 % in the volume of the peridotite layer of oceanic lithosphere during its serpentinization can cause the horizontal expansion of the layer in any direction of at least 5–8 %.
- Serpentine minerals (lizardite, chrysotile, and antigorite) contain up to 13 wt% in water, have a low density of about  $2600 \text{ kg/m}^3$ , and a low viscosity of about  $4 \times 10^{19} \text{ Pa s}$ .
- Lizardite is stable at  $T$  358–458 K, chrysotile at  $T$  403-458 and antigorite at 493–733 K. Since magnetite is a main mineral of serpentinite, a significant amount of serpentinization should take place at  $T$  above the lower limit of TFFI (473–523 K).

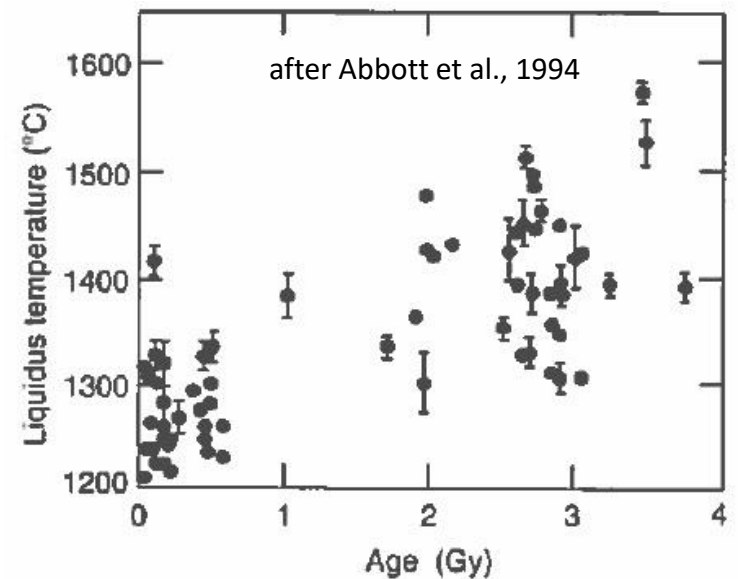
# Average secular cooling rate

- After solidification of the magma ocean (at the end of the Early Archean) the potential temperature ( $T_p$ ) of a pyrolitic mantle (peridotite + basalt) was  $\sim 1800$  K.
- According to petrological data,  $T_p$  decreased from the Archean to  $137 \pm 8$  -  $187 \pm 42$  K, which leads to a cooling rate of  $\sim 50 \pm 20$  K Gyr $^{-1}$ .

The temperature of a given portion of the mantle if it was adiabatically decompressed to the surface of the Earth.



$T_L$  for basalts (ophiolites and greenstone belts)



# Heat transfer mechanisms

## conduction

from Latin conductionere  
“to bring together”

## convection

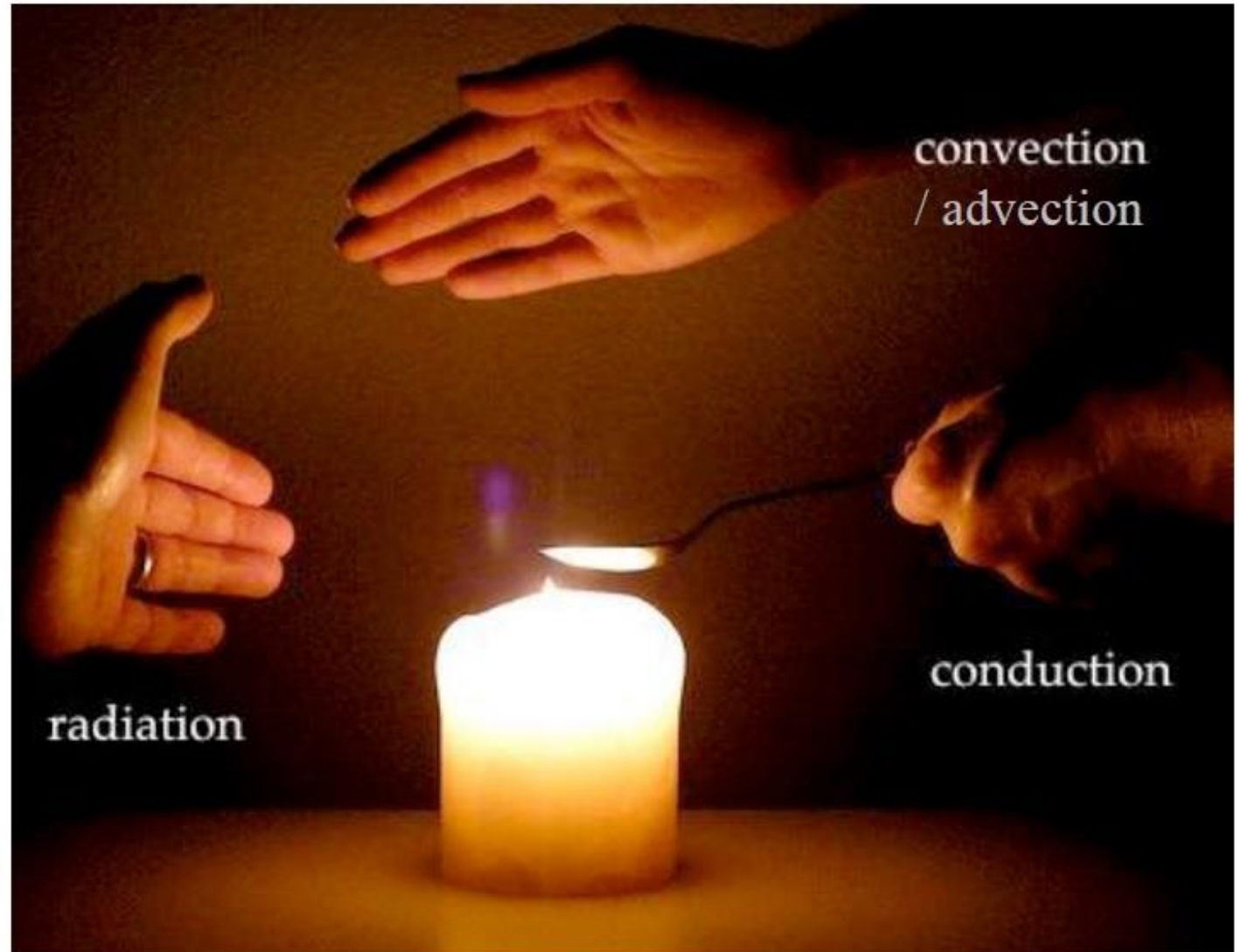
from Latin convehere  
“to carry together”

## advection

from Latin advehere  
“to carry to”

## radiation

from Latin radius  
“ray, spoke”





# Heat transfer mechanisms

- **Conduction**

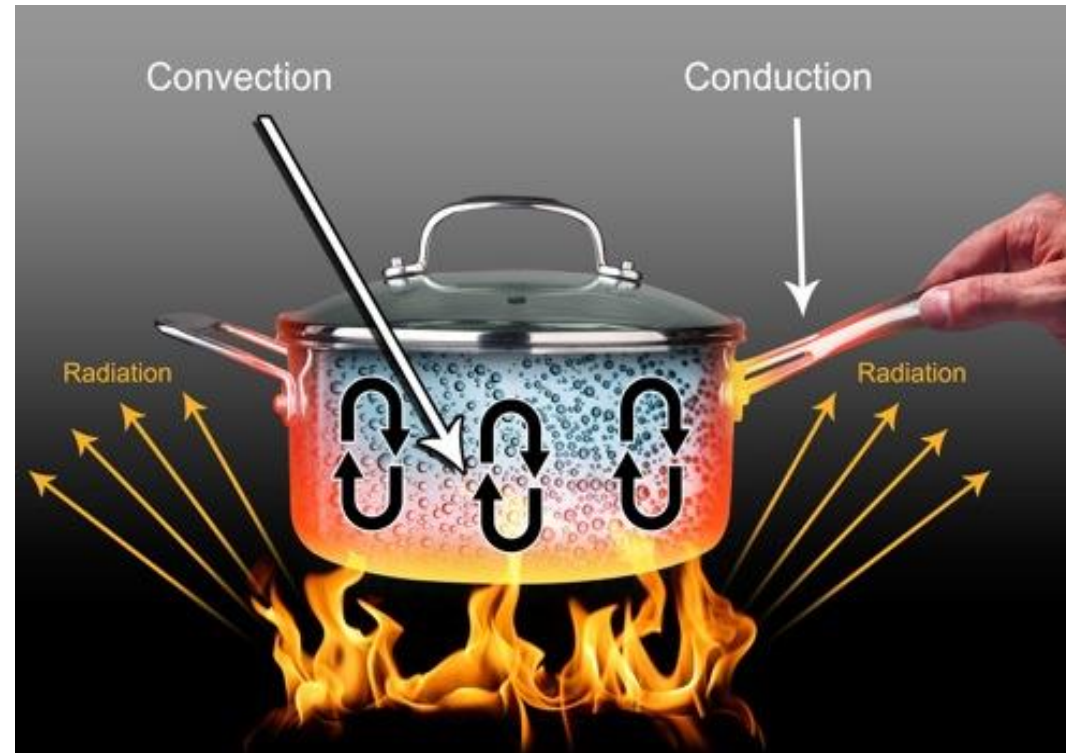
- It is the slowest kind of heat transfer, which occurs through a material by atomic or molecular interaction with the material. It requires direct contact between medias transferring heat.

- **Radiation**

- Direct transfer of heat as electromagnetic radiation It dominates the Earth's surface, since it requires an open surface

- **Convection**

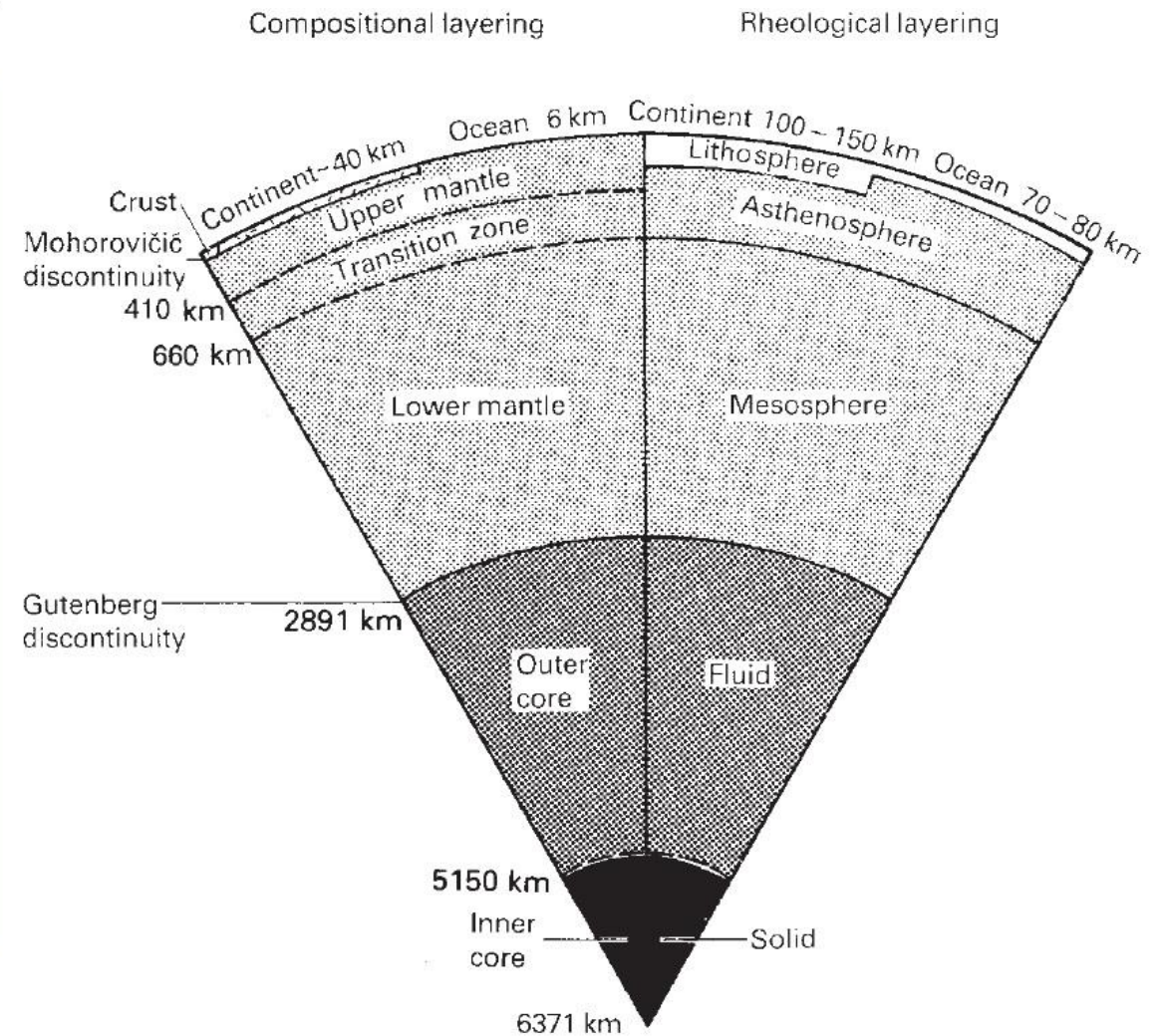
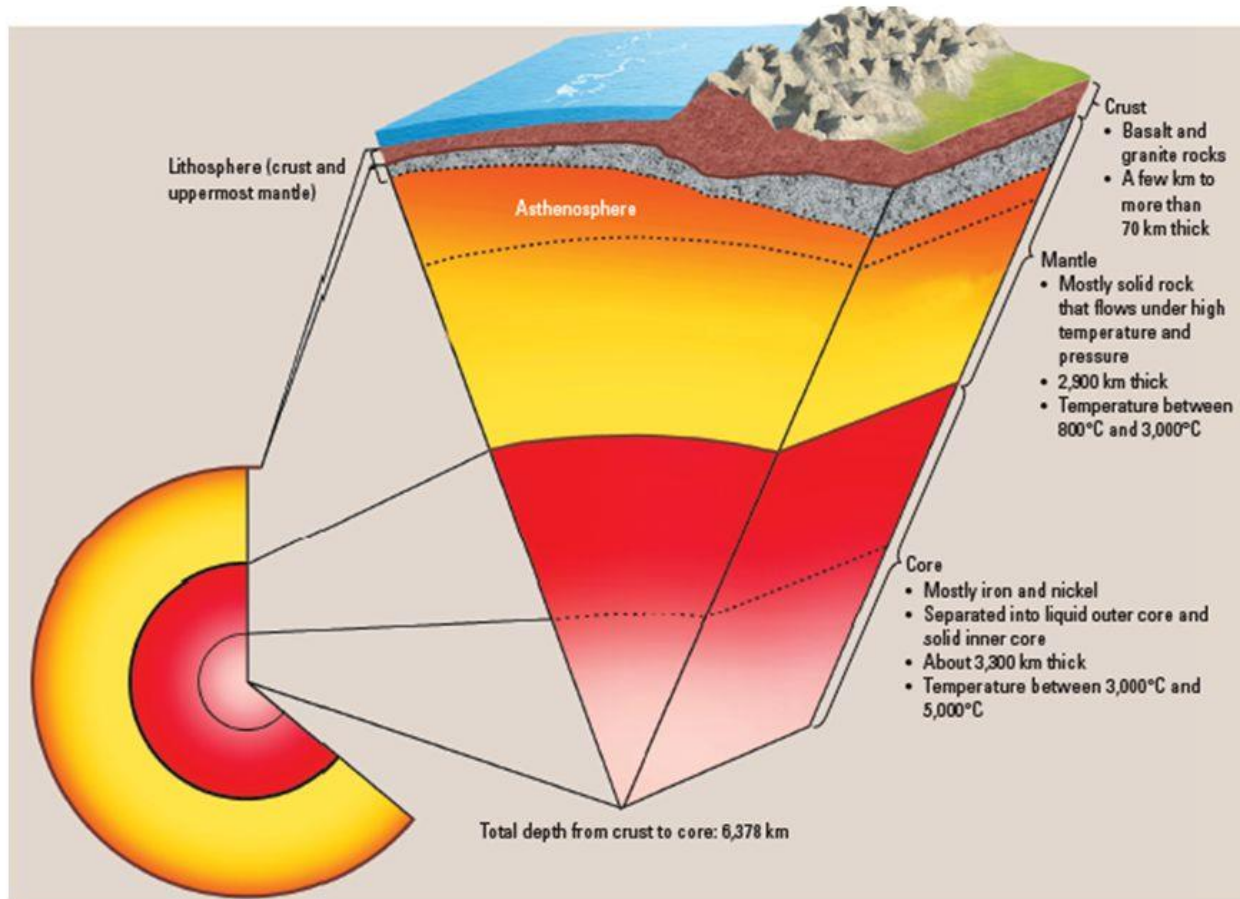
- Transfer of heat by movement of the molecules themselves. It is a very effective method of heat transfer by a fluid medium, based on circulation of cold fluid down and hot fluid up. It requires an open system conditions for the free movement of fluids.



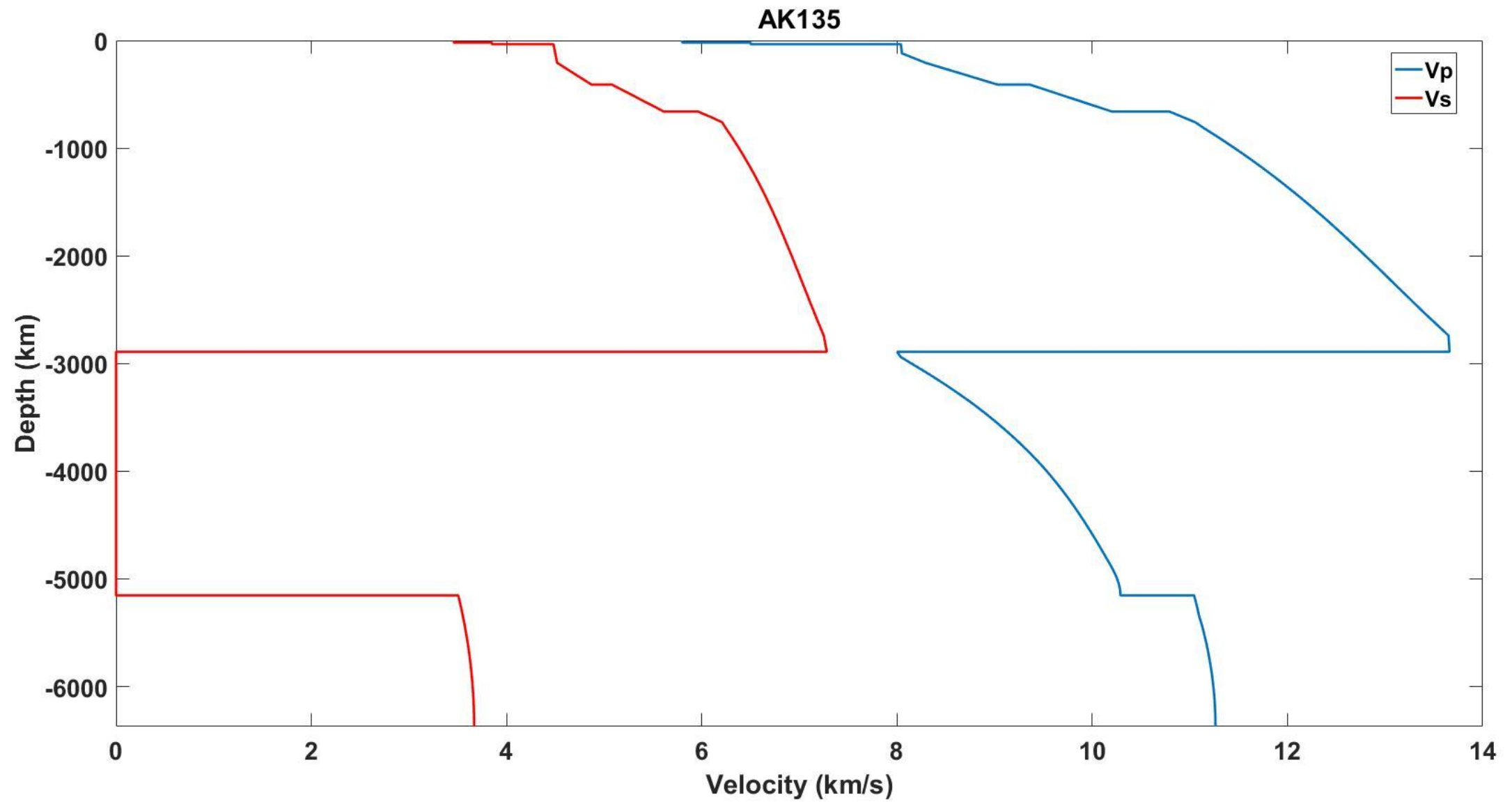


# Earth's Structure

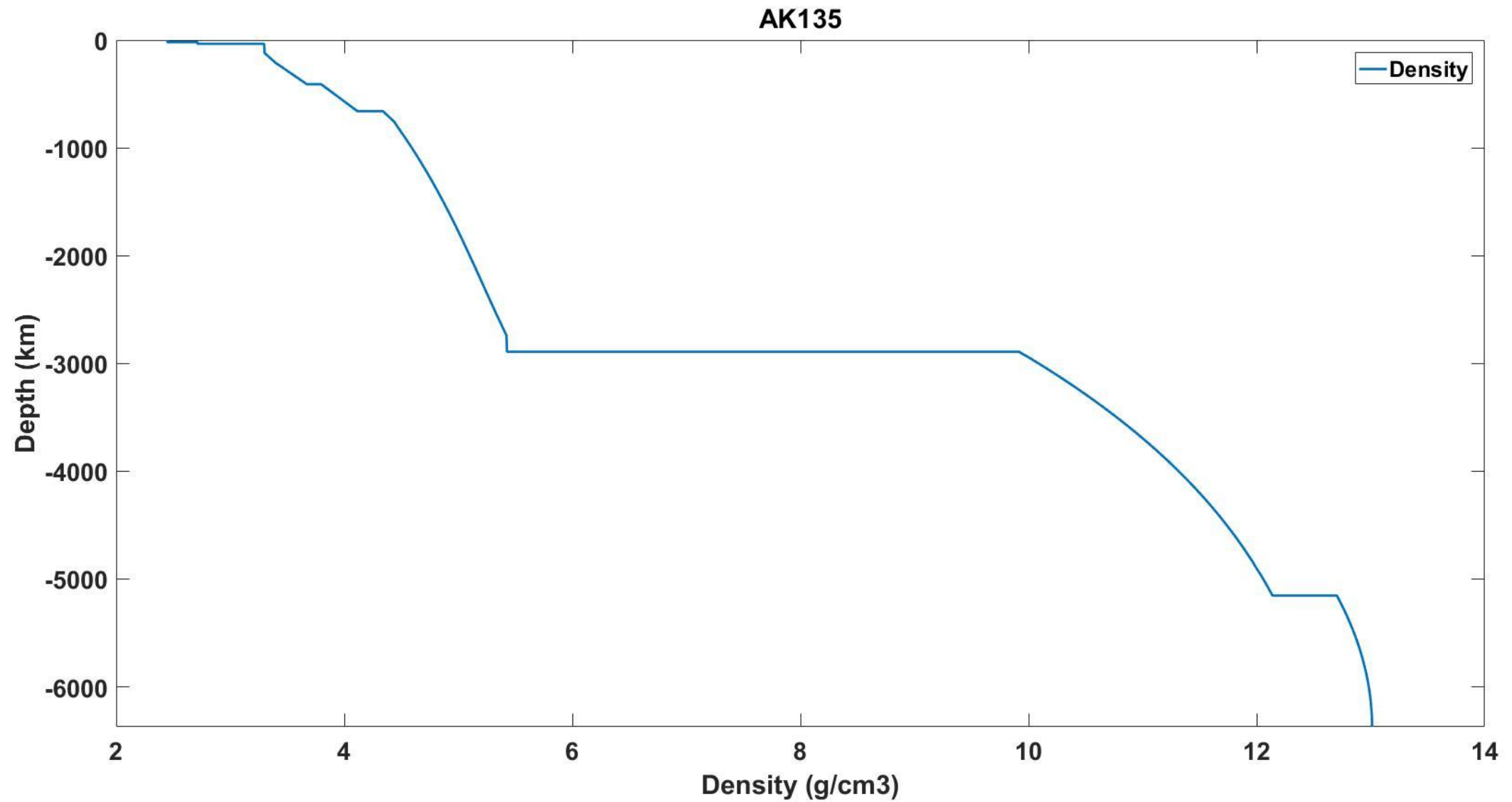
## What is the internal structure of the earth?



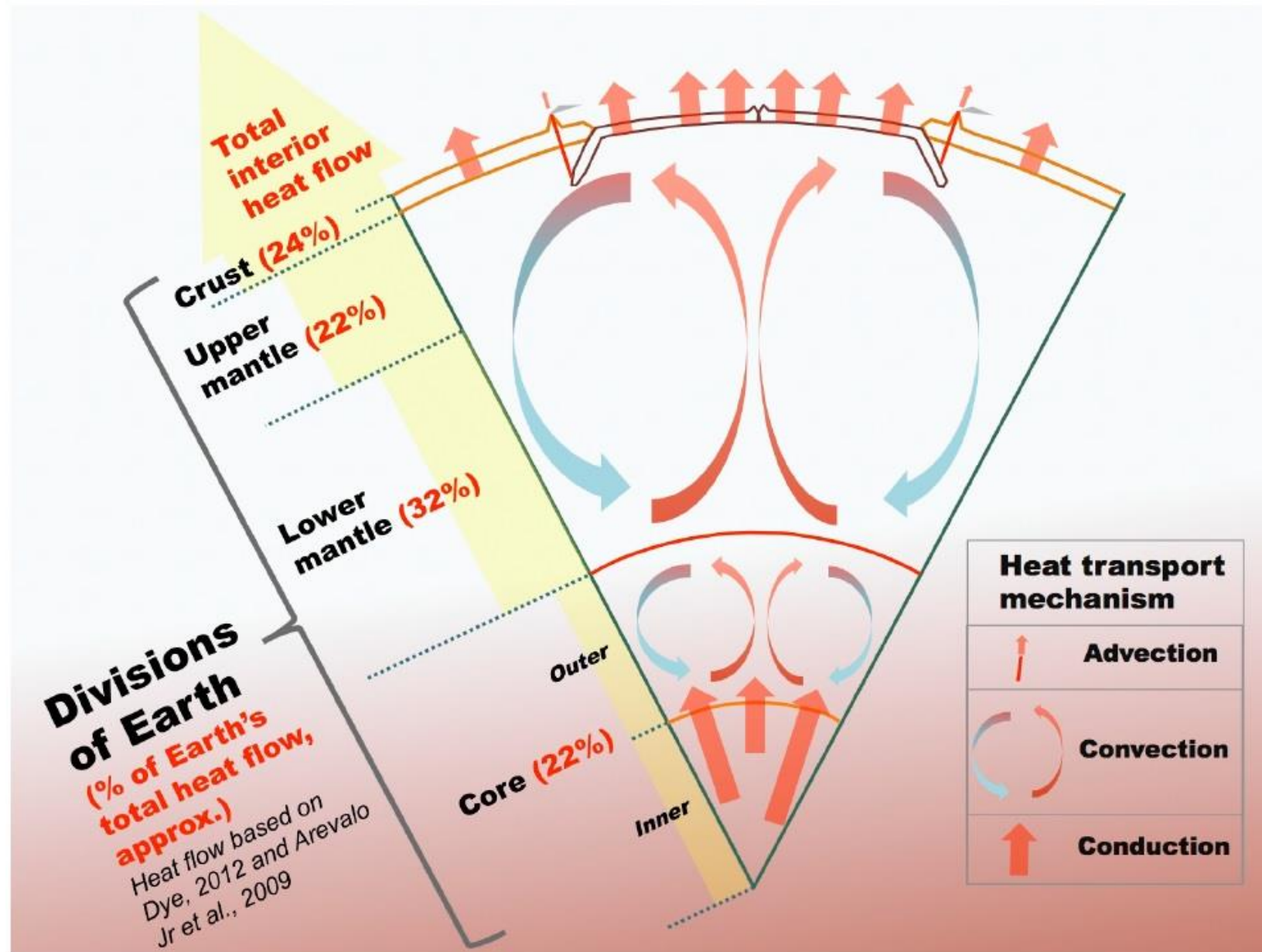
# Earth's Velocity



# Earth's Density

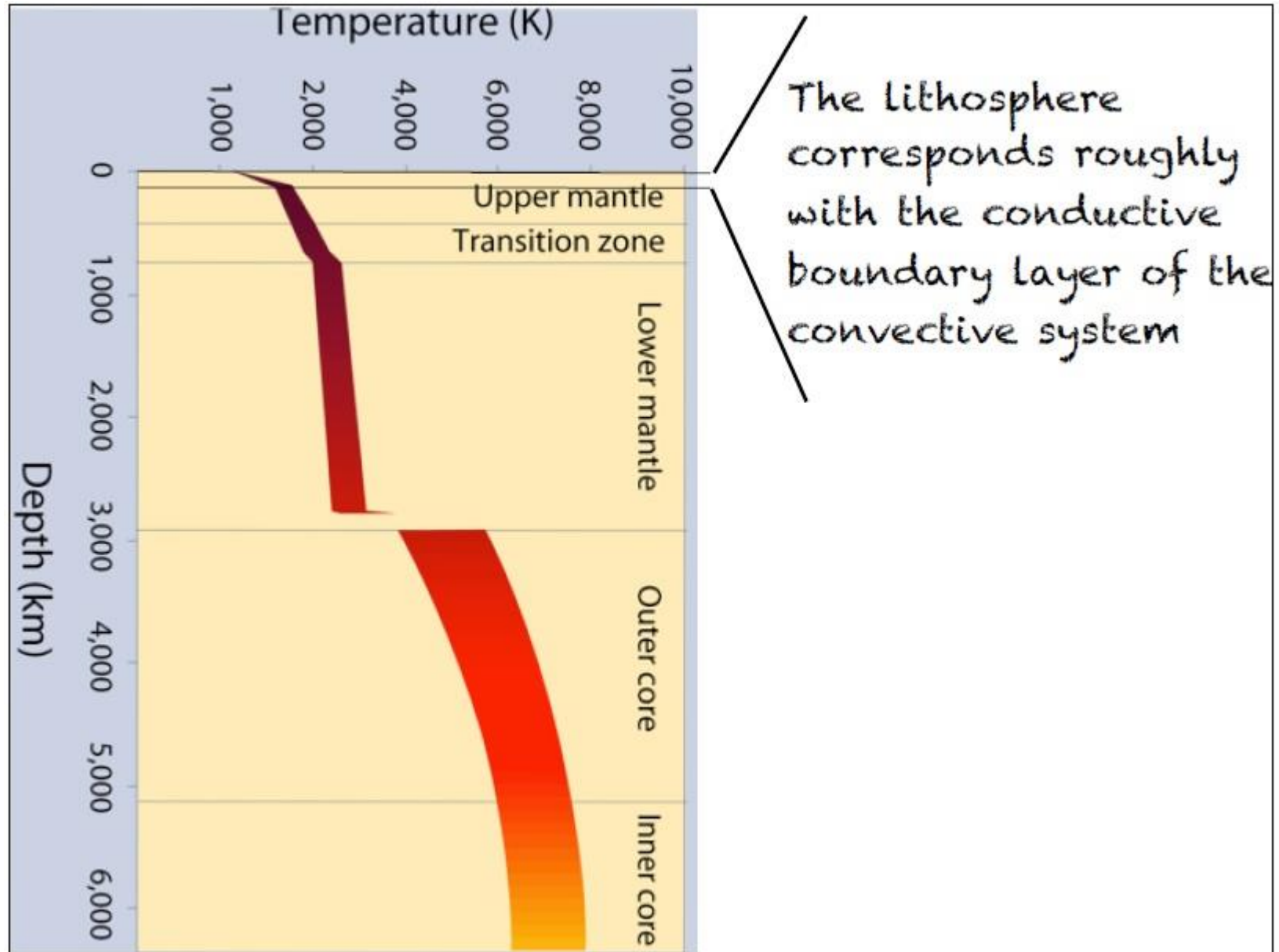


# Heat Transport Mechanisms in the Earth



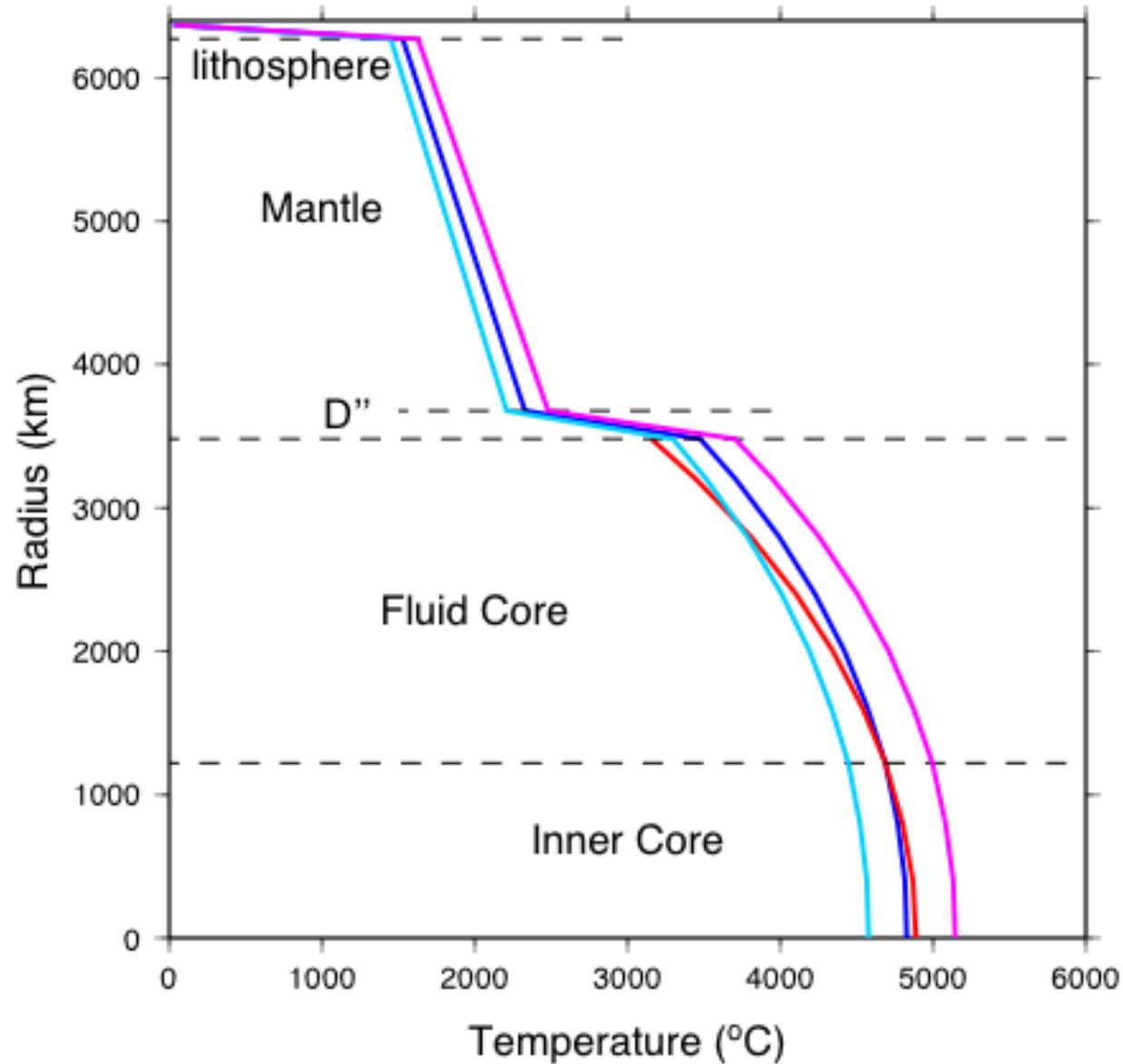


# Temperature profile inside Earth





# Thermal evolution of the Earth



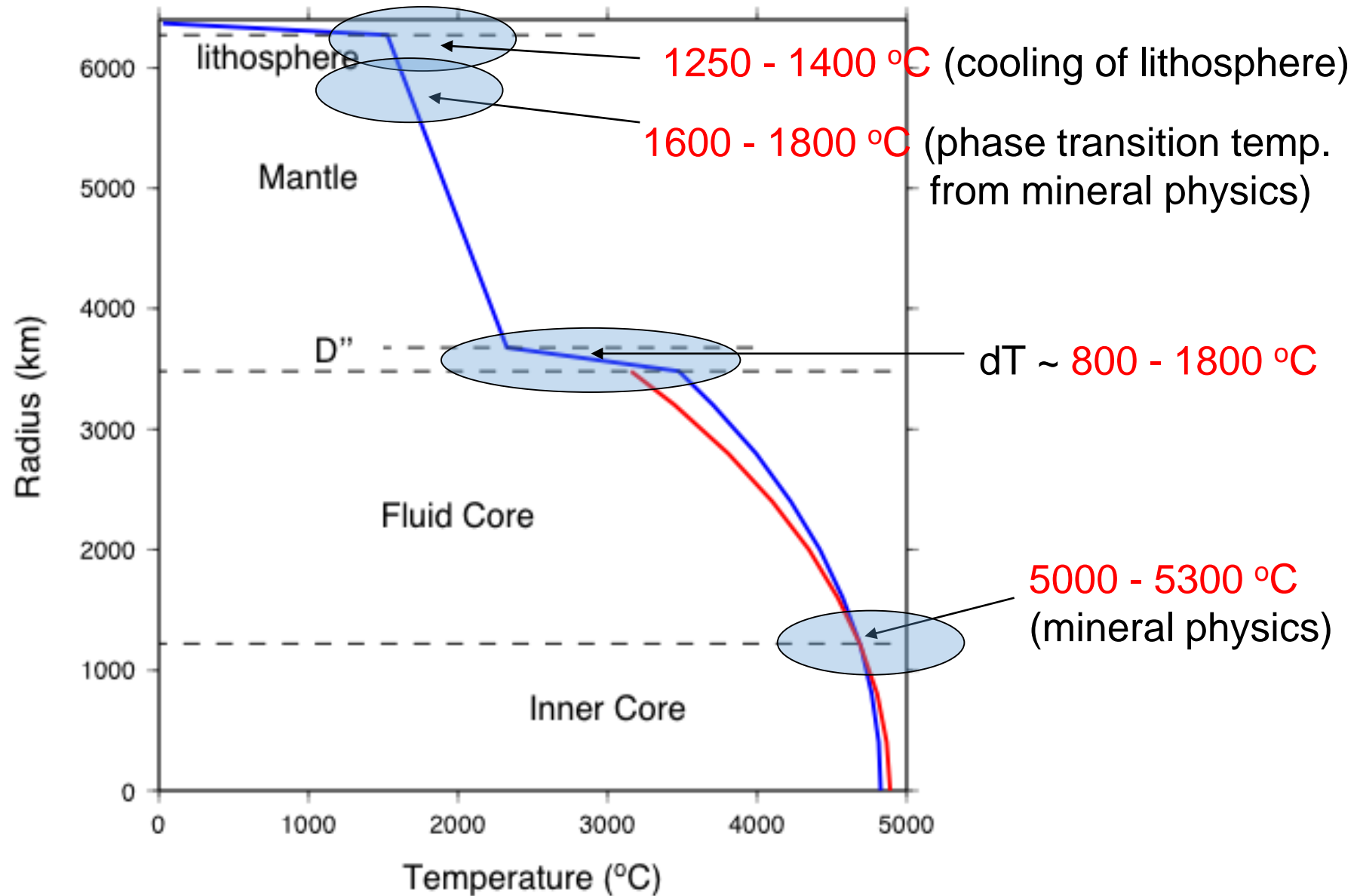
Present Temp.

Past Temp.

Future Temp.

Fe melting curve

# Temperature profile inside Earth



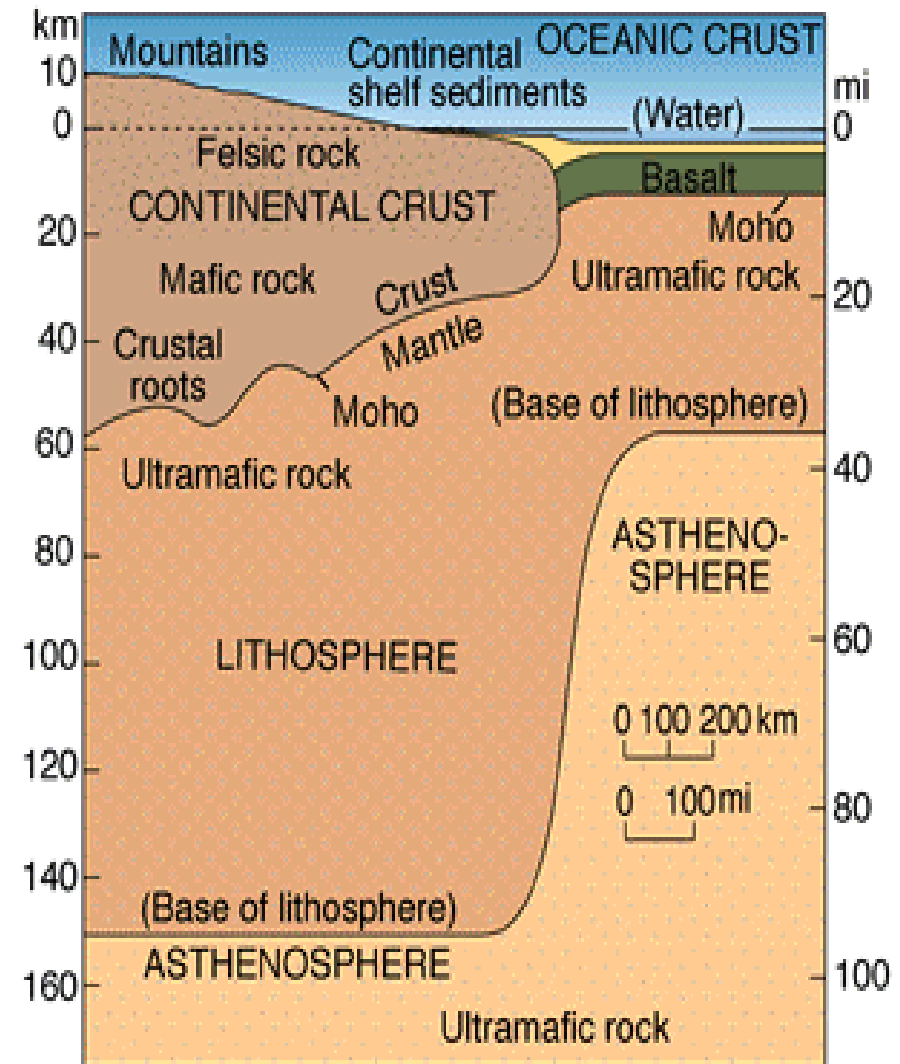
# Oceanic and continental lithosphere

## Oceanic lithosphere

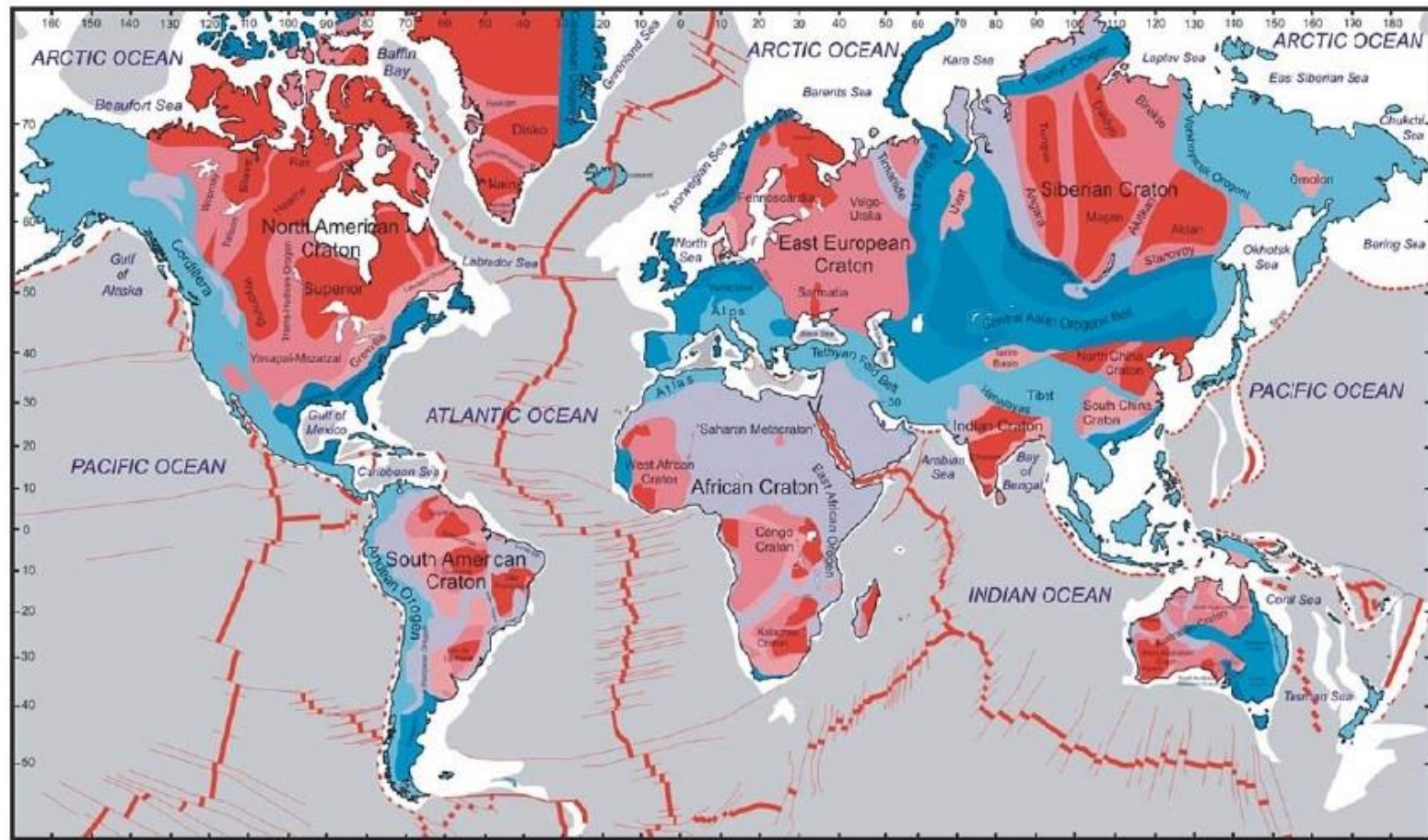
- Thin
  - Crust: 5 – 8 km
  - Lithospheric thickness increases with age (100-125 km)
- Young: less than 200 million years
- Heavy: ultimately always subduction
- Enriched in FeO and MgO
- Hardly any heat production

## Continental lithosphere

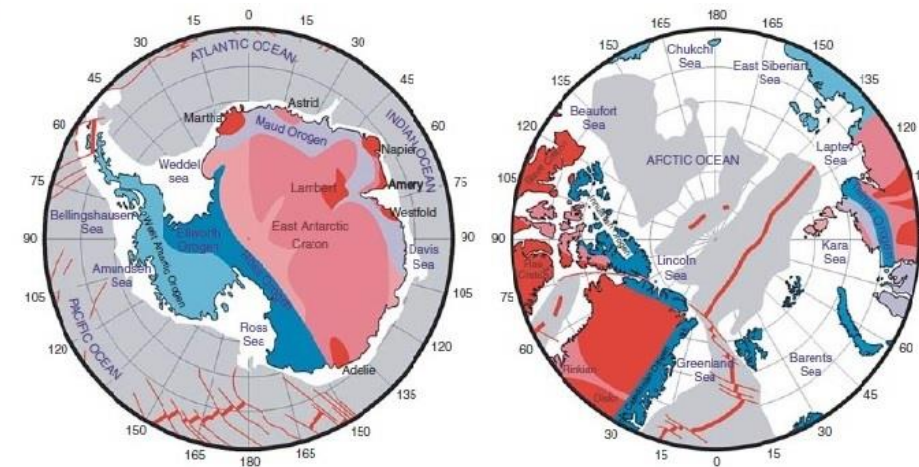
- Thick
  - Crust: 20 – 60 km
  - Lithosphere: 25 – 250 km
- Old: More than 4 billion years
- Light: virtually never subduction
- Enriched in SiO<sub>2</sub>
- Substantial heat production



# Basement age of continental crust

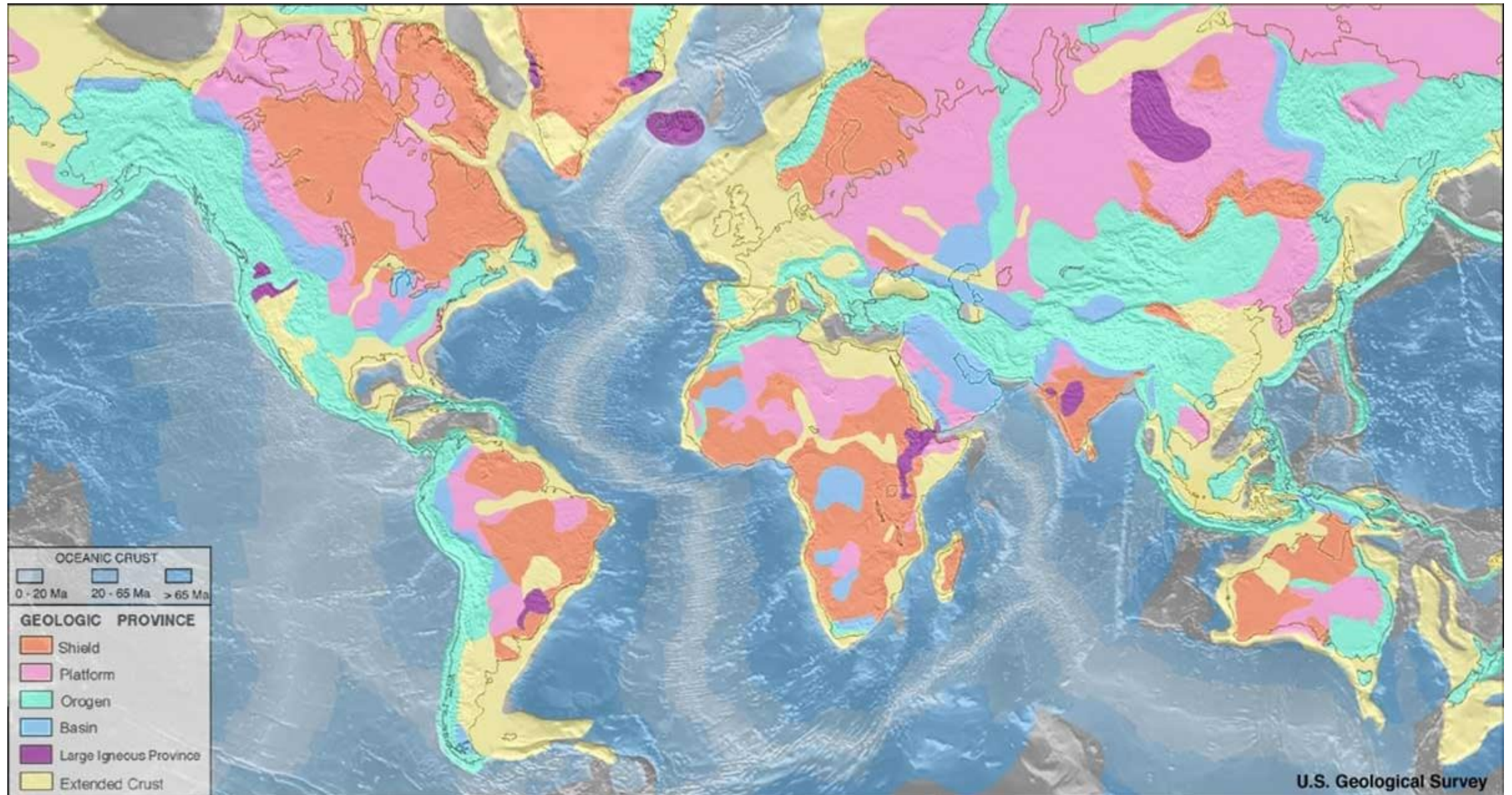


(Mooney, 2013, Treatise of Geophysics)



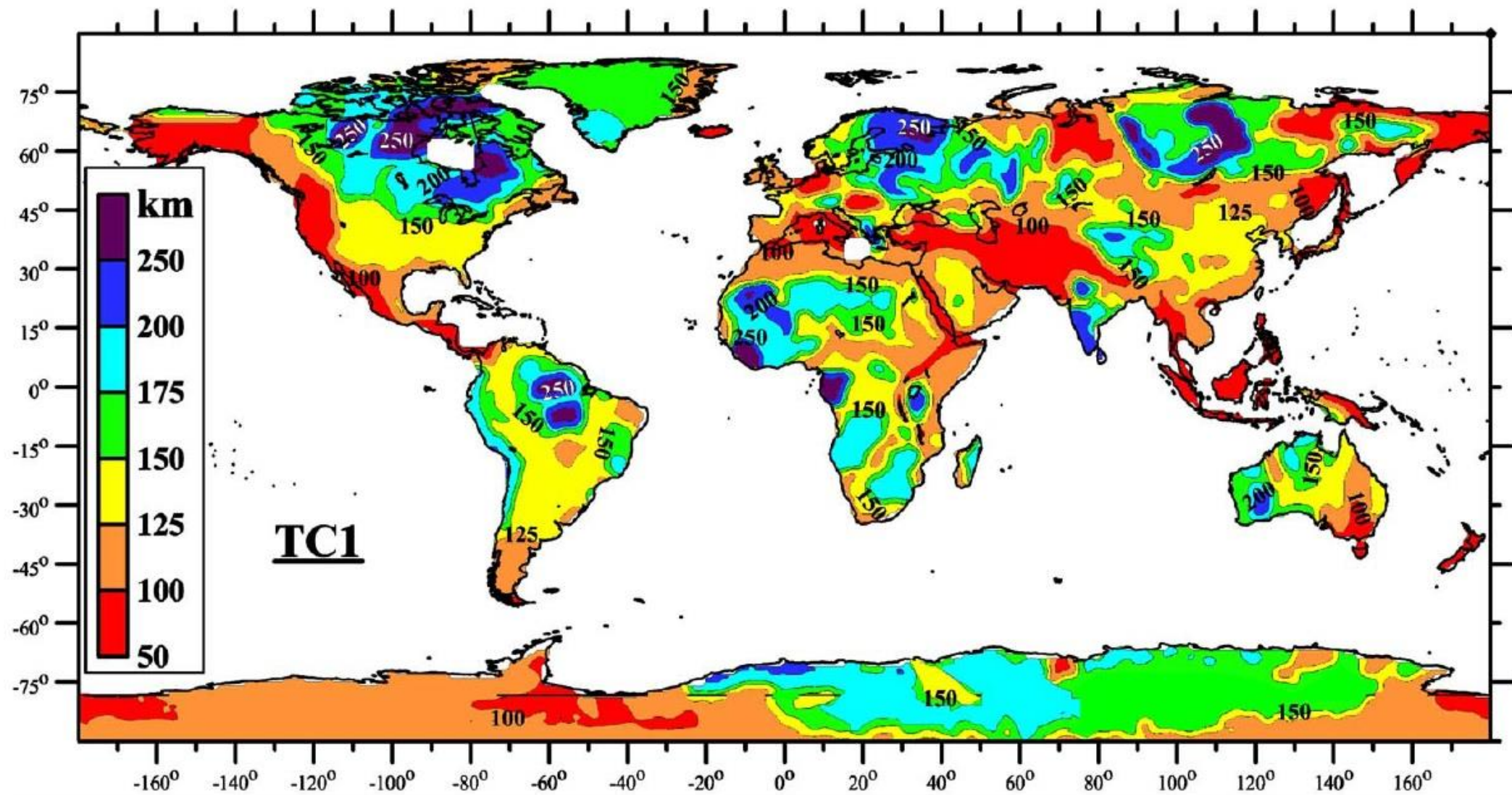


## Continental crustal type



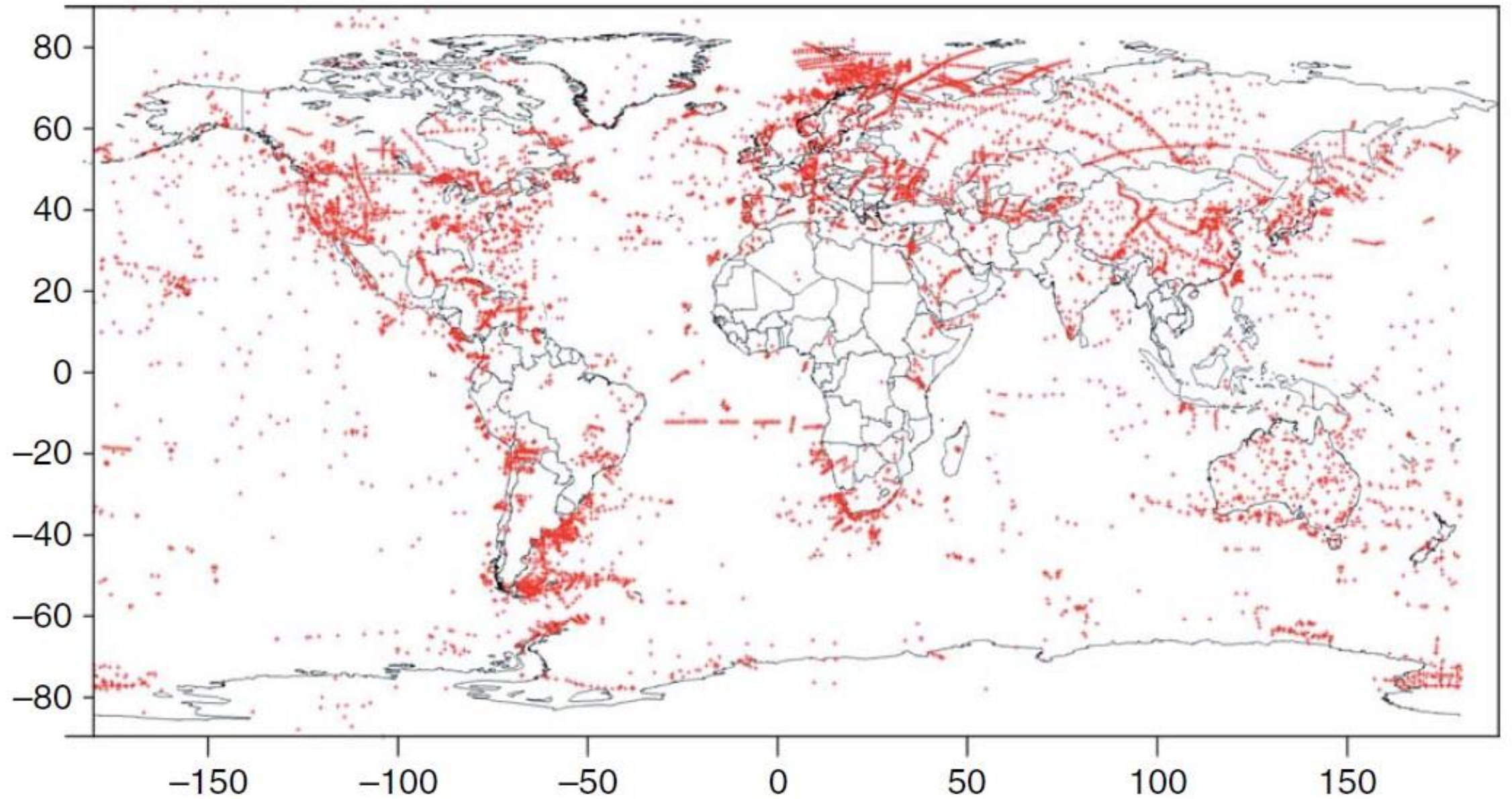


# Thickness of the thermal lithosphere



# Seismic-depth measurements (1920-present)

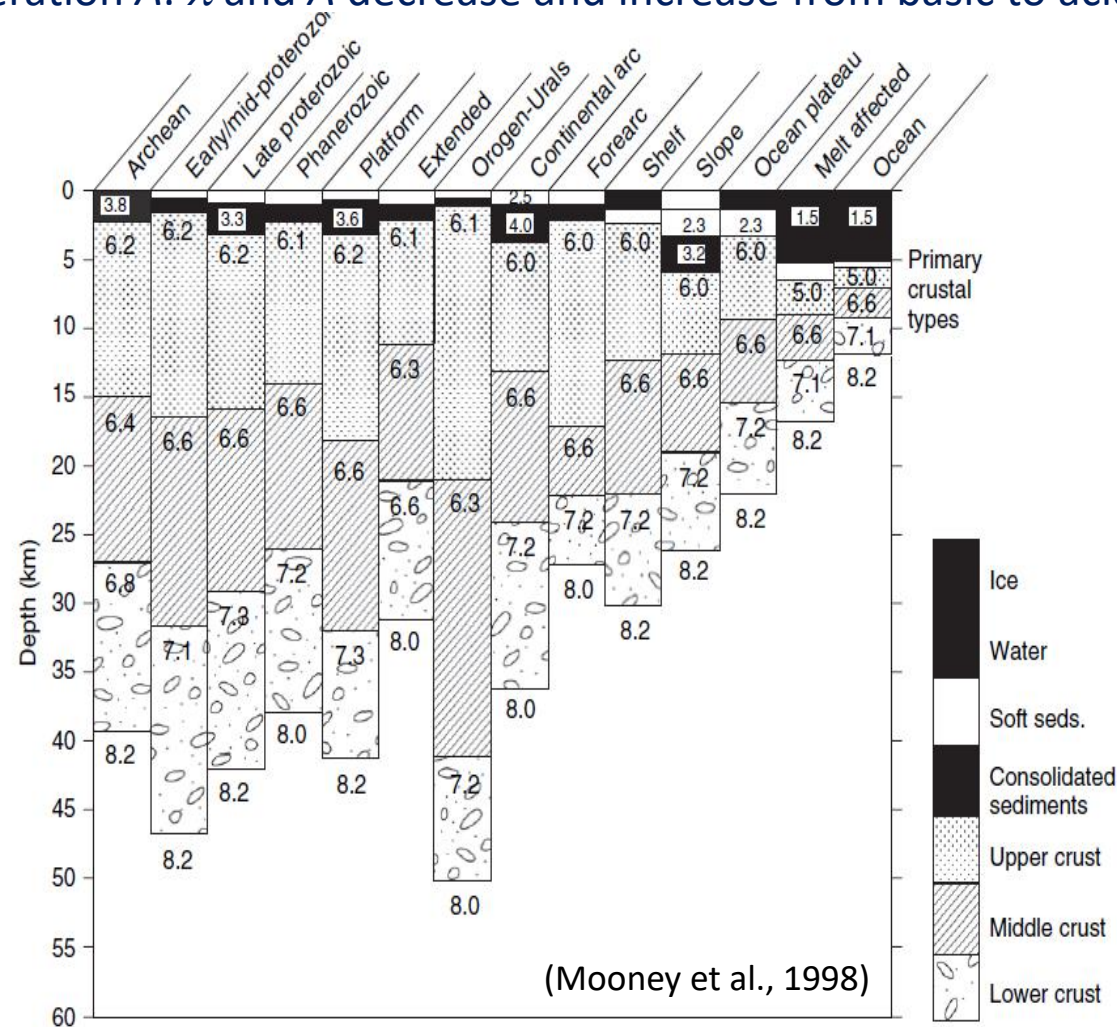
(USGS Database)





# Continental and Oceanic Crust

- The crust is the outer shell of the Earth (constitutes about 0.7% of the total mass of the crust–mantle system), involving the transfer of heat from the inner layers of the Earth and particularly from the mantle to the surface.
- Heat conduction occurring in the crust is extremely lithology dependent, since is due to (1) thermal conductivity  $\lambda$  and (2) heat generation  $A$ .  $\lambda$  and  $A$  decrease and increase from basic to acidic rocks, respectively.



Continental crust (weighted average values):

Thickness = 41 km (SD=6.2 km)

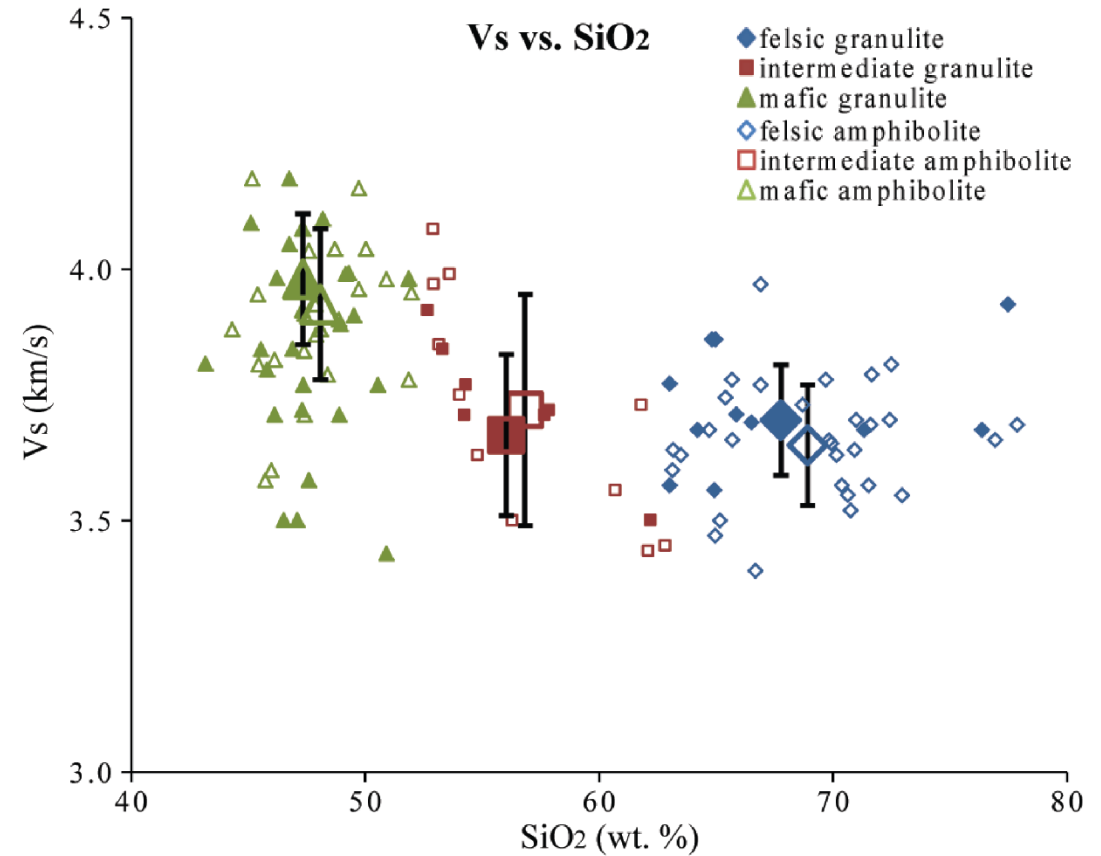
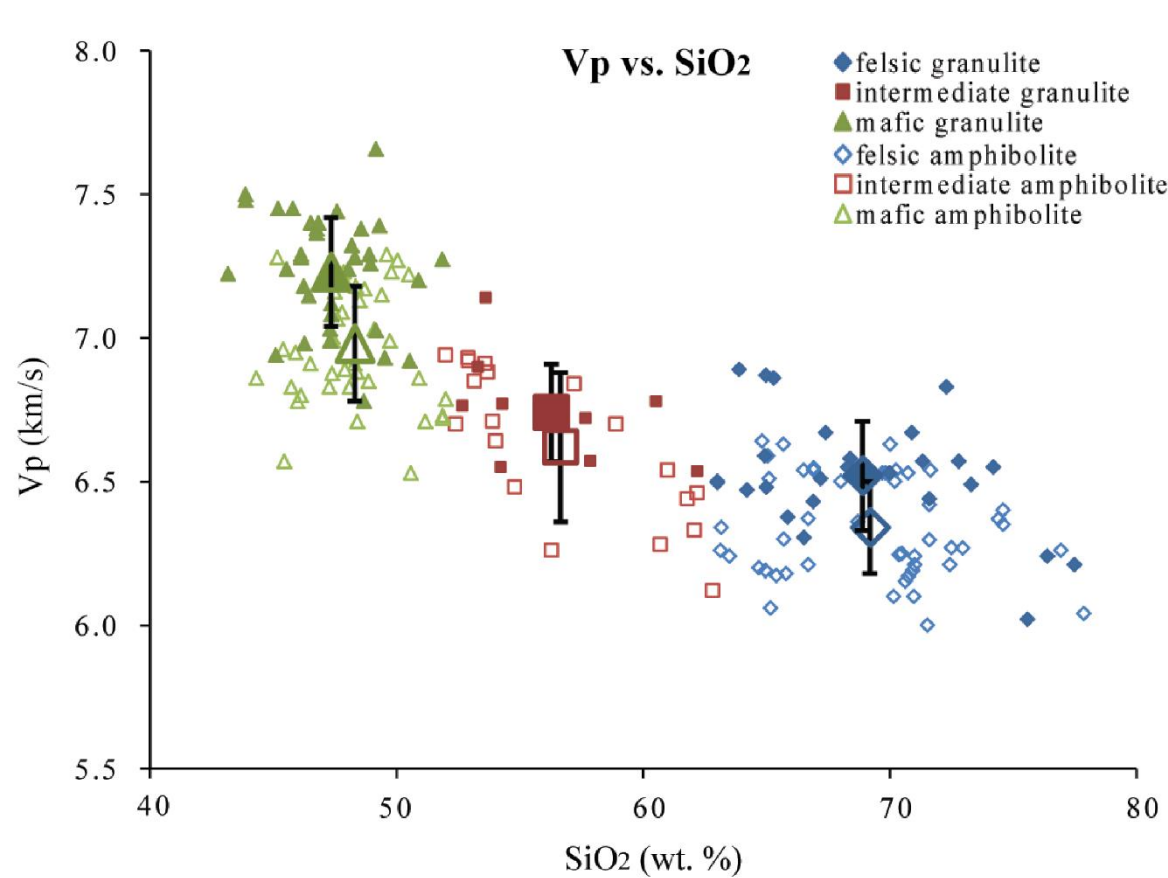
$V_p$ =6.45 km/s (SD=0.21 km/s)

Oceanic crust (average values):

Thickness = 6 km,  $\rho$ =3 g/cm<sup>3</sup>,

Age <=200 My

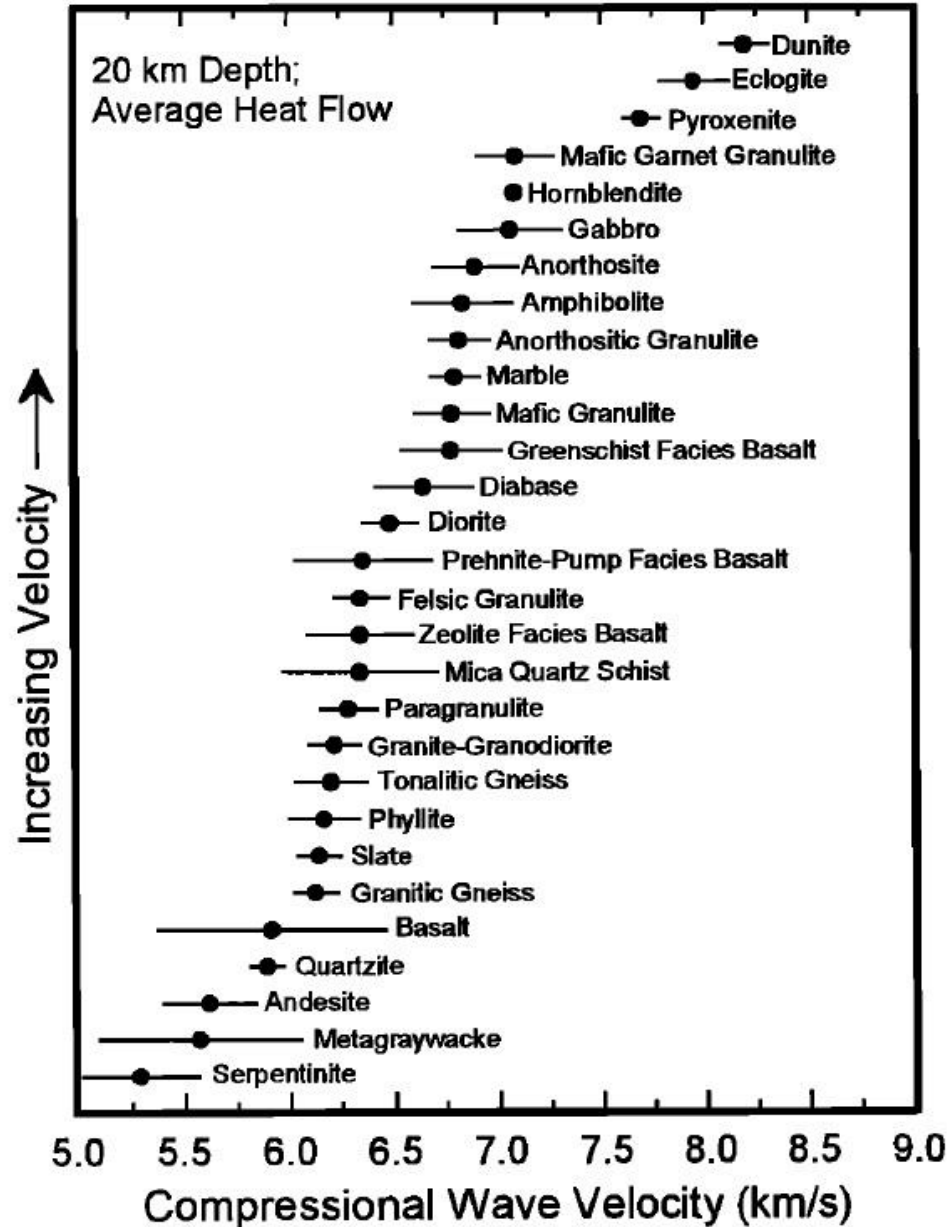
# ***P*-wave and *S*-wave velocity correlates with bulk composition**



*P*=0.6 GPa, room *T*

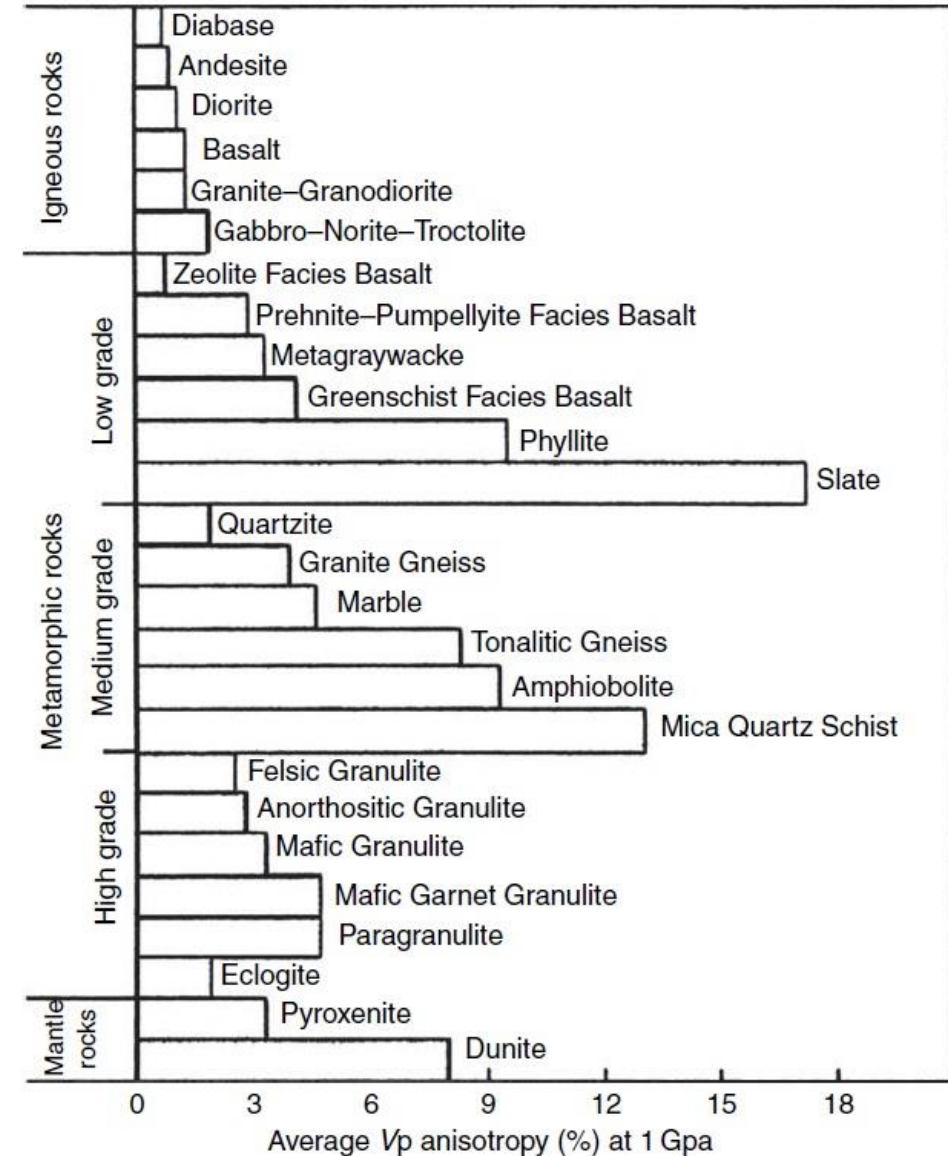
*Huang et al., 2013*

## Rocks' P-wave velocity



## Average Anisotropy $100x (V_{max}-V_{min})/V_{avg}$

Elastic waves show a directional dependence in wave speed in many minerals





# Rocks' Density vs *T* and *P*

Densities and Compressional Wave Velocities as Functions of Temperature and Depth

| Name                           |      | 5 km           |       |       |       |       | 10 km          |       |       |       |       | 15 km          |       |       |       |       | 20 km          |       |       |       |       | 25 km          |       |       |       |       |  |
|--------------------------------|------|----------------|-------|-------|-------|-------|----------------|-------|-------|-------|-------|----------------|-------|-------|-------|-------|----------------|-------|-------|-------|-------|----------------|-------|-------|-------|-------|--|
| Specimens (S)                  |      | ρ <sub>s</sub> | Room  | Low   | Avg   | High  | ρ <sub>s</sub> | Room  | Low   | Avg   | High  | ρ <sub>s</sub> | Room  | Low   | Avg   | High  | ρ <sub>s</sub> | Room  | Low   | Avg   | High  | ρ <sub>s</sub> | Room  | Low   | Avg   | High  |  |
| Rocks (R)                      |      | kg/m³          | 20°C  | 64°C  | 84°C  | 138°C | kg/m³          | 20°C  | 116°C | 157°C | 263°C | kg/m³          | 20°C  | 160°C | 225°C | 381°C | kg/m³          | 20°C  | 200°C | 309°C | 501°C | kg/m³          | 20°C  | 247°C | 389°C | 645°C |  |
| Andesite (AND)                 |      |                |       |       |       |       |                |       |       |       |       |                |       |       |       |       |                |       |       |       |       |                |       |       |       |       |  |
| S=30                           | Avg  | 2627           | 5.429 | 5.393 | 5.381 | 5.351 | 2630           | 5.627 | 5.561 | 5.538 | 5.477 | 2633           | 5.731 | 5.640 | 5.603 | 5.514 | 2635           | 5.800 | 5.686 | 5.623 | 5.514 | 2638           | 5.851 | 5.710 | 5.629 | 5.483 |  |
| R=10                           | S.D. | 71             | 0.280 | 0.280 | 0.280 | 0.280 | 70             | 0.239 | 0.239 | 0.239 | 0.239 | 70             | 0.227 | 0.227 | 0.227 | 0.227 | 70             | 0.224 | 0.224 | 0.224 | 0.224 | 69             | 0.224 | 0.224 | 0.224 | 0.224 |  |
| Basalt (BAS)                   |      |                |       |       |       |       |                |       |       |       |       |                |       |       |       |       |                |       |       |       |       |                |       |       |       |       |  |
| S=415                          | Avg  | 2878           | 5.877 | 5.852 | 5.845 | 5.823 | 2883           | 5.954 | 5.908 | 5.892 | 5.851 | 2889           | 6.003 | 5.940 | 5.915 | 5.854 | 2894           | 6.039 | 5.961 | 5.918 | 5.843 | 2899           | 6.067 | 5.971 | 5.915 | 5.815 |  |
| R=149                          | S.D. | 144            | 0.547 | 0.547 | 0.547 | 0.547 | 144            | 0.543 | 0.543 | 0.543 | 0.543 | 144            | 0.542 | 0.542 | 0.542 | 0.542 | 144            | 0.541 | 0.541 | 0.541 | 0.541 | 144            | 0.540 | 0.540 | 0.540 | 0.540 |  |
| Diabase (DIA)                  |      |                |       |       |       |       |                |       |       |       |       |                |       |       |       |       |                |       |       |       |       |                |       |       |       |       |  |
| S=54                           | Avg  | 2946           | 6.673 | 6.648 | 6.640 | 6.619 | 2952           | 6.719 | 6.674 | 6.658 | 6.617 | 2957           | 6.747 | 6.685 | 6.659 | 6.599 | 2962           | 6.765 | 6.687 | 6.645 | 6.570 | 2967           | 6.779 | 6.683 | 6.628 | 6.528 |  |
| R=18                           | S.D. | 85             | 0.253 | 0.253 | 0.253 | 0.253 | 85             | 0.245 | 0.245 | 0.245 | 0.245 | 85             | 0.239 | 0.239 | 0.239 | 0.239 | 85             | 0.235 | 0.235 | 0.235 | 0.235 | 85             | 0.232 | 0.232 | 0.232 | 0.232 |  |
| Granite-Granodiorite (GRA)     |      |                |       |       |       |       |                |       |       |       |       |                |       |       |       |       |                |       |       |       |       |                |       |       |       |       |  |
| S=134                          | Avg  | 2654           | 6.215 | 6.179 | 6.182 | 6.161 | 2661           | 6.287 | 6.221 | 6.226 | 6.184 | 2667           | 6.321 | 6.230 | 6.234 | 6.173 | 2673           | 6.344 | 6.230 | 6.224 | 6.149 | 2679           | 6.361 | 6.220 | 6.209 | 6.110 |  |
| R=52                           | S.D. | 24             | 0.135 | 0.135 | 0.135 | 0.135 | 24             | 0.125 | 0.125 | 0.125 | 0.125 | 24             | 0.124 | 0.124 | 0.124 | 0.124 | 24             | 0.124 | 0.124 | 0.124 | 0.124 | 24             | 0.125 | 0.125 | 0.125 | 0.125 |  |
| Diorite (DIO)                  |      |                |       |       |       |       |                |       |       |       |       |                |       |       |       |       |                |       |       |       |       |                |       |       |       |       |  |
| S=24                           | Avg  | 2810           | 6.443 | 6.418 | 6.410 | 6.389 | 2815           | 6.528 | 6.483 | 6.467 | 6.426 | 2820           | 6.575 | 6.513 | 6.487 | 6.427 | 2825           | 6.608 | 6.530 | 6.487 | 6.412 | 2831           | 6.633 | 6.536 | 6.481 | 6.381 |  |
| R=8                            | S.D. | 85             | 0.167 | 0.167 | 0.167 | 0.167 | 85             | 0.155 | 0.155 | 0.155 | 0.155 | 85             | 0.144 | 0.144 | 0.144 | 0.144 | 85             | 0.134 | 0.134 | 0.134 | 0.134 | 85             | 0.126 | 0.126 | 0.126 | 0.126 |  |
| Gabbro-Norite-Troctolite (GAB) |      |                |       |       |       |       |                |       |       |       |       |                |       |       |       |       |                |       |       |       |       |                |       |       |       |       |  |
| S=187                          | Avg  | 2966           | 7.096 | 7.060 | 7.048 | 7.018 | 2971           | 7.167 | 7.101 | 7.078 | 7.017 | 2975           | 7.210 | 7.118 | 7.081 | 6.992 | 2981           | 7.240 | 7.126 | 7.063 | 6.954 | 2985           | 7.262 | 7.122 | 7.041 | 6.895 |  |
| R=69                           | S.D. | 71             | 0.246 | 0.246 | 0.246 | 0.246 | 70             | 0.247 | 0.247 | 0.247 | 0.247 | 70             | 0.248 | 0.248 | 0.248 | 0.248 | 69             | 0.250 | 0.250 | 0.250 | 0.250 | 68             | 0.251 | 0.251 | 0.251 | 0.251 |  |
| Metagraywacke (MGW)            |      |                |       |       |       |       |                |       |       |       |       |                |       |       |       |       |                |       |       |       |       |                |       |       |       |       |  |
| S=87                           | Avg  | 2615           | 5.369 | 5.344 | 5.336 | 5.315 | 2621           | 5.522 | 5.477 | 5.461 | 5.420 | 2627           | 5.624 | 5.561 | 5.536 | 5.475 | 2632           | 5.701 | 5.623 | 5.580 | 5.505 | 2638           | 5.764 | 5.668 | 5.613 | 5.513 |  |
| R=29                           | S.D. | 112            | 0.615 | 0.615 | 0.615 | 0.615 | 112            | 0.564 | 0.564 | 0.564 | 0.564 | 112            | 0.519 | 0.519 | 0.519 | 0.519 | 112            | 0.479 | 0.479 | 0.479 | 0.479 | 112            | 0.443 | 0.443 | 0.443 | 0.443 |  |
| Slate (SLT)                    |      |                |       |       |       |       |                |       |       |       |       |                |       |       |       |       |                |       |       |       |       |                |       |       |       |       |  |
| S=30                           | Avg  | 2801           | 6.098 | 6.073 | 6.065 | 6.044 | 2807           | 6.172 | 6.127 | 6.111 | 6.070 | 2813           | 6.227 | 6.164 | 6.139 | 6.078 | 2818           | 6.268 | 6.190 | 6.148 | 6.073 | 2824           | 6.302 | 6.206 | 6.151 | 6.051 |  |
| R=10                           | S.D. | 28             | 0.131 | 0.131 | 0.131 | 0.131 | 28             | 0.124 | 0.124 | 0.124 | 0.124 | 28             | 0.117 | 0.117 | 0.117 | 0.117 | 28             | 0.110 | 0.110 | 0.110 | 0.110 | 28             | 0.103 | 0.103 | 0.103 | 0.103 |  |
| Phyllite (PHY)                 |      |                |       |       |       |       |                |       |       |       |       |                |       |       |       |       |                |       |       |       |       |                |       |       |       |       |  |
| S=144                          | Avg  | 2728           | 6.105 | 6.080 | 6.073 | 6.052 | 2734           | 6.210 | 6.164 | 6.148 | 6.107 | 2740           | 6.260 | 6.197 | 6.172 | 6.111 | 2745           | 6.292 | 6.214 | 6.171 | 6.096 | 2751           | 6.316 | 6.220 | 6.165 | 6.065 |  |
| R=48                           | S.D. | 58             | 0.258 | 0.258 | 0.258 | 0.258 | 58             | 0.206 | 0.206 | 0.206 | 0.206 | 58             | 0.183 | 0.183 | 0.183 | 0.183 | 58             | 0.168 | 0.168 | 0.168 | 0.168 | 58             | 0.158 | 0.158 | 0.158 | 0.158 |  |
| Zeolite Facies Basalt (BZE)    |      |                |       |       |       |       |                |       |       |       |       |                |       |       |       |       |                |       |       |       |       |                |       |       |       |       |  |
| S=57                           | Avg  | 2916           | 6.277 | 6.253 | 6.245 | 6.224 | 2922           | 6.368 | 6.323 | 6.307 | 6.266 | 2927           | 6.425 | 6.363 | 6.337 | 6.277 | 2932           | 6.465 | 6.387 | 6.344 | 6.269 | 2937           | 6.495 | 6.399 | 6.344 | 6.244 |  |
| R=19                           | S.D. | 81             | 0.269 | 0.269 | 0.269 | 0.269 | 81             | 0.261 | 0.261 | 0.261 | 0.261 | 81             | 0.257 | 0.257 | 0.257 | 0.257 | 81             | 0.254 | 0.254 | 0.254 | 0.254 | 81             | 0.252 | 0.252 | 0.252 | 0.252 |  |

# Rocks' Density vs $T$ and $P$

Variations in the density of minerals and rocks with  $T$  and  $P$  depend on the thermal expansion ( $\alpha$ ) and compressibility ( $\beta$ ):

$$\alpha = \frac{(\frac{\partial V}{\partial T})_P}{V_0} \quad \beta = -\frac{(\frac{\partial V}{\partial P})_T}{V_0} \quad \alpha = -\frac{1}{\rho} \frac{\partial \rho}{\partial T} \quad \beta = \frac{1}{\rho} \frac{\partial \rho}{\partial P} \quad \alpha \sim 3.5 \times 10^{-5} \text{ K}^{-1} \quad \frac{1}{K} = \frac{1}{\rho} \left( \frac{\partial \rho}{\partial P} \right)$$

$\beta \sim 10^{-11} \text{ Pa}^{-1}$   
 $K = \text{bulk modulus (1/\beta)}$

$$d\rho(T, P) = \left( \frac{\partial \rho}{\partial T} dT + \frac{\partial \rho}{\partial P} dP \right) = \rho(-\alpha dT + \beta dP) \Rightarrow d \ln \rho = \beta dP - \alpha dT$$

- Density decreases with increasing  $T$  and increases with increasing  $P$ .
- In cases of constant  $\alpha$  and  $\beta$ , integration of equations versus  $T$  and  $P$  gives:

$$\int_{\rho_0}^{\rho} d \ln \rho = \int_{P_0}^P \beta dP - \int_{T_0}^T \alpha dT \Rightarrow \rho = \rho_0 e^{\beta(P-P_0) - \alpha(T-T_0)}$$

$$\alpha_v = \frac{1}{V} \frac{\partial V}{\partial T} = \frac{1}{\frac{1}{\rho}} \frac{\partial \left( \frac{1}{\rho} \right)}{\partial T} = \rho \frac{\partial (\rho^{-1})}{\partial T} = -\frac{\rho}{\rho^2} \frac{\partial \rho}{\partial T} = -\frac{1}{\rho} \frac{\partial \rho}{\partial T} = -\frac{\partial \ln(\rho)}{\partial T}$$

$\rho_0$  = density of a given material at *reference* pressure  $P_0$  ( $10^5 \text{ Pa} = 1 \text{ bar}$ ) and temperature  $T_0$  (typically  $298.15 \text{ K} = 25^\circ \text{C}$ ).

Since both  $\alpha(T - T_0)$  and  $\beta(P - P_0)$  are typically very small, the equations can be simplified, using the rules that  $e^a \approx 1 + a$  and  $e^{-a} \approx 1 - a$  when  $a \ll 1$ ):

$$\rho = \rho_0 [1 + \beta(P - P_0)] \times [1 - \alpha(T - T_0)] \quad \text{or} \quad \rho(P, T) = \rho(P_0, T_0) \left[ 1 - \alpha_0(T - T_0) + \frac{(P - P_0)}{K} \right]$$

The equation is based on the assumption that  $\alpha$  and  $\beta$  remain constant with  $P$  and  $T$

# Heat transfer in the crust

**At the present-day the crust is the layer of the Earth that**

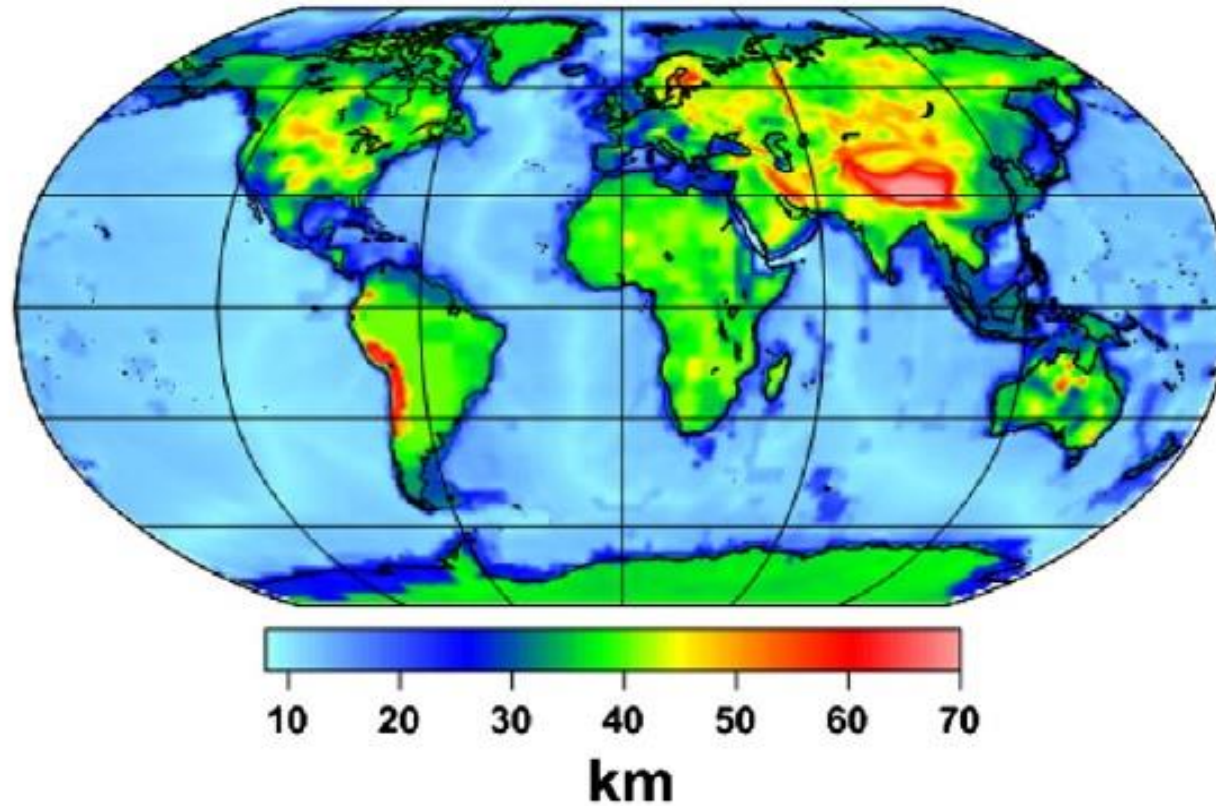
- (1) has an open surface for heat radiation and heat convection within the atmosphere and ocean.
  - (2) has sedimentary layer for heat convection by fluids within sediments.
  - (3) has direct contact with such cooling agents as the atmosphere and ocean.
  - (4) has the highest geothermal gradient, which gives importance to the heat transfer by conduction.
  - (5) has open faults and fracture systems for fluid and heat convection within the sediments.
- **During the Hadean and Early Archean the most effective kinds of heat transfer were: heat radiation from the surface of magma-ocean and convection within its layers, radiation by hot thick atmosphere and convection within it.**
  - **The geothermal gradient was too low (about  $0.3 \text{ K km}^{-1}$ ) to make effective heat transfer by conduction.**
  - **The role of mass transfer by magmatic activity is increased with time (max in the Mesozoic), together with the iron content in magmas and average density of the lithosphere, which favored the conditions for the subduction process.**

| Age         | Iron content of regular magmas as FeO total    | Iron content of Fe-rich magmas as FeO total | Rate of magmatism in LIP, $\text{km}^2/100 \text{ M.y.}$ |
|-------------|--|---|--|
| Archean     | $<10.00\text{--}11.00^{\text{a}}$ (7.57–12.72) | 13.33–17.73                                 | $136,514^{\text{b}}$ (34,129)                            |
| Proterozoic | $11.00\text{--}12.00^{\text{a}}$ (8.06–14.60)  | 13.58–21.10                                 | 961,578  |
| Paleozoic   | $11.00\text{--}12.00^{\text{a}}$ (8.42–16.13)  | 13.41–23.30                                 | 3,014,130  |
| Mesozoic    | $>12.00^{\text{a}}$ (9.17–15.98)               | 16.03–25.92                                 | 12,530,055   |
| Cenozoic    | $12.25\text{--}14.00^{\text{a}}$ (9.25–15.90)  | 16.00–23.70                                 | 8,098,462  |

<sup>a</sup> Estimated average iron content

<sup>b</sup> the rate in brackets is for the whole Archean eon

## Moho Depth



Tesauro et al., 2012, Global and Planetary Change, 90-91

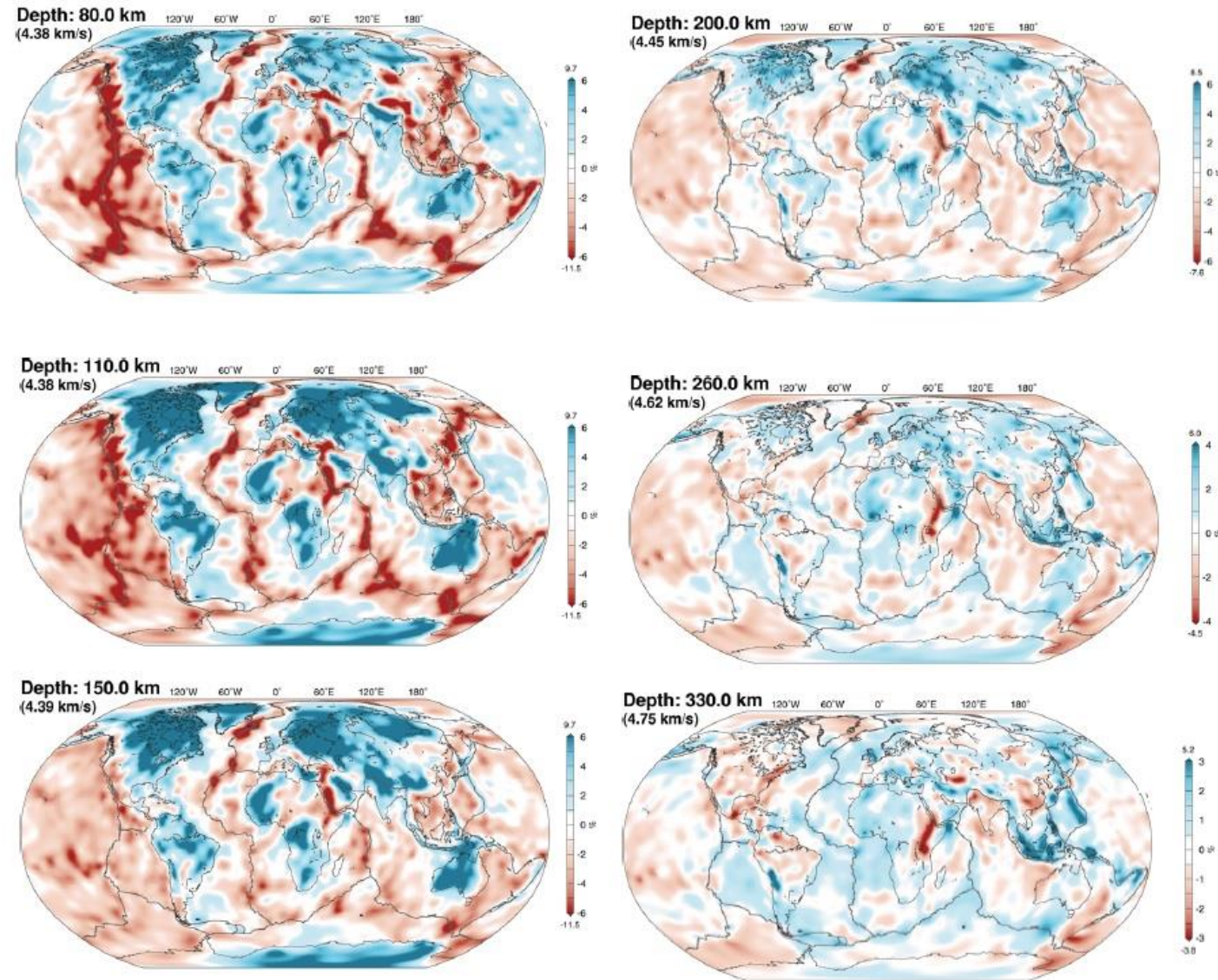
- Moho temperature in the continental areas depends on age, tectonic activity, thermal regime and the thickness of the crust.
- At a depth of ~40 km, Moho temperatures vary from 300-450 °C beneath the cratons, to about 800-1100 °C in thermally active areas (e.g., rift areas).



# Upper mantle velocities

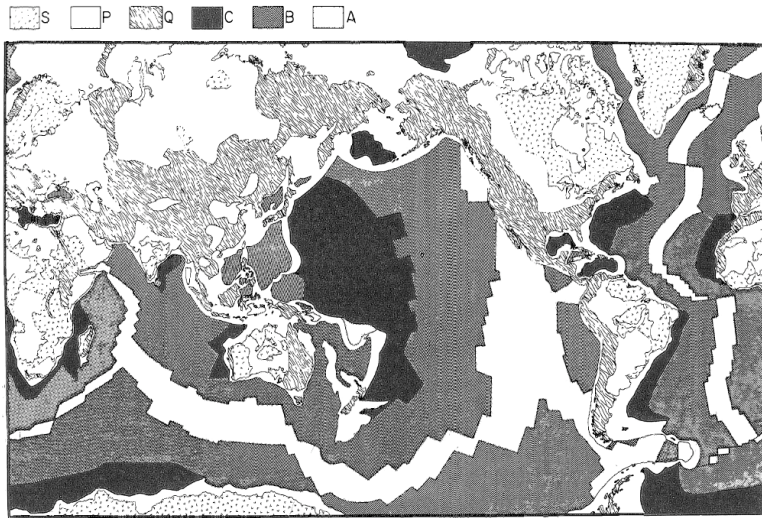
Seismic wave velocity is mainly a function of temperature:

Warm → slower  
Cold → faster



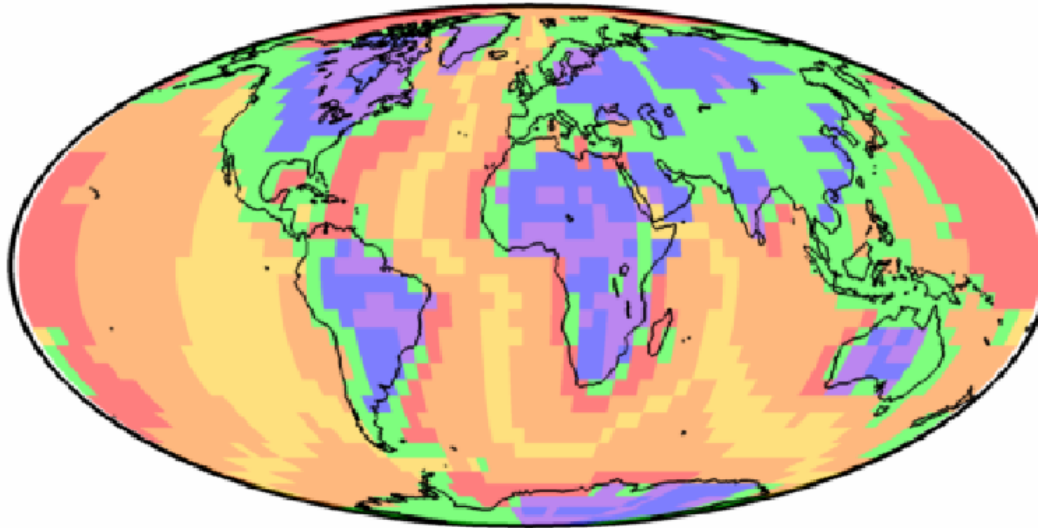


# Global Tectonic Regionalization



## GRT1 (Jordan, 1981)

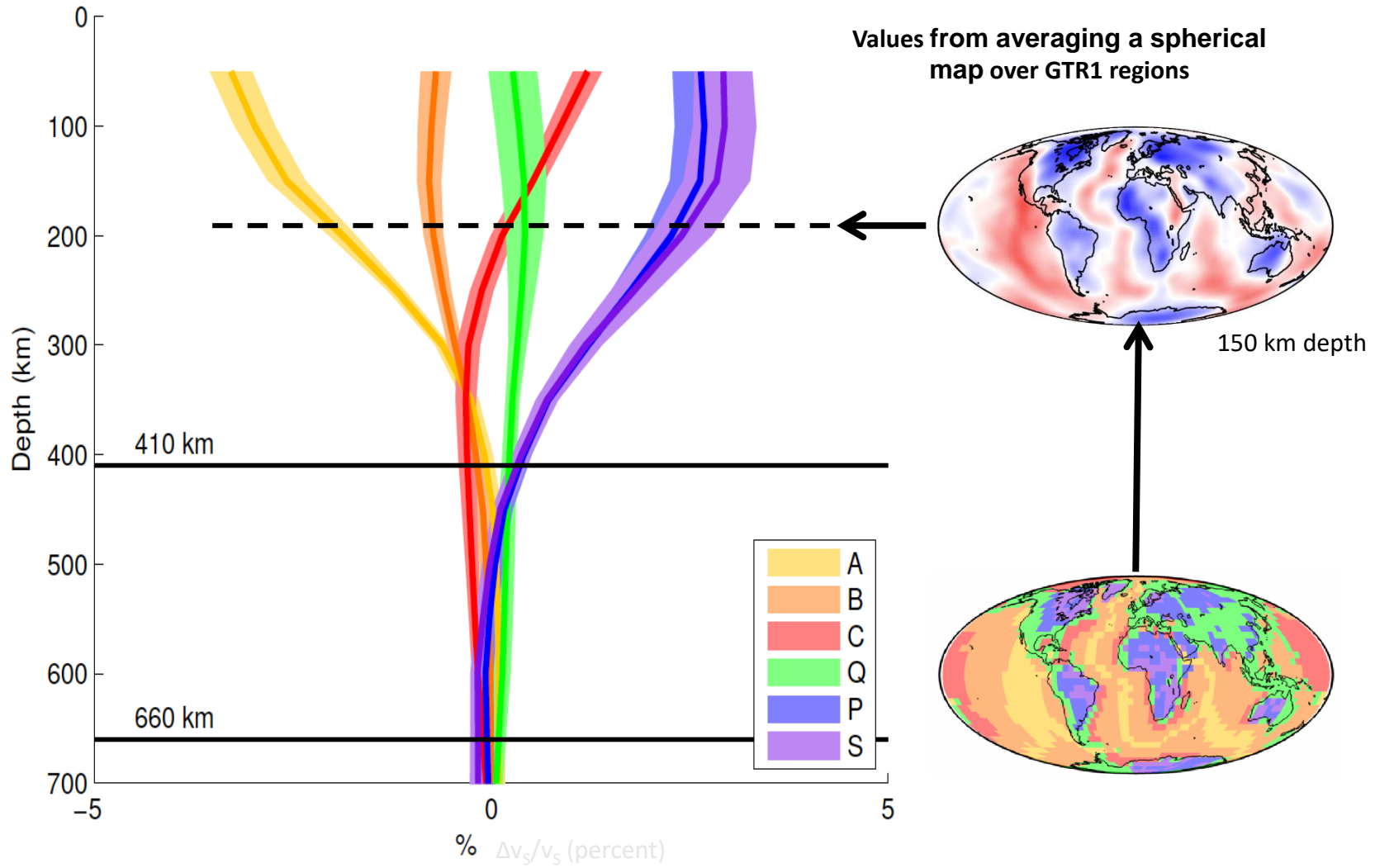
- Three oceanic regions **A**, **B**, **C**
  - based on lithospheric age
- Three continental regions **Q**, **P**, **S**
  - based on generalized tectonic behavior during the Phanerozoic



**Precambrian Platform**  
**Precambrian Shield**

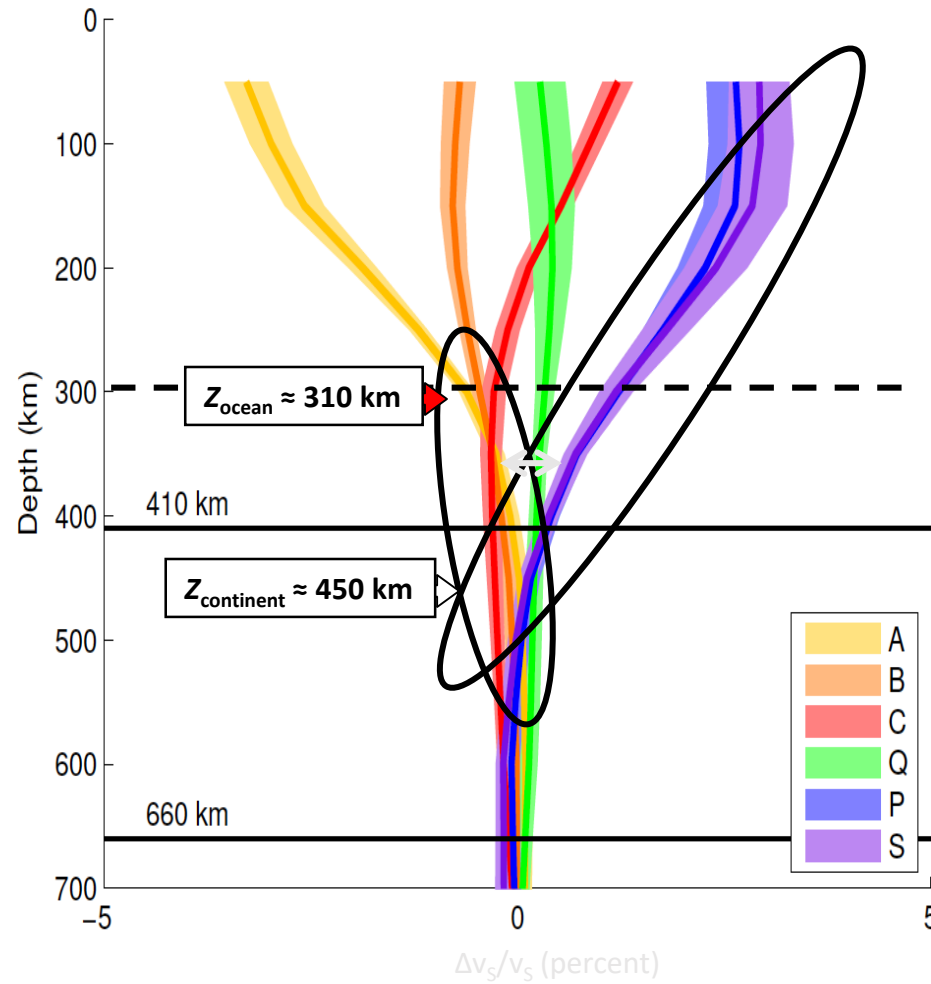
- A- Young Oceans
- B- Intermediate Oceans
- C- Old Oceans
- Q- Phanerozoic Orogenic Zones and Magmatic Belts
- P - Precambrian Platform
- S- Precambrian Shields and Platforms

# Regional average seismic velocity



**Model TX208 (Simmons et al., 2009)**

# Regional average seismic velocity



## Common Features:

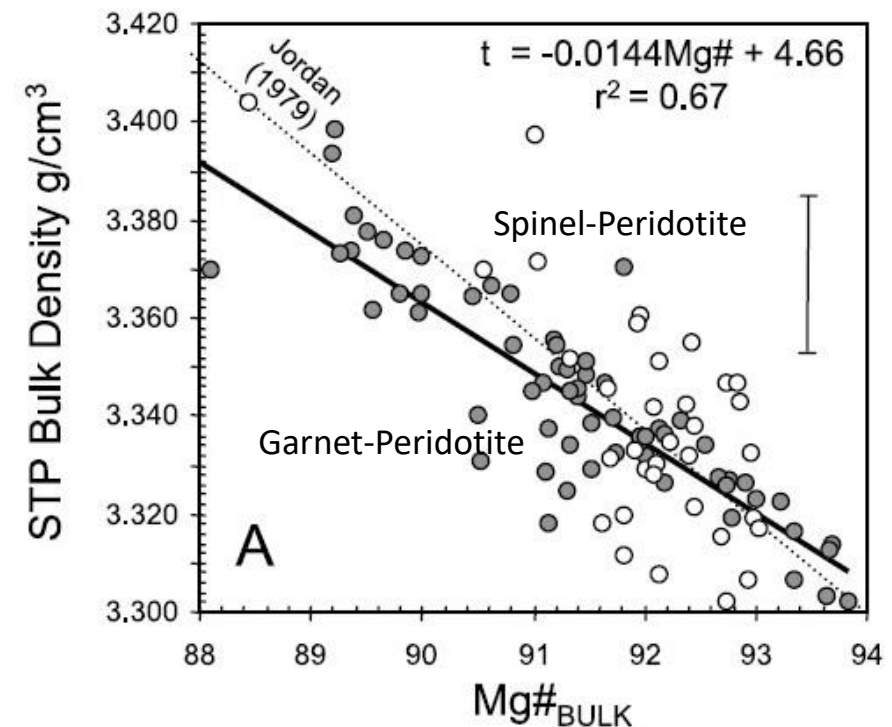
1. Platform and shield regions (P, S) show similar variations at all mantle depths
2. Ocean regions (A, B, C) show similar variations below 250-300 km
3. Differences between stable continents and oceans persist below 300 km

Model TX2008 (Simmons et al., 2009)

# Thickness and composition of the cratonic lithosphere

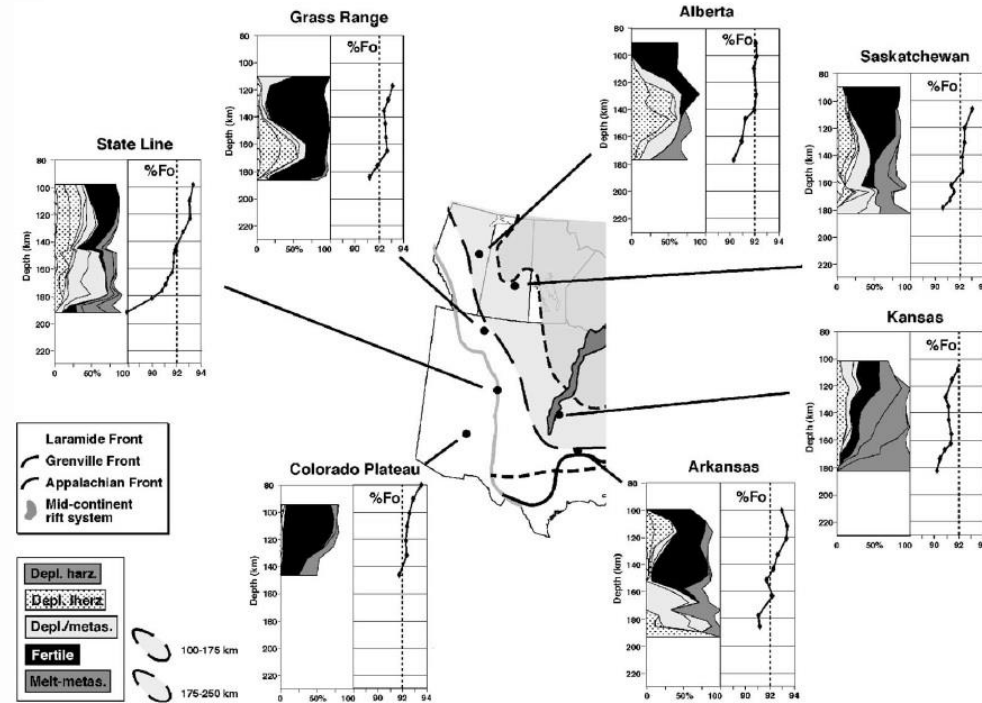
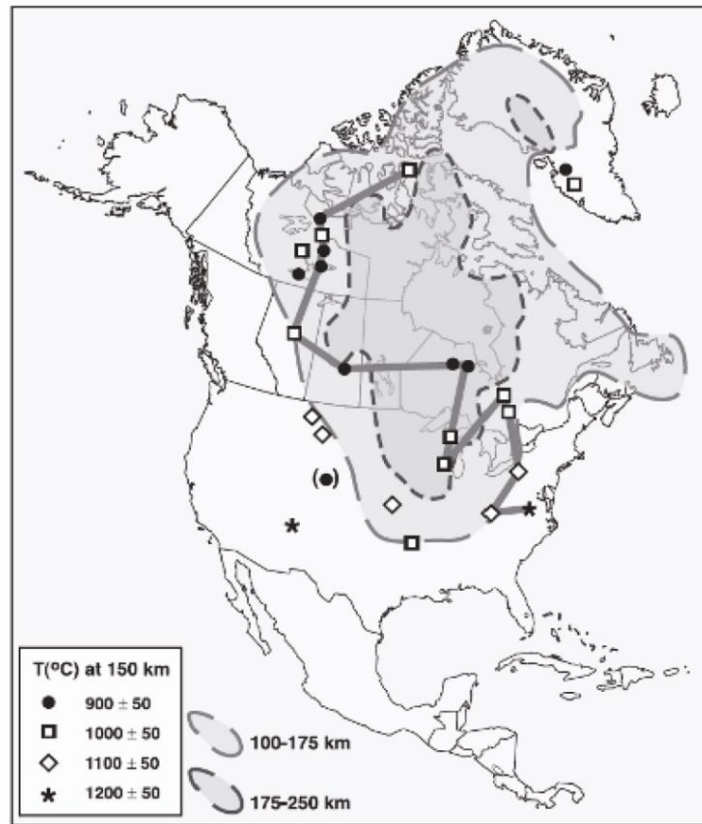
- The thickness of the lithosphere increases in general with increases in age of the lithosphere and those younger magmatic rocks are usually richer in *Fe* than older rocks, because they erupted from greater depths.
- The melting point of rocks decreases with depth according to the increase of *Fe* content, as a result of the stratification of the magma-ocean. Then, the formation of partial melt should increase with depth below the forsterite layer.
- Peridotitic komatiites are restricted to the oldest cratons and were formed only in the Early Archean (~3.3 Ga) at temperatures ~2073 K, very close to the melting point of forsterite. These Mg-rich rocks, depleted in incompatible elements, had a very low density and were formed just below the forsterite layer, when the layers above had already solidified.

| Fo#               | Melting point (in K) at 4 GPa |
|-------------------|-------------------------------|
| Fo <sub>100</sub> | 2,339                         |
| Fo <sub>90</sub>  | 2,271                         |
| Fo <sub>80</sub>  | 2,204                         |
| Fo <sub>70</sub>  | 2,136                         |
| Fo <sub>60</sub>  | 2,069                         |
| Fo <sub>50</sub>  | 2,002                         |
| Fo <sub>40</sub>  | 1,934                         |
| Fo <sub>30</sub>  | 1,867                         |
| Fo <sub>20</sub>  | 1,800                         |
| Fo <sub>10</sub>  | 1,733                         |
| Fo <sub>0</sub>   | 1,666                         |

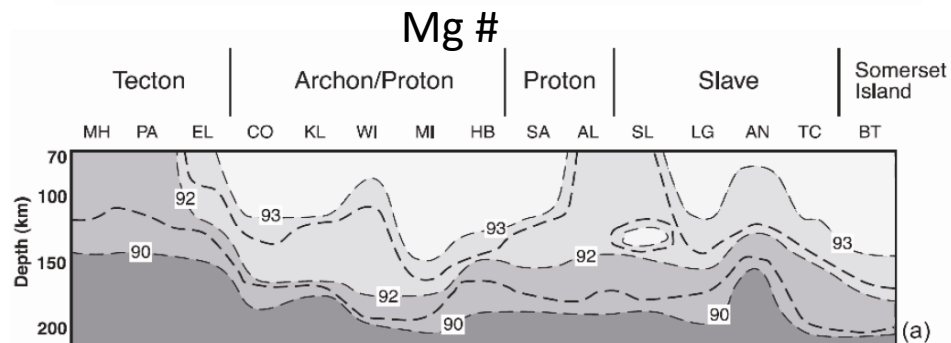


# Thickness and composition of the cratonic lithosphere

The lithosphere is *Fe* depleted up to a depth of 100-150 km



Griffin et al., 2003, Precambrian Research, 127





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## Main Readings:

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