



# La struttura della Terra: metodi geologici, fisici e chimici di investigazione

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*Perché studiare  
la nostra Terra?*



*Our Earth is beautiful!*

# *Geologia attorno noi...*

# Exploding volcanoes....



# Lava.....



# Ancient ocean floors.....



# Folded mountains.....



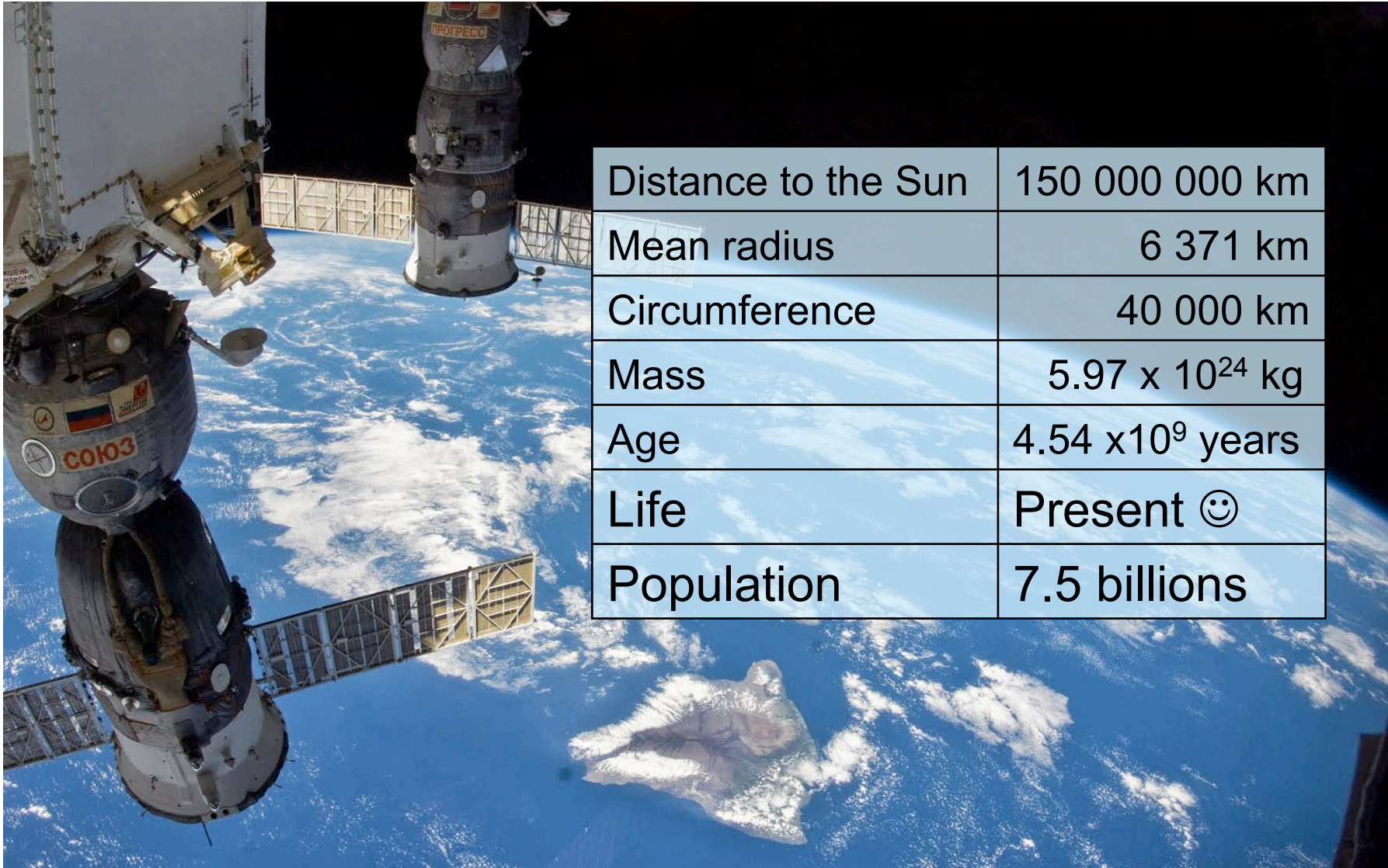


# Earthquakes.....

Amatrice 2016

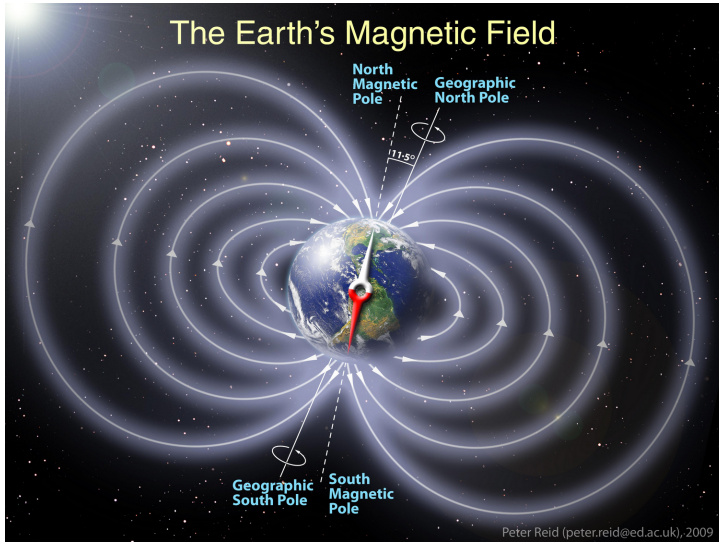


*Cosa sappiamo  
della nostra Terra?*



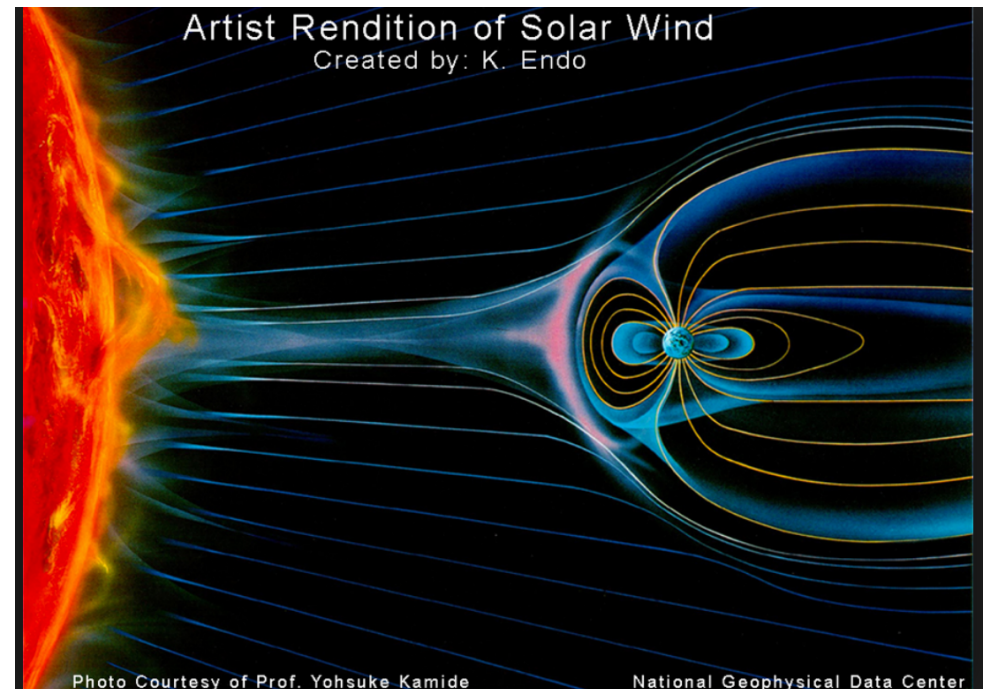
Distance to the Sun	150 000 000 km
Mean radius	6 371 km
Circumference	40 000 km
Mass	$5.97 \times 10^{24}$ kg
Age	$4.54 \times 10^9$ years
Life	Present 😊
Population	7.5 billions

# Earth magnetic field



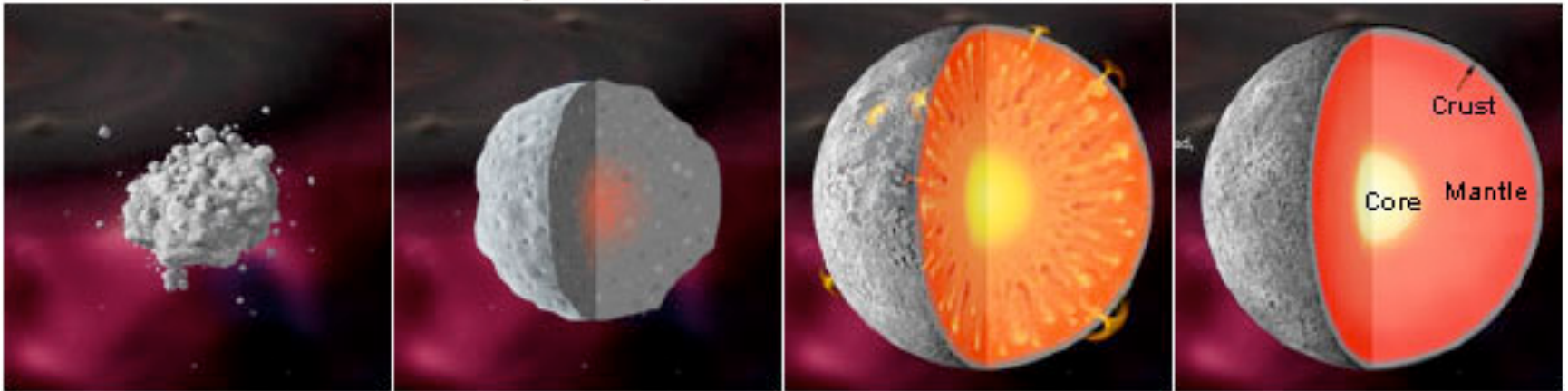
**Protection against cosmic radiation!!!**

**Life on Earth  
would be not possible without it!**



# Earth formation

## *A Rocky Body Forms and Differentiates*



(From Smithsonian National Museum of Natural History - [http://www.mnh.si.edu/earth/text/5\\_1\\_4\\_0.html](http://www.mnh.si.edu/earth/text/5_1_4_0.html))

**Accretion**

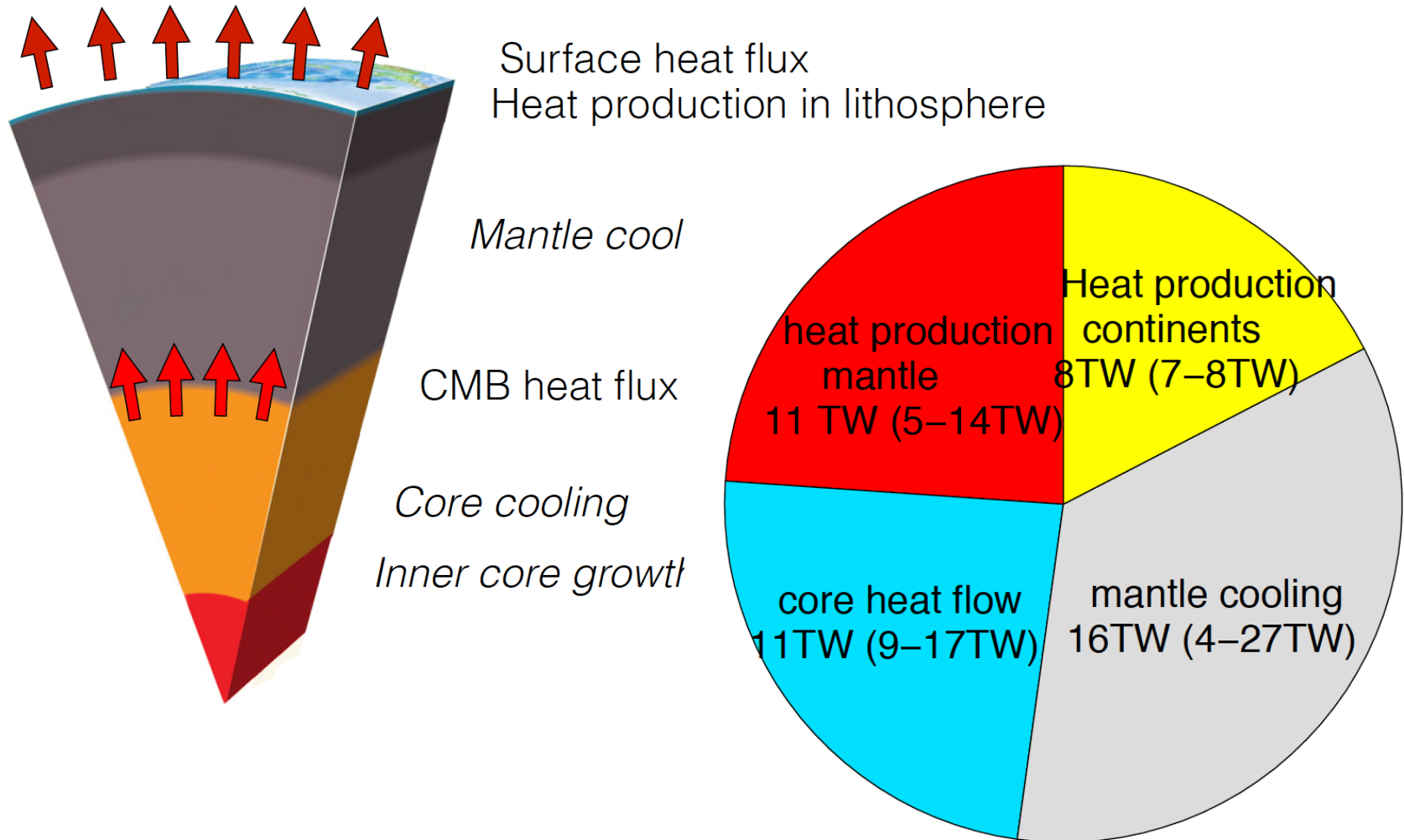
**Magma sea  
(Primitive mantle)**

**Mantle-crust  
differentiation**

**Metallic core  
segregation**

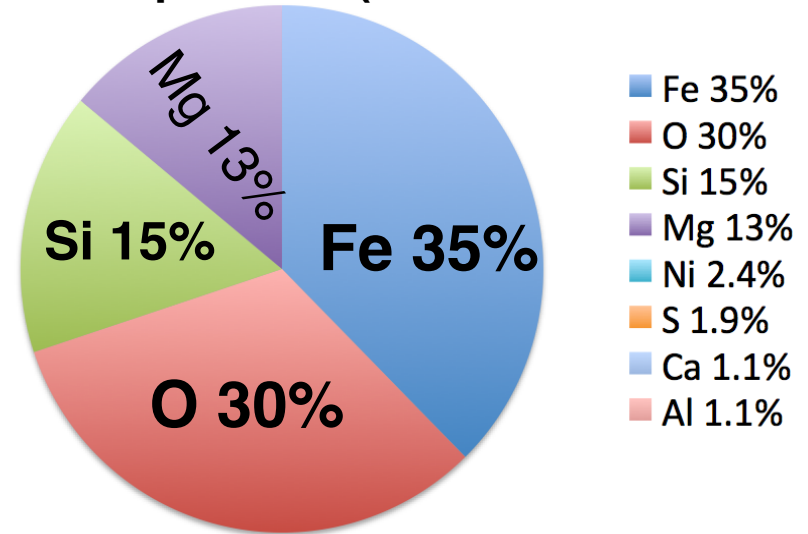
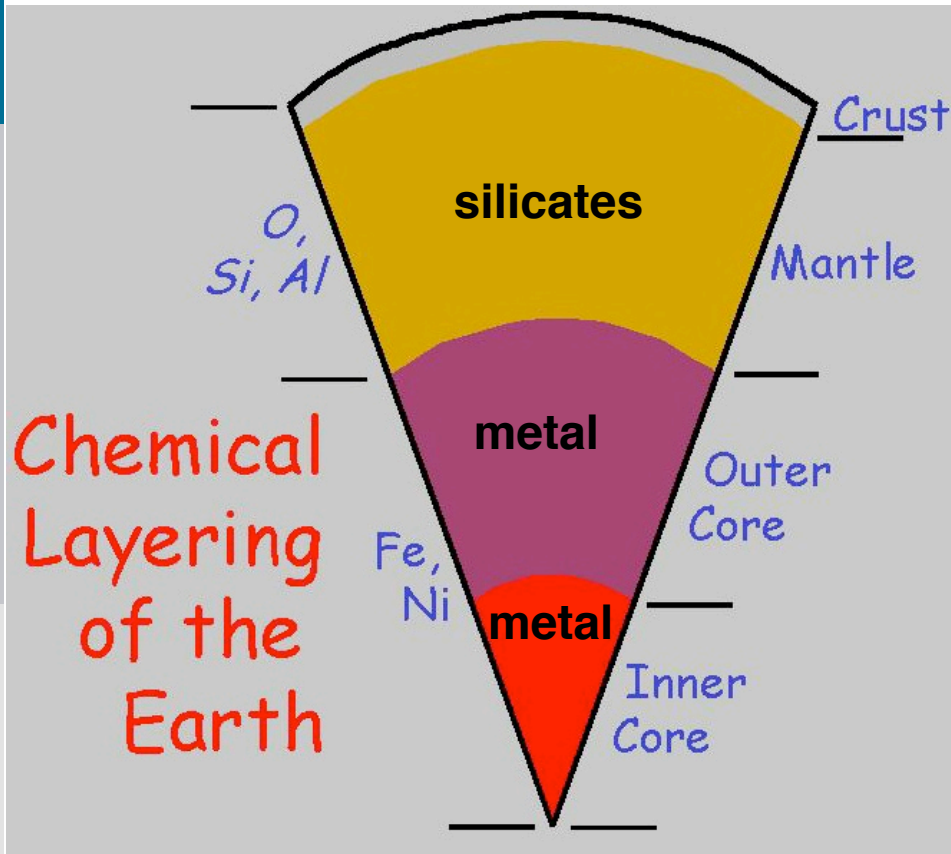
# Earth heat budget

Surface heat flux:  $47 \pm 3$  TW

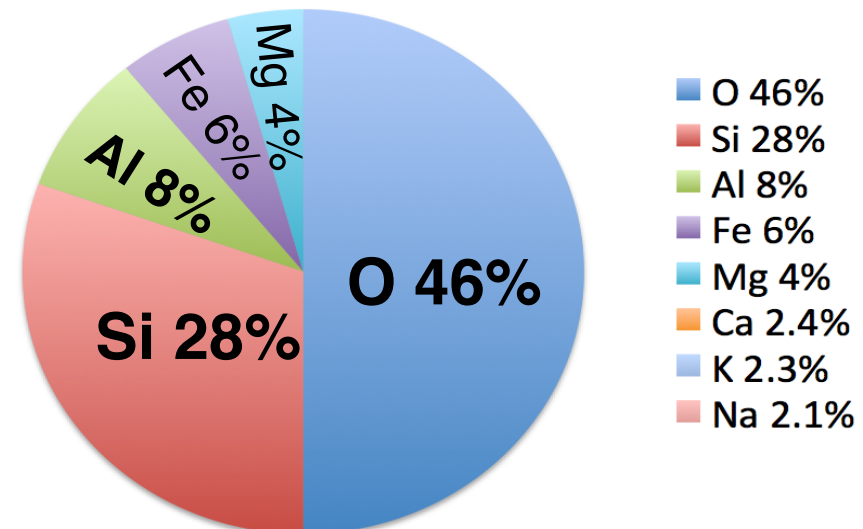


# Earth chemical composition

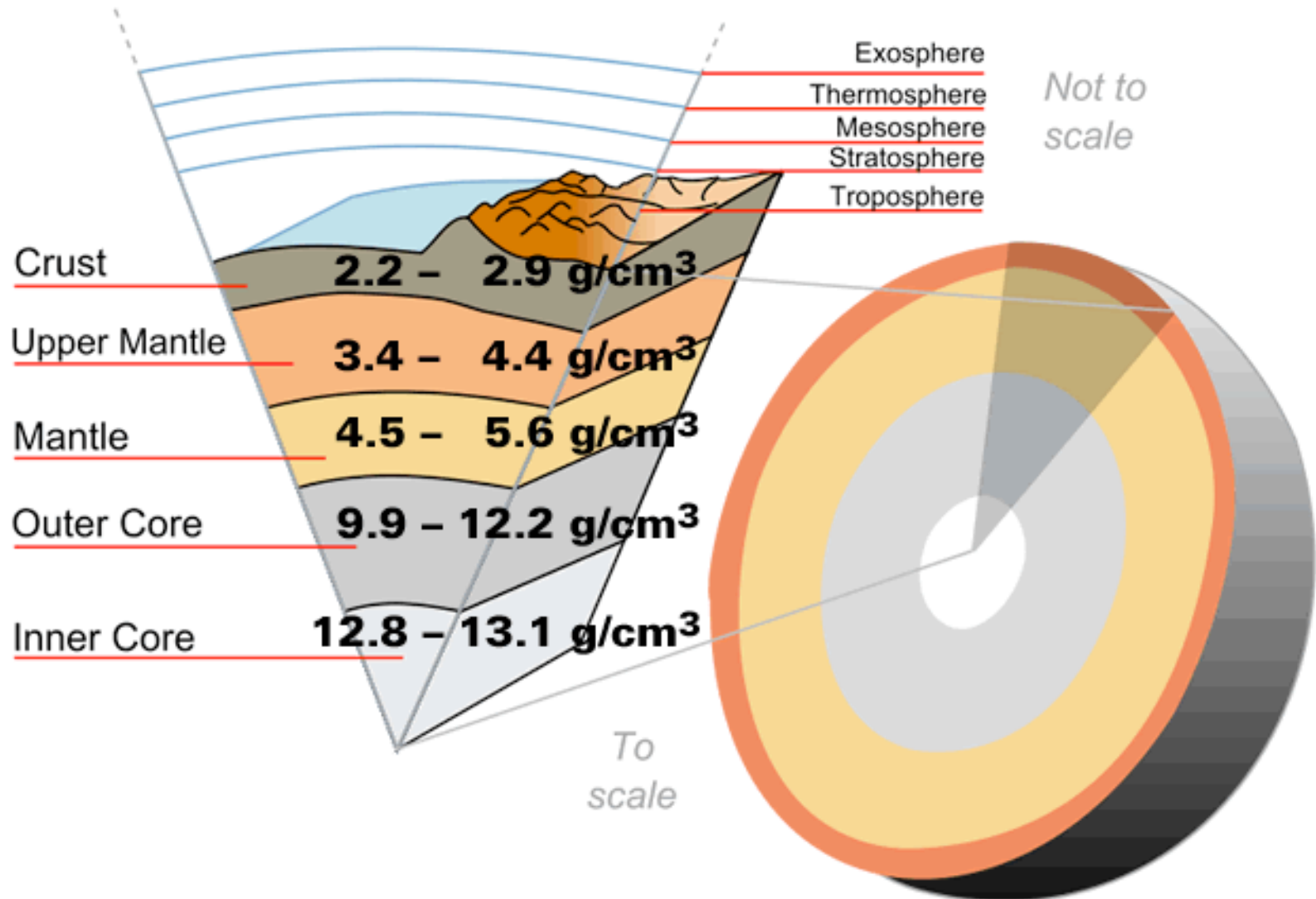
## Global composition (core + mantle + crust)



## Crustal composition

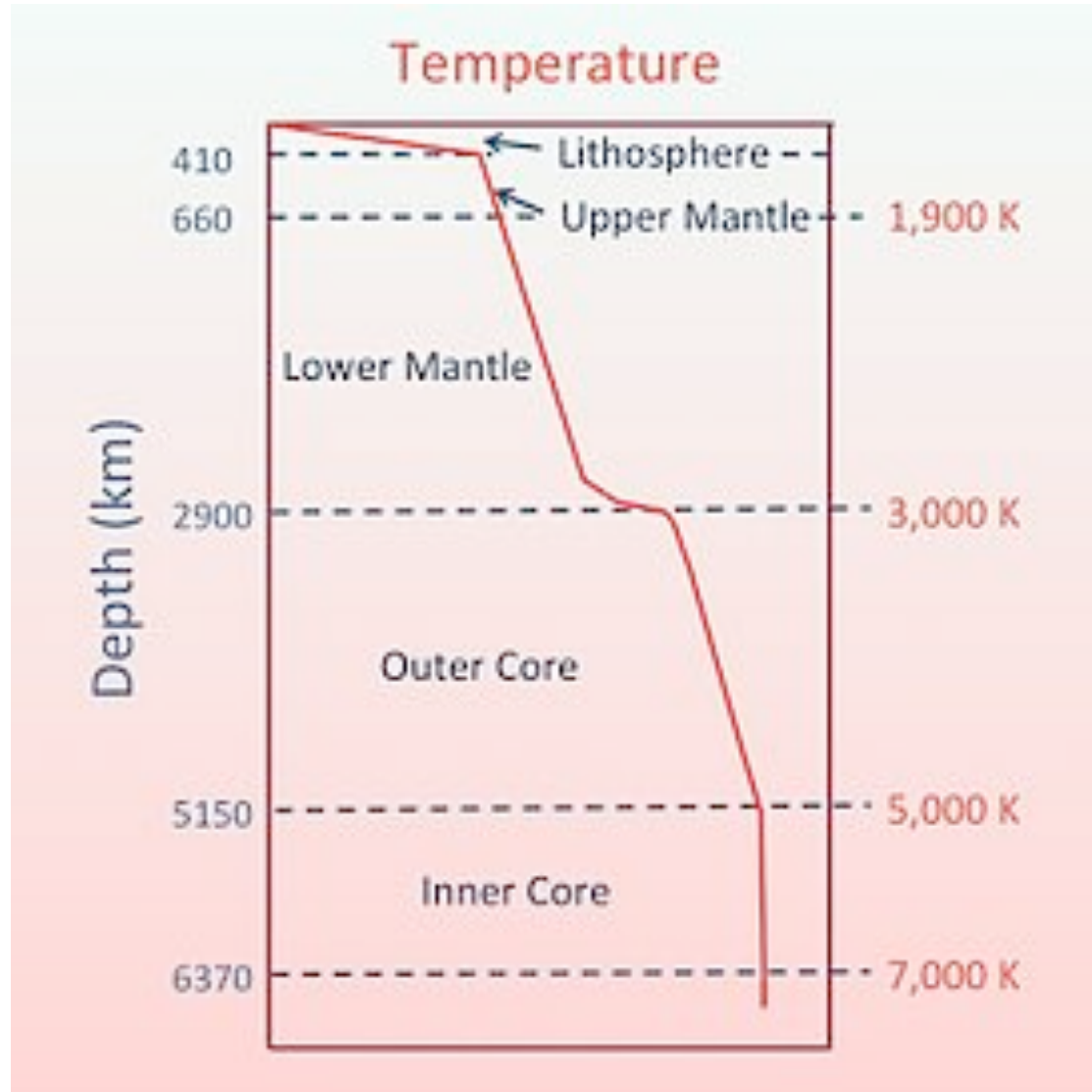


# Earth density

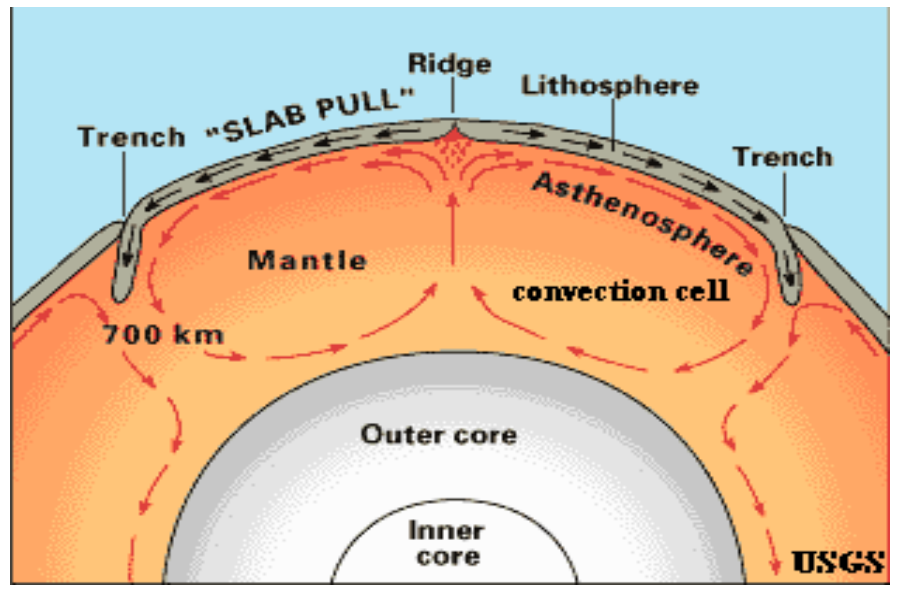
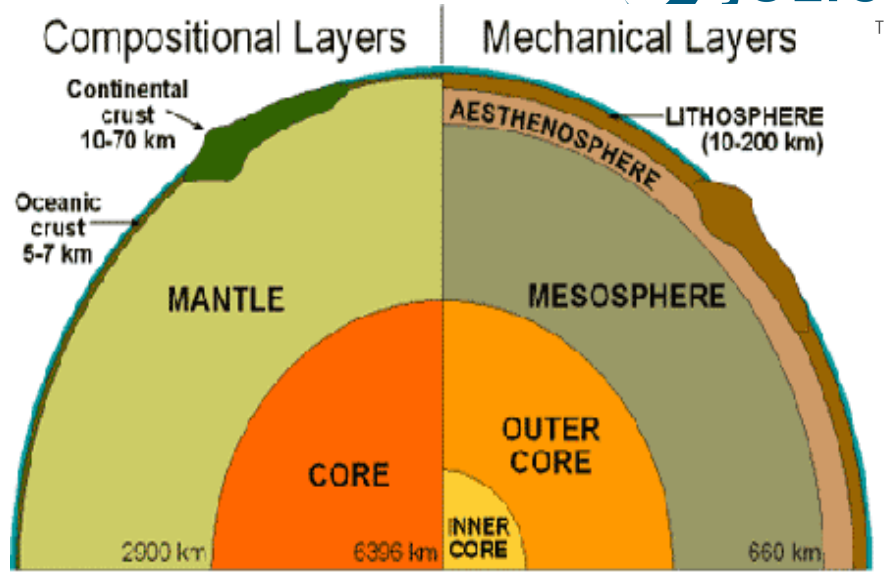
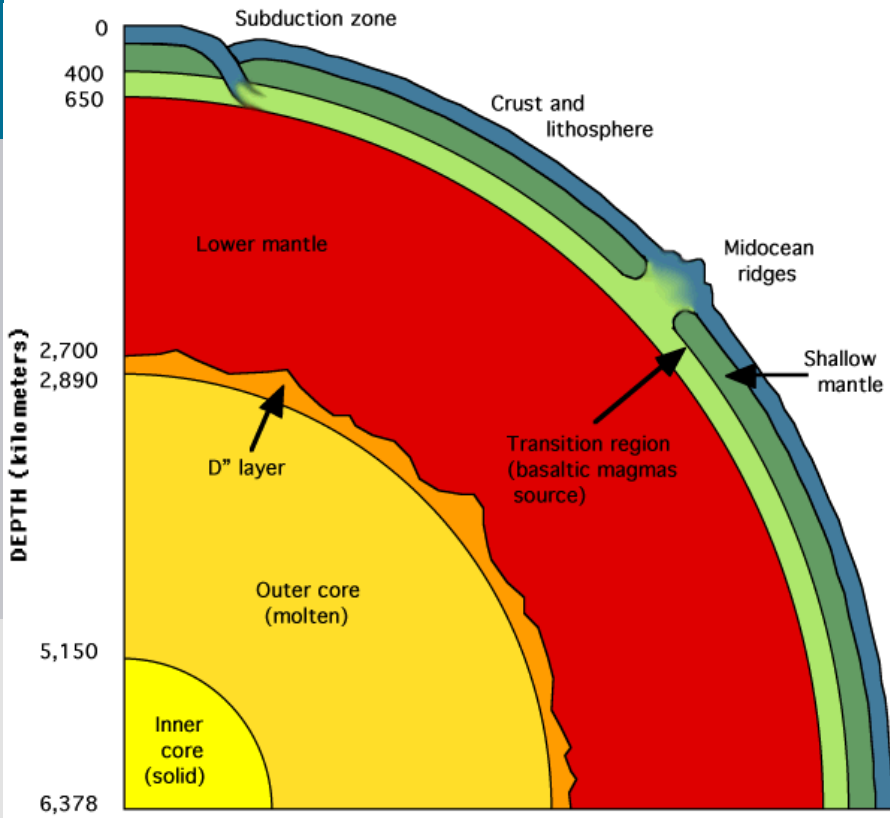




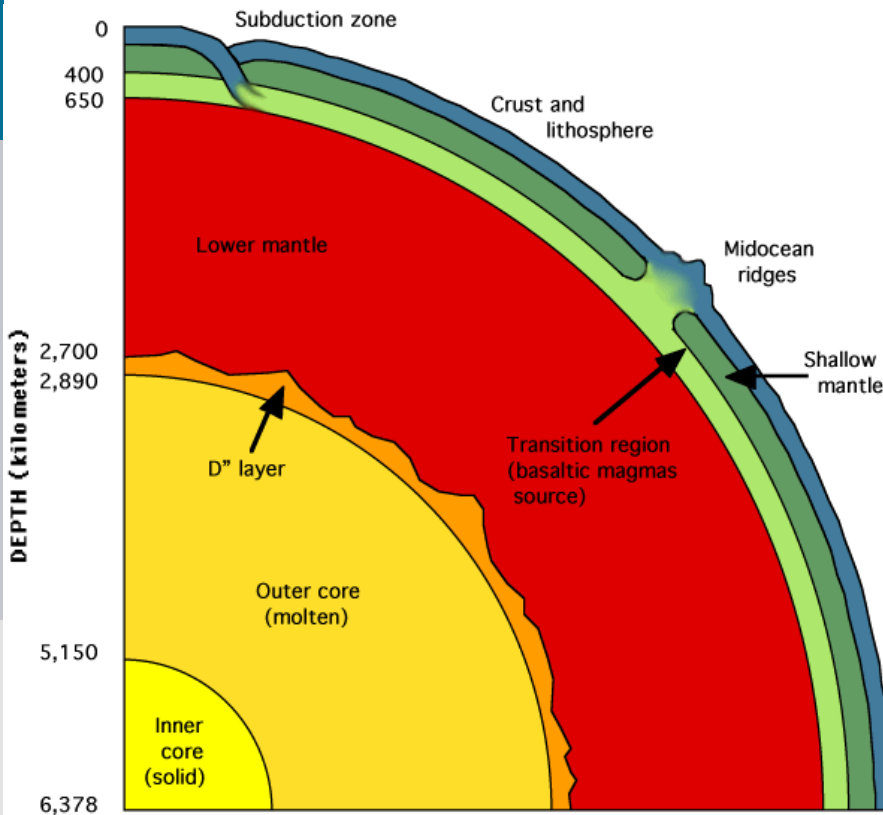
# Earth temperature



# Earth structure



# Earth structure



## Inner Core - SOLID

- about the size of the Moon;
- Fe – Ni alloy;
- **solid** (high pressure ~ 330 GPa);
- temperature ~ 6000-7000 K;

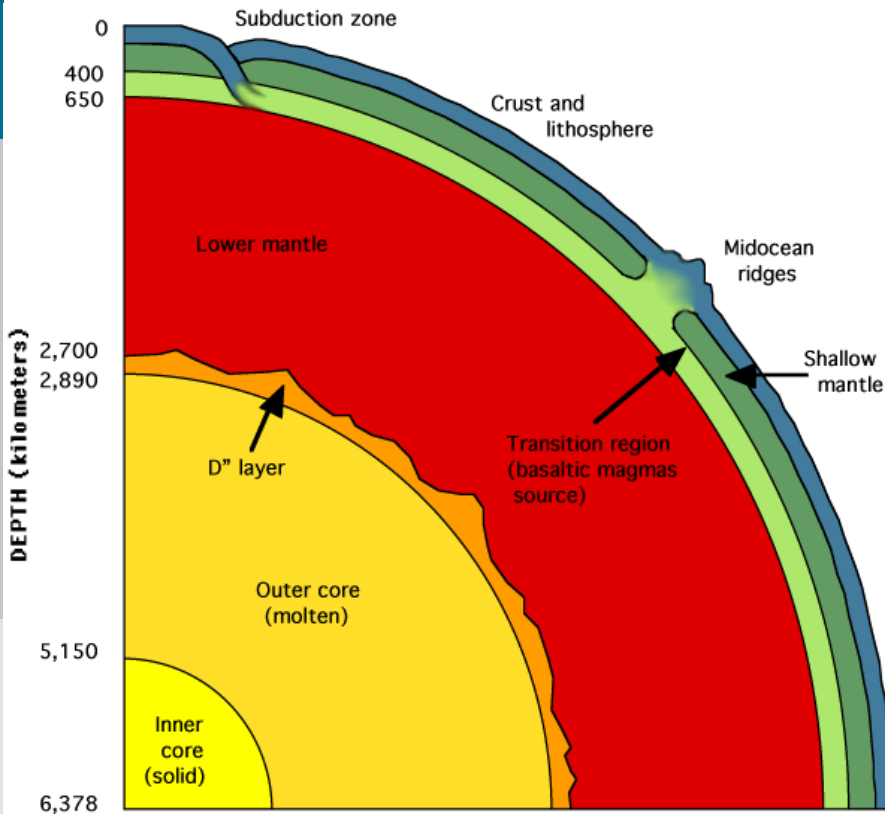
## Outer Core - LIQUID

- 2260 km thick;
- FeNi alloy + 10% light elem. (S, O?);
- **liquid**;
- temperature ~ 4000 – 600 K;
- **geodynamo**: motion of conductive liquid within the Sun's magnetic field;

## D'' layer: mantle –core transition

- ~200 km thick;
- seismic discontinuity;
- unclear origin;

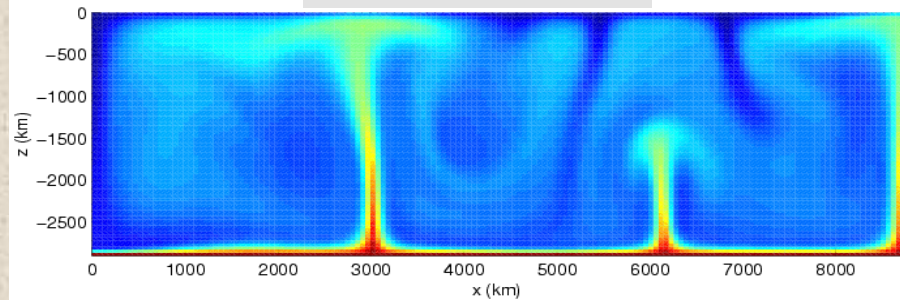
# Earth structure



## Lower mantle (mesosphere)

- rocks: high Mg/Fe, < Si + Al;
- T: 600 – 3700 K;
- high pressure: solid, but viscose;
- “plastic” on long time scales:

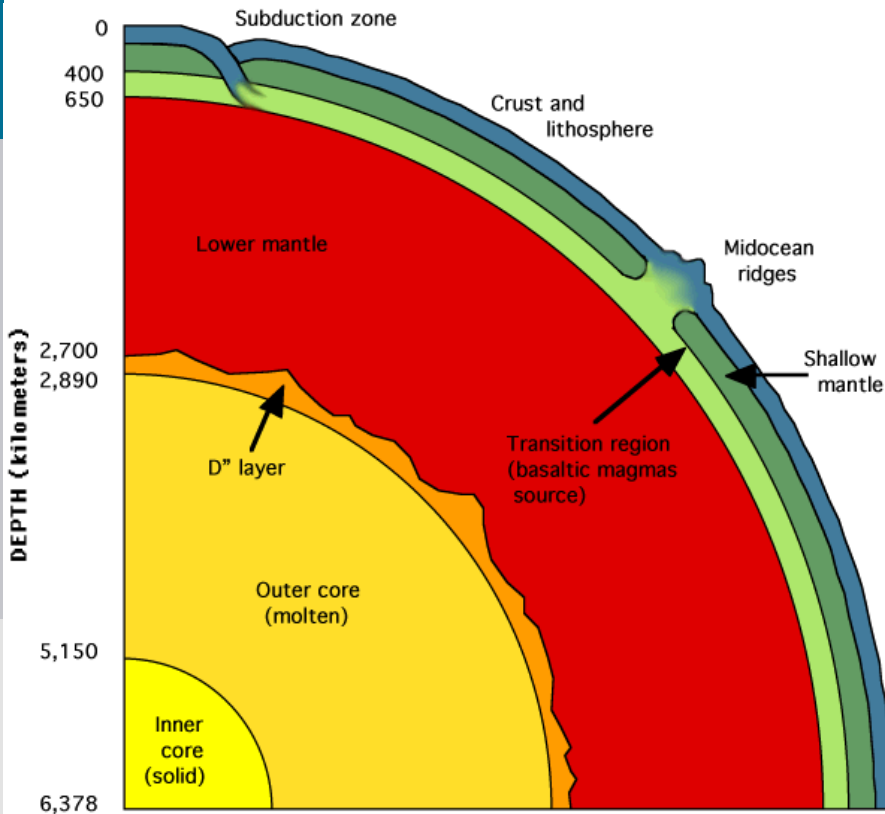
### CONVECTION



## Transition zone (400 -650 km)

- seismic discontinuity;
- mineral recrystallization;
- partial melting: the source of mid-ocean ridges basalts;

# Earth structure



## Upper mantle

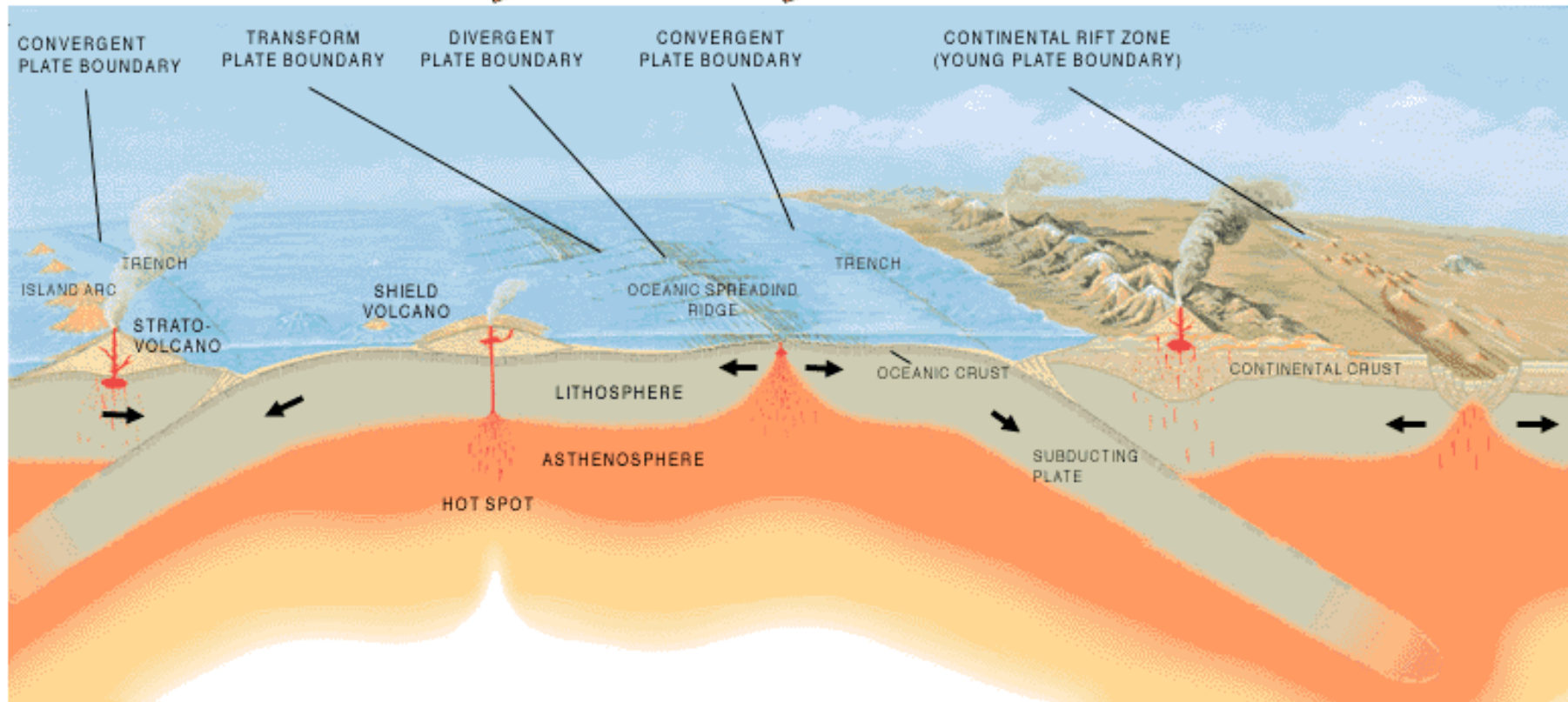
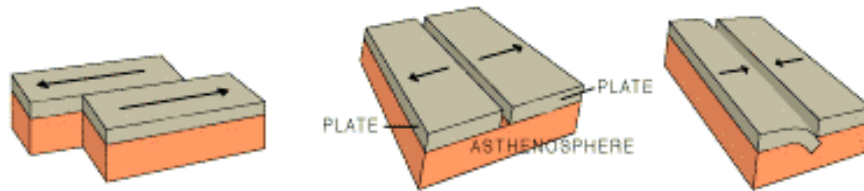


- composition: rock type peridotite
- includes highly viscose **asthenosphere** on which are floating lithospheric tectonic plates (**lithosphere** = more rigid upper mantle + crust);

## Crust: the uppermost part

- **OCEANIC CRUST:**
- created at mid-ocean ridges;
- ~ 10 km thick;
- **CONTINENTAL CRUST:**
- the most differentiated;
- 30 – 70 km thick;
- igneous, metamorphic, and sedimentary rocks;
- obduction and orogenesis;

# Earth's crust dynamics

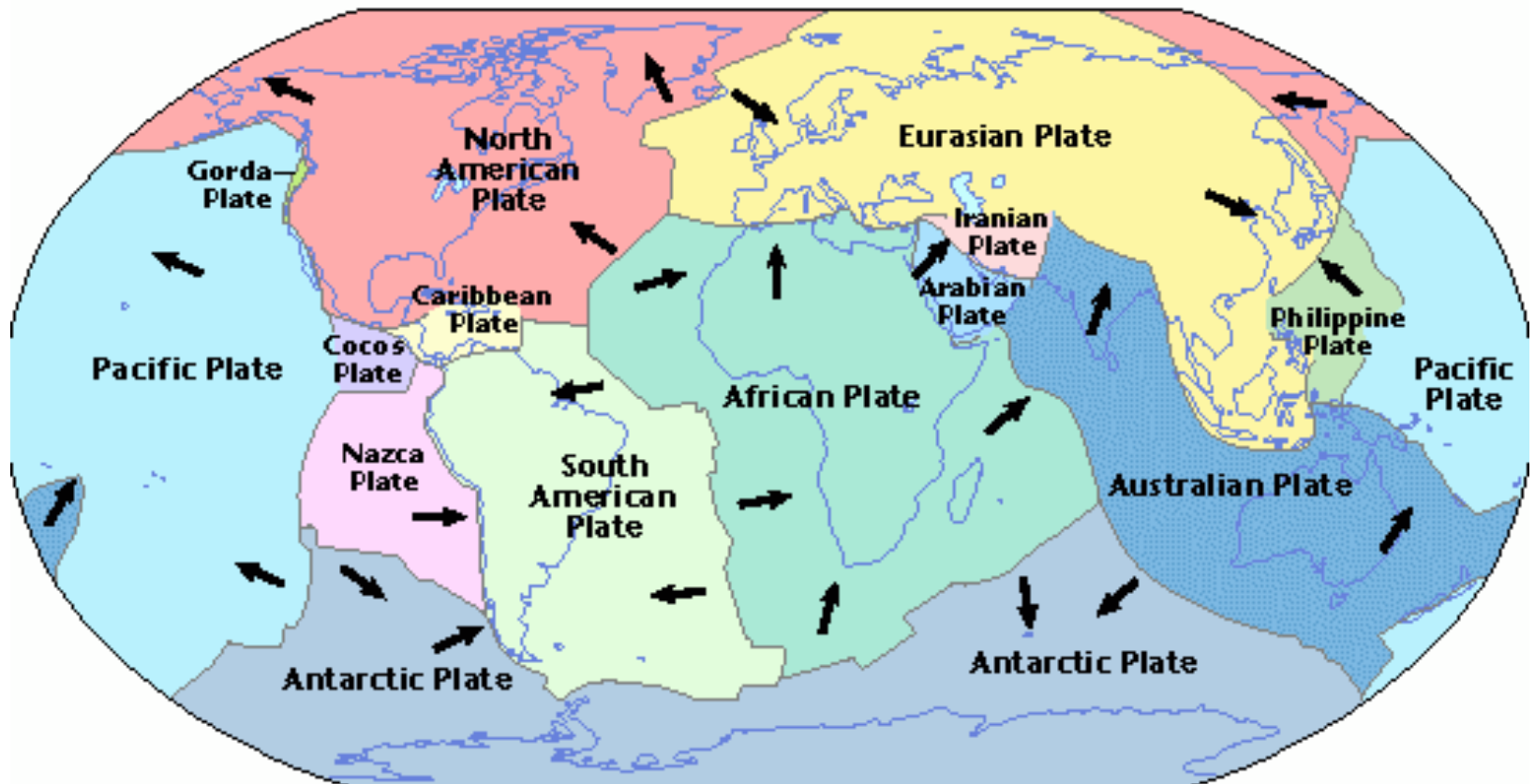


# Tectonic plates

Movement of few cm / year measured by satellites.

Tectonic plates float on plastic asthenosphere.

Movement driven by mantle convection.



# Rock types

## Igneous (from melt)

## Metamorphic (new p and T, no/partial melt)

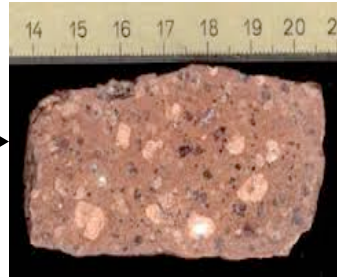
## Sedimentary

**Plutonic  
from magma  
(below surface)**

**Vulcanic  
from lava  
(on surface)**



granite



rhyolite



gabbro



basalt



gneis



amphibolite



marble



conglomerates



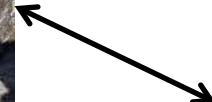
shales



sandstone

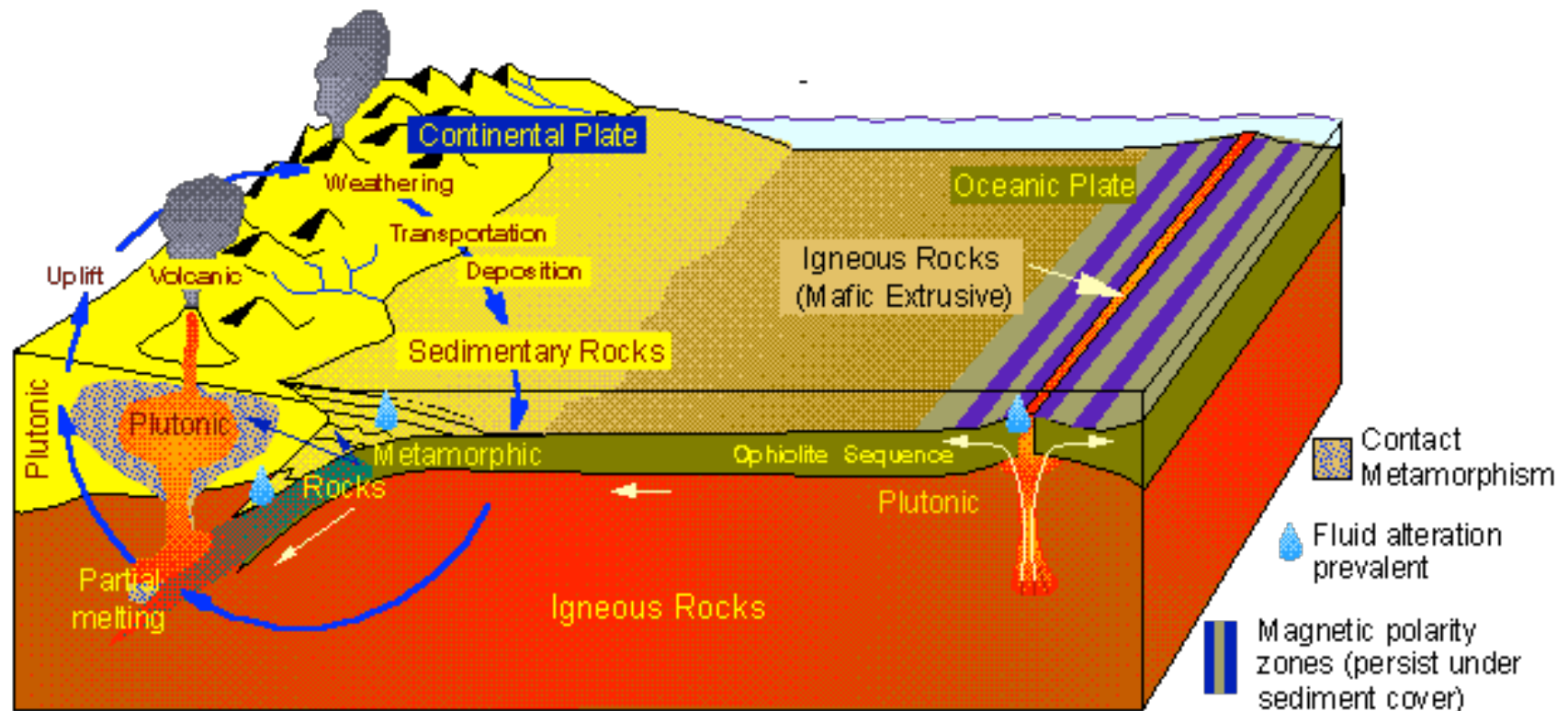


limestone





# Rock types in tectonic settings



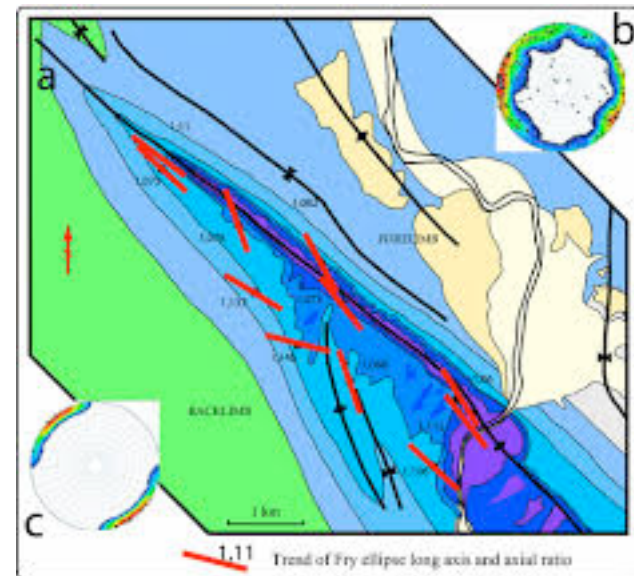
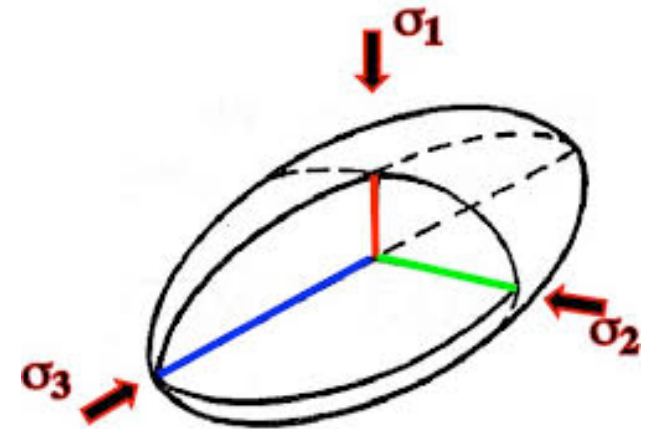
Redrawn by W. Milner, as modified from Montgomery (1990) and Monroe and Wicander (1994).

# *Come studiare la Terra?*



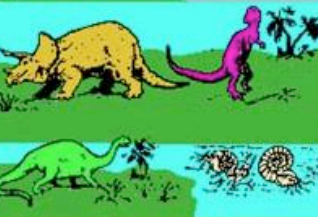
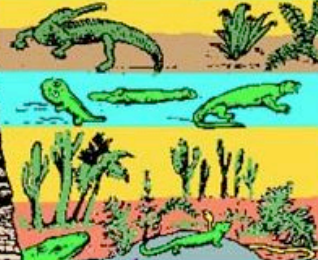

# Classical and structural geology



**Strain Ellipsoid**



# Stratigraphy and paleontology

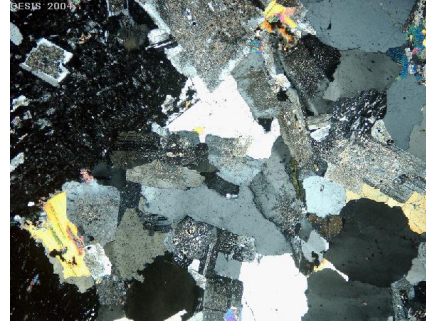
Era		Period	Rocks	Dominant Life	Index Fossils		
Cenozoic 65	Quaternary	2			Mammals	Pecten, Neptunea	
	Tertiary	65			Reptiles & Ammonites	Venericardia, Calyptraphorus	
Mesozoic 225	Cretaceous	136			Reptiles & Ammonites	Inoceramus, Scaphites	
	Jurassic	190			Seed Plants	Perisphinctes, Nerinea	
	Triassic	225			Seed Plants	Trophites, Monotis	
	Palaeozoic 570	Permian			280		Amphibians
Carboniferous		Pennsylvanian		310	Spore Bearing Plants		Dictyoclostus
		Mississippian		345	Spore Bearing Plants		Cactocrinus, Prolecanites
Devonian		395		Fish	Mucrospirifer, Palmatolepus		
Silurian		430		Invertebrates	Hexamoceras, Crystiphyllum		
Proterozoic Archaeozoic	Precambrian	570			Sea-Weeds	Tetragraptus, Bathyrurus (Trilobite)	
						Paradoxides (Trilobite), Billingsella	

# Petrology (study of rocks)

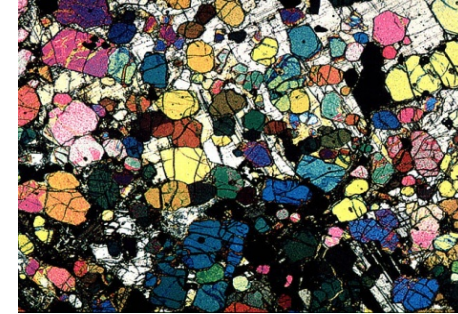
## Rocks under the polarized light microscope



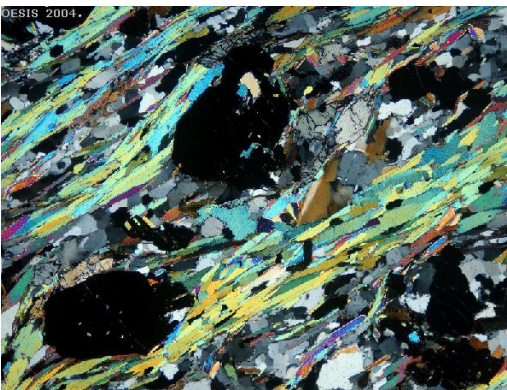
**igneous: basalt  
(oceanic crust)**



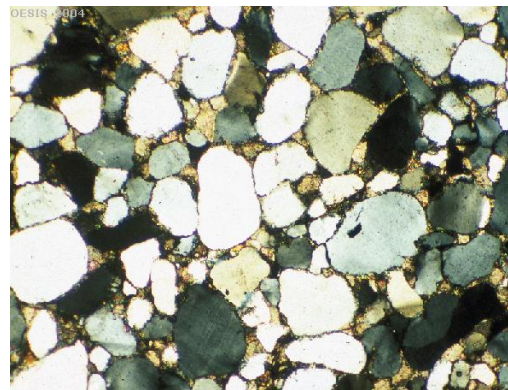
**igneous: granite  
(continental crust)**



**igneous: peridotite  
(upper mantle)**



**metamorphic: micashist  
(continental crust)**



**sedimentary: sandstone  
(continental crust)**

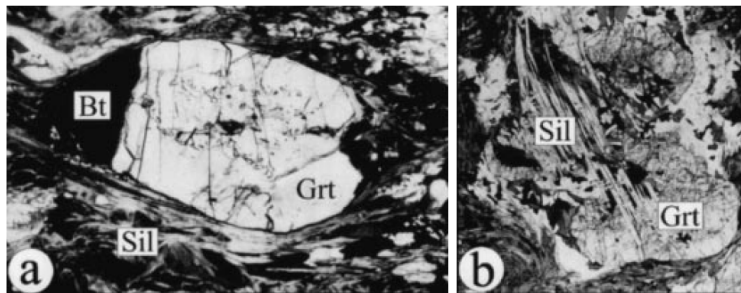


**sedimentary: limestone  
(continental crust)**

# Thermo-barometry

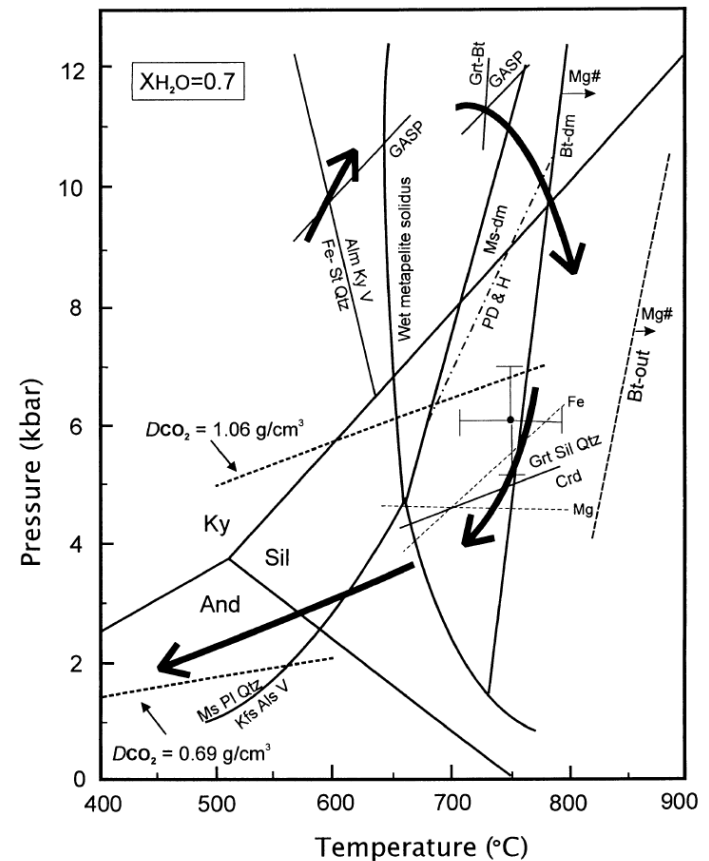
## Evolution of metamorphic rocks

### Traces of different orogenies (Alpine, Variscan, Caledonian...)



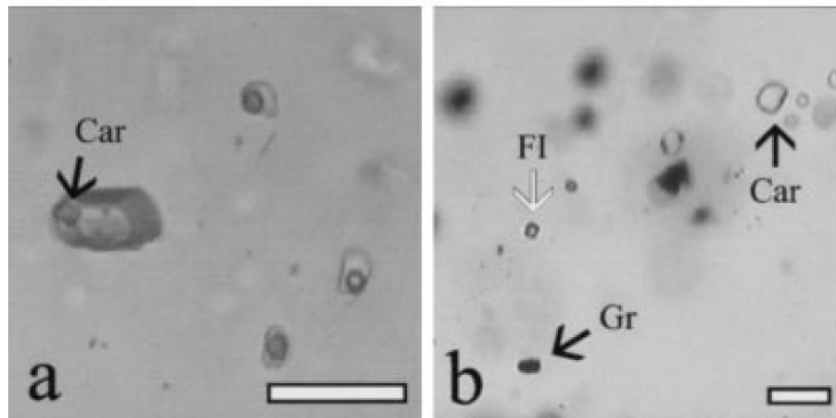
- 1) **Identify suitable reactions**  
(Fe – Mg exchange between garnet and biotite)
- 2) **Polarized microscopy**: find mineral grains in equilibrium
- 3) **Electron microprobe**: get chemical compositions from points in equilibrium
- 4) **Calculate** equilibrium (p,T) conditions

### Variscan metamorphism in Tatra Mts., Slovakia



# Fluid inclusions

## CO<sub>2</sub> – N<sub>2</sub> fluid inclusions in Quartz grains

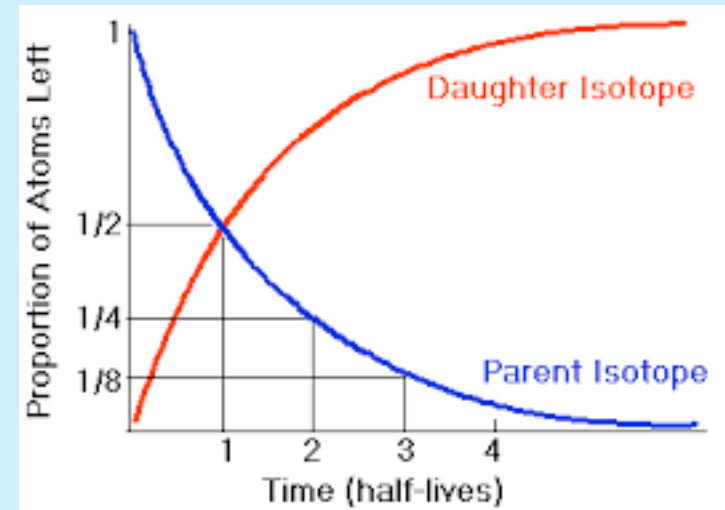


10 microns

### Microthermometry with fluid inclusions

- 1) Analyzing chemical composition of fluid inclusions
- 2) Observing temperature of phase transitions by heating and cooling

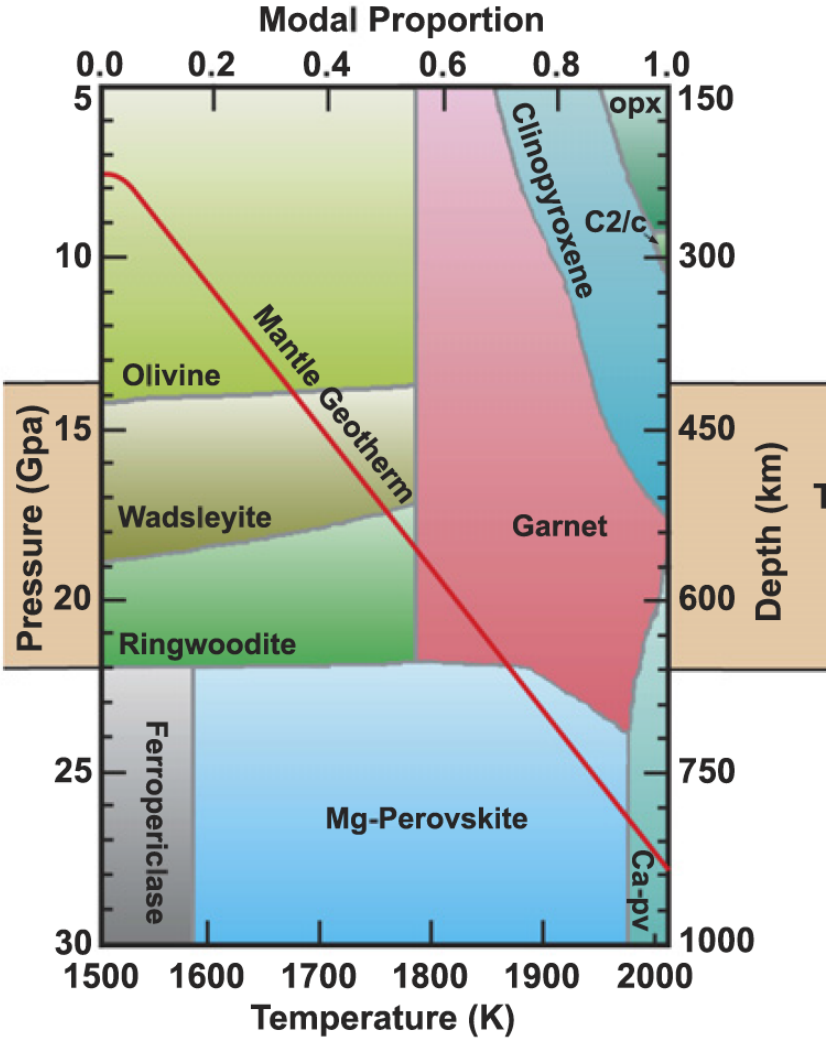
# Radio geochronology



- 1) Identify decay reaction
- 2) Identify closed system
- 3) Measure content of parent and daughter elements
- 4) Calculate time from the closure of the system

K-Ar system, Ar-Ar, U-Th, <sup>14</sup>C

# Mineralogy

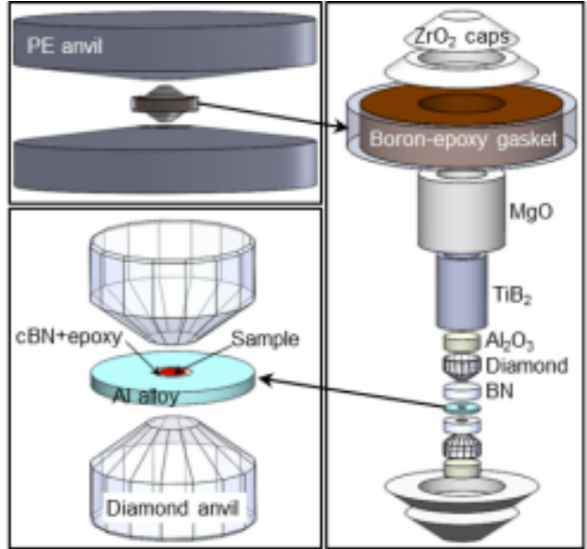


## Crystallography

Crystal Systems and Examples / Kristallsysteme und Beispiele

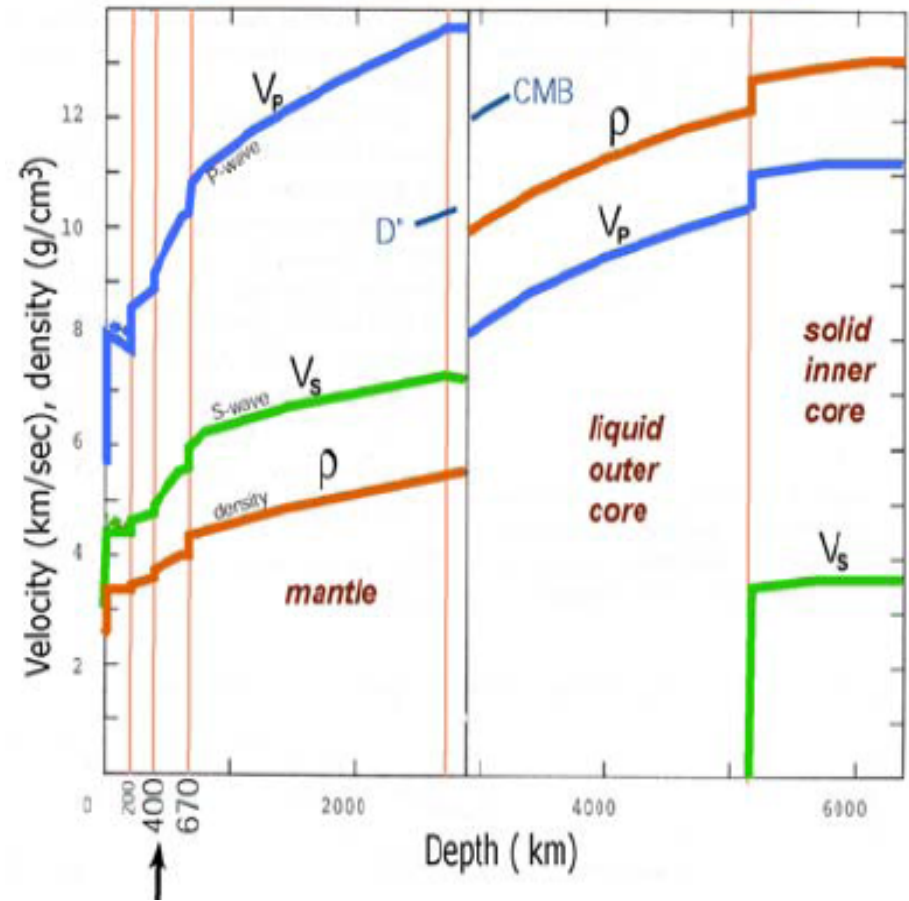
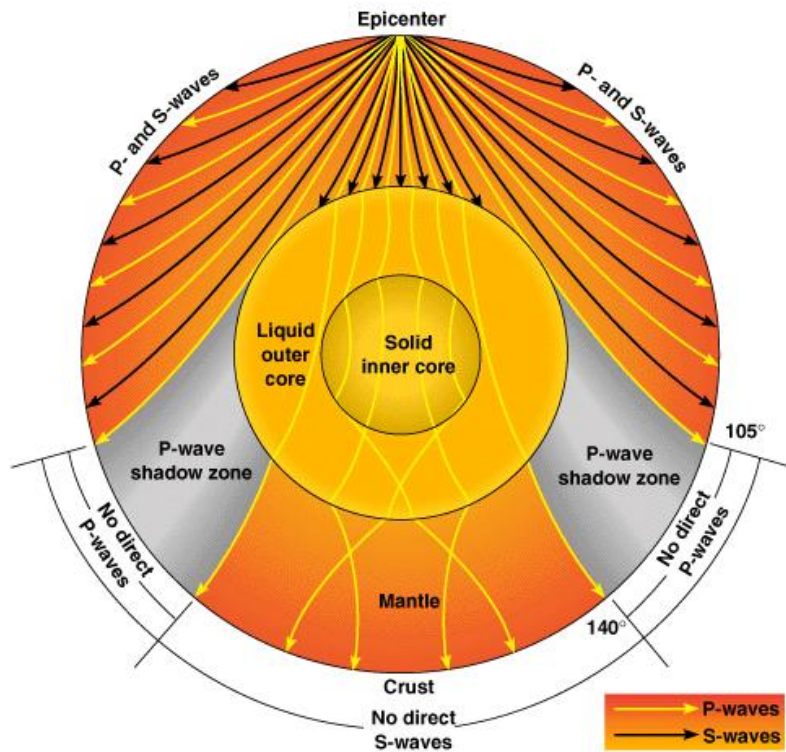
cubic kubisch						
tetragonal						
hexagonal trigonal						
rhombic rhombisch						
monoclinic monoklin						
triclinic triklin						

## Ultra high pressure lab experiments





# Seismology



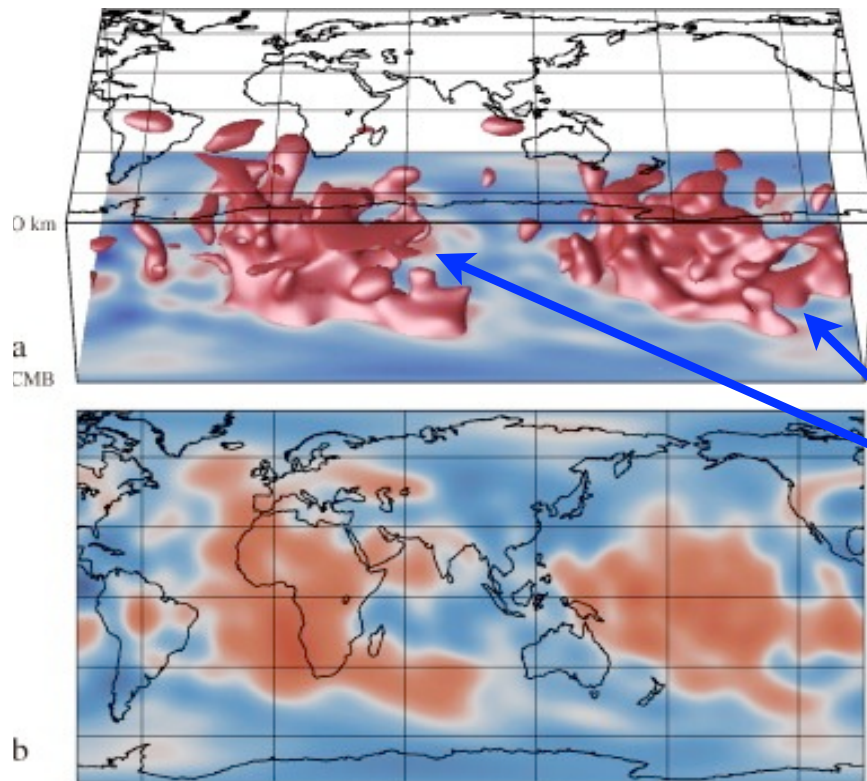
P – primary, longitudinal waves  
 S – secondary, transverse/shear waves

**Discontinuities in the waves propagation and the density profile but no info about the chemical composition of the Earth**

# Seismic tomography image of present-day mantle

## Seismic shear wave speed anomaly

Tomographic model S20RTS (Ritsema et al.)

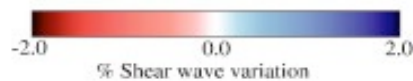


Two large scale seismic speed anomalies  
– below Africa and below central Pacific

Anti-correlation of shear and sound  
wavespeeds + sharp velocity gradients  
suggest a **compositional component**

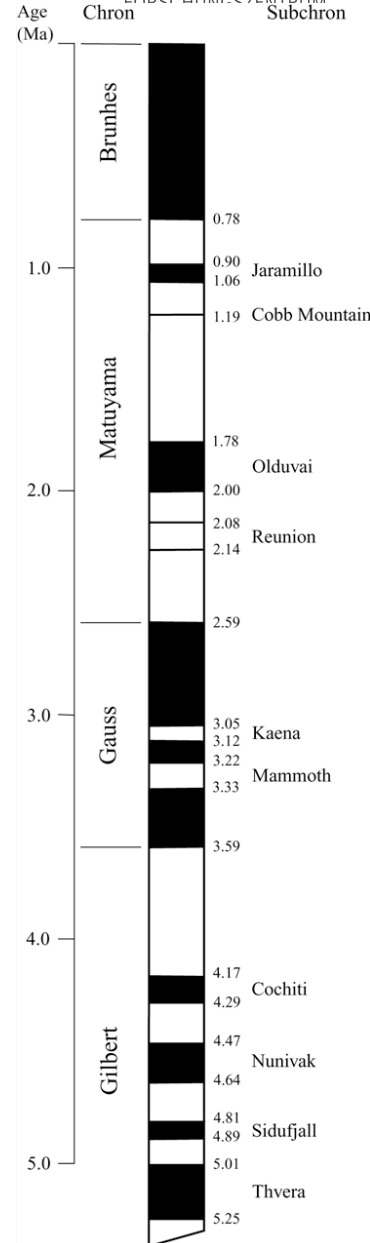
“piles” or “LLSVPs” or “superplumes”

**Candidate for an distinct  
chemical reservoir**

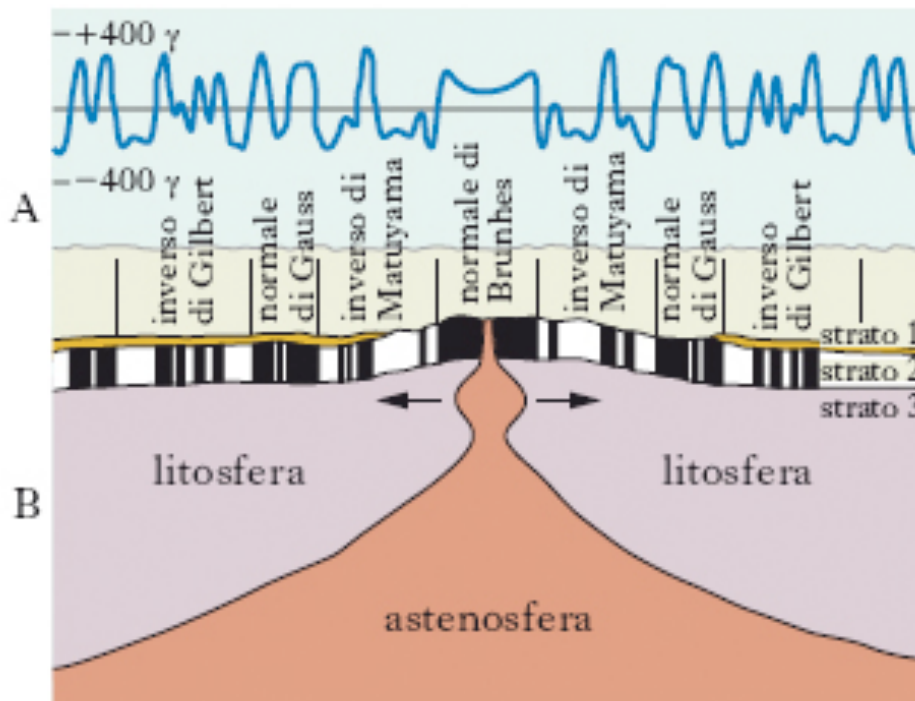


Bull et al. EPSL 2009

**Sat AM: Ed Garnero**



# Paleomagnetismo & magnetostratigraphia



- Measuring original magnetization in volcanic and sedimentary rocks;
- Discovery of fast (5-10,000 years) inversions of the Earth's magnetic field
- Double structure around rift zones

# Geochemistry



## 1) Direct rock samples

- \* surface and bore-holes (max. 12 km);
  - \* mantle rocks brought up by tectonics and **vulcanism**;
- BUT: POSSIBLE ALTERATION DURING THE TRANSPORT

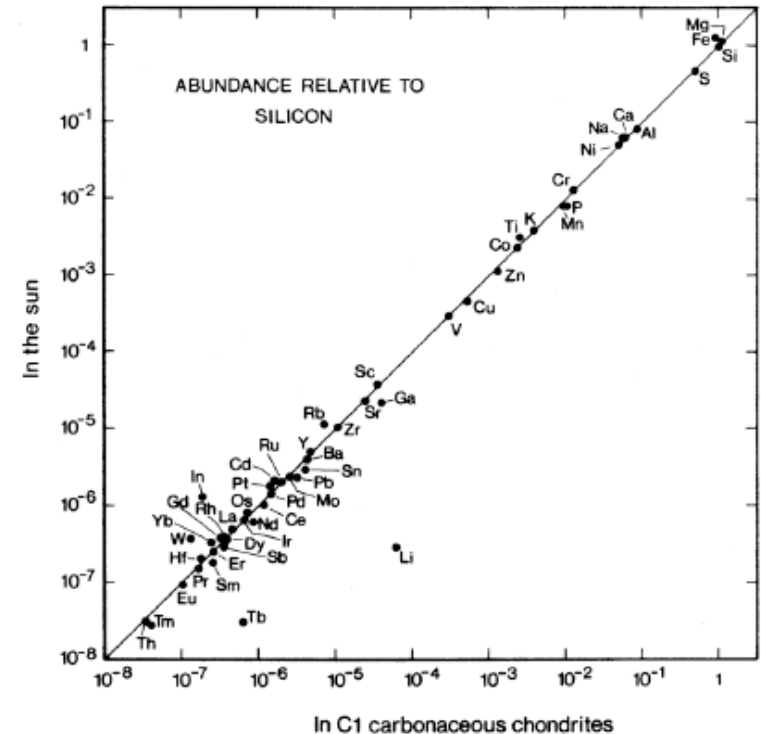
## 2) Geochemical models:

composition of direct rock samples +  
C1 carbonaceous chondrites meteorites +  
Sun's photosphere;

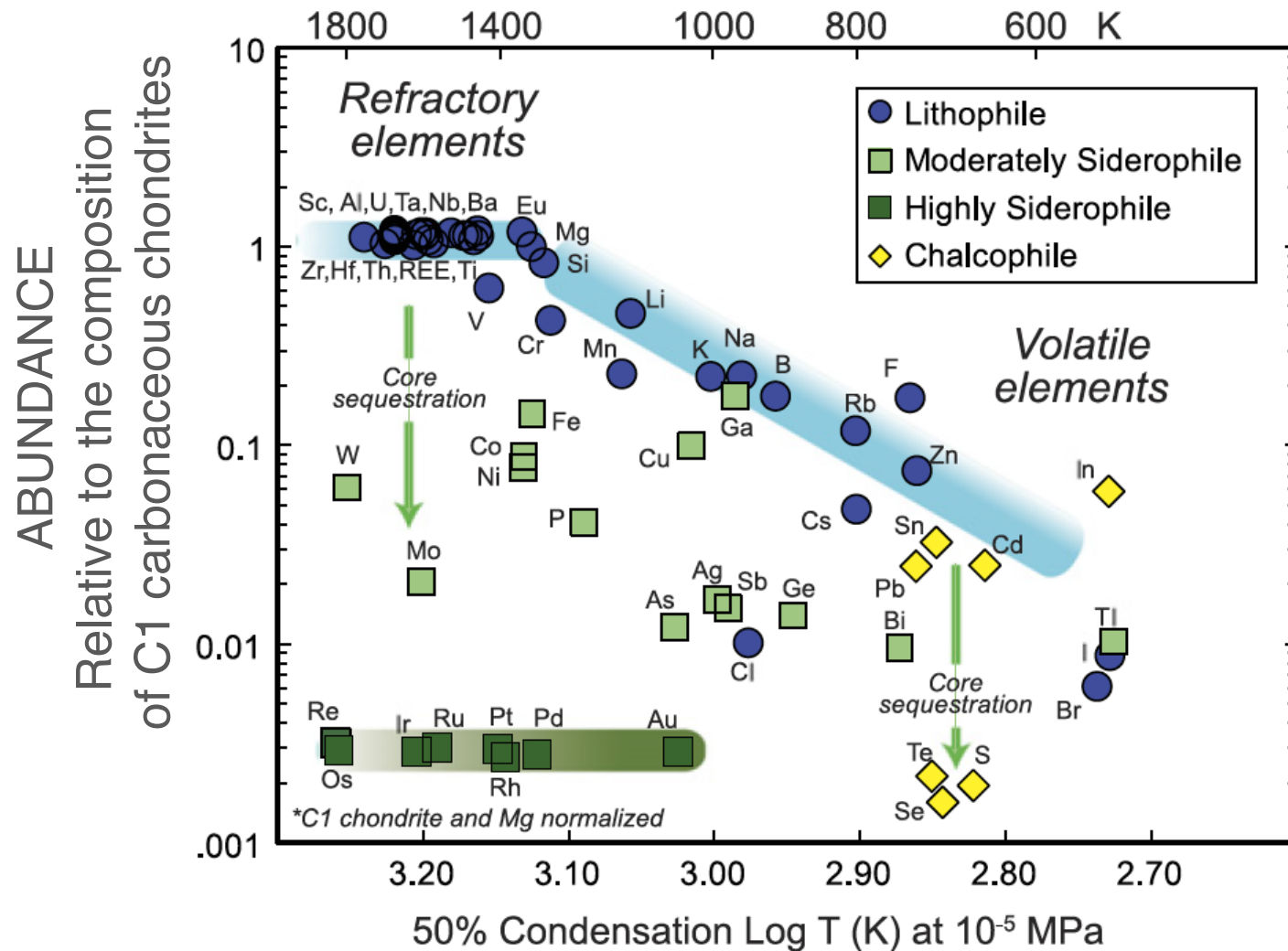
**Bulk Silicate Earth** (BSE) models  
(several!):

medium composition  
of the "re-mixed" crust + mantle,

*i.e.*, **primordial mantle** before the crust  
differentiation and after the Fe-Ni core  
separation;

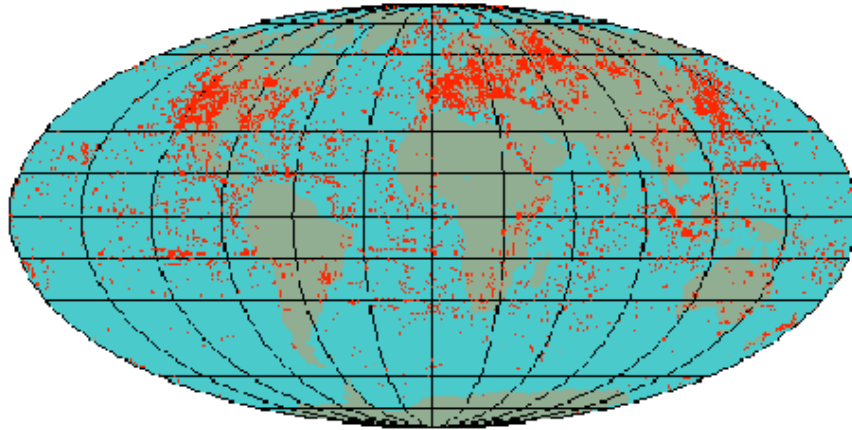


# Primitive-mantle composition

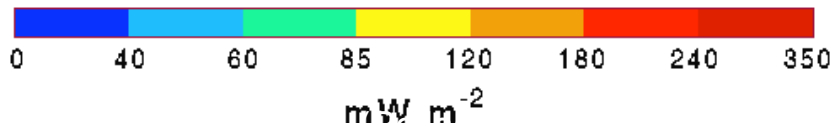
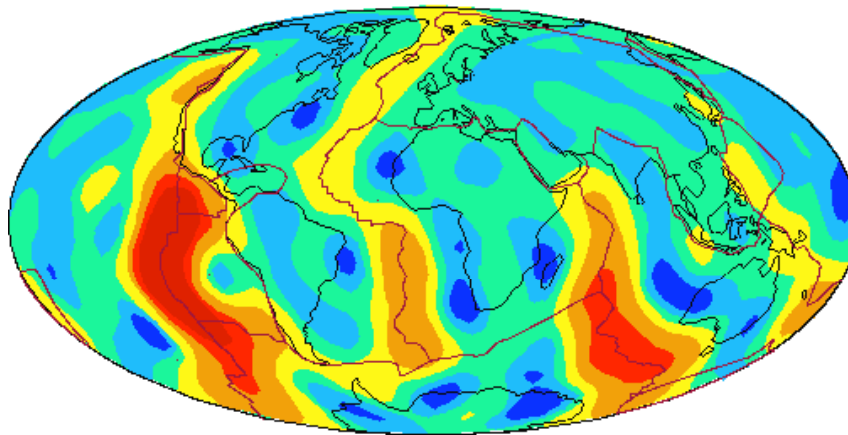


# Surface heat flux

38 000 bore-hole measurements

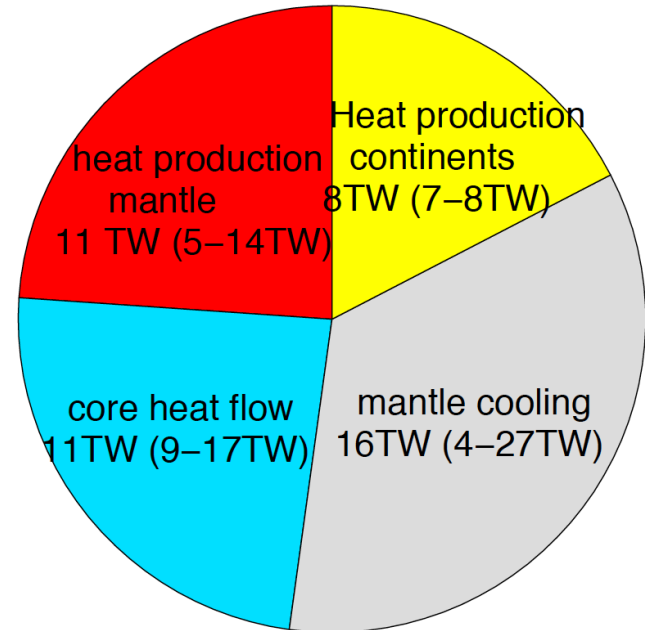


Heat Flow



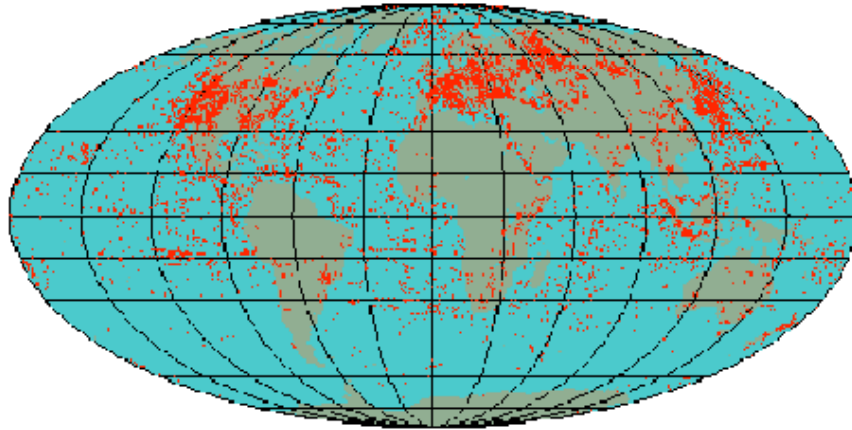
Conductive heat flow from bore-hole temperature gradient;

**Total surface heat flux:  
46 ± 3 TW**

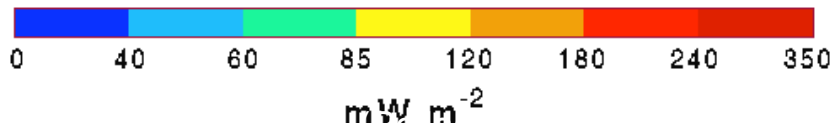
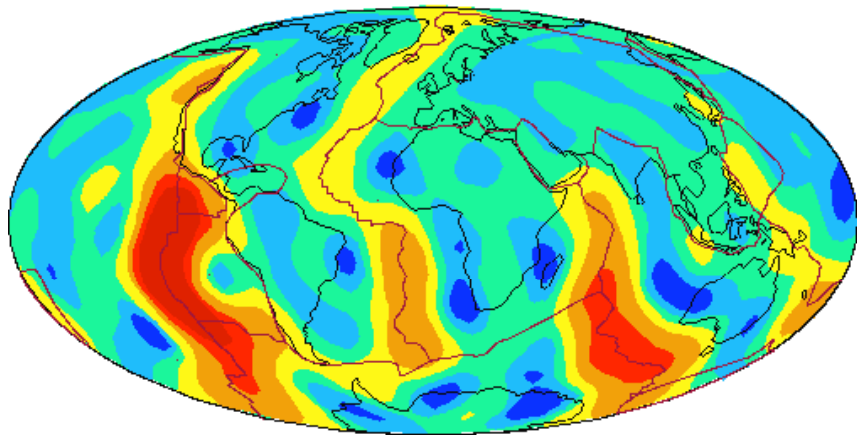


# Surface heat flux

38 000 bore-hole measurements



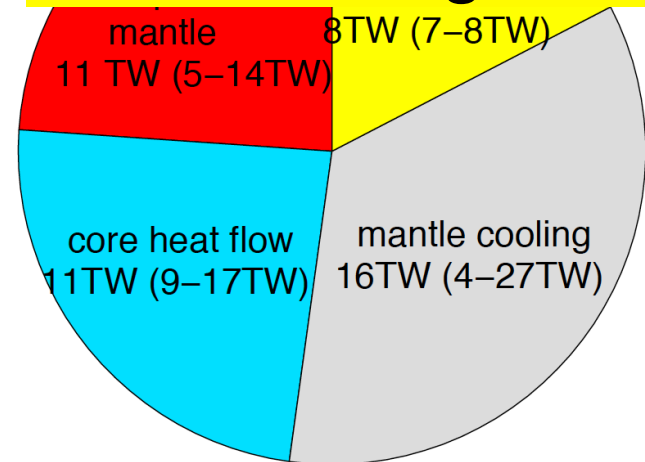
Heat Flow



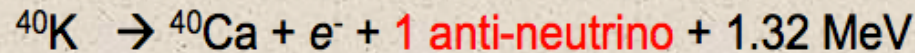
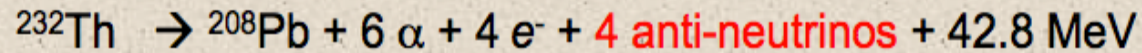
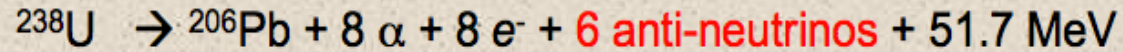
Conductive heat flow from  
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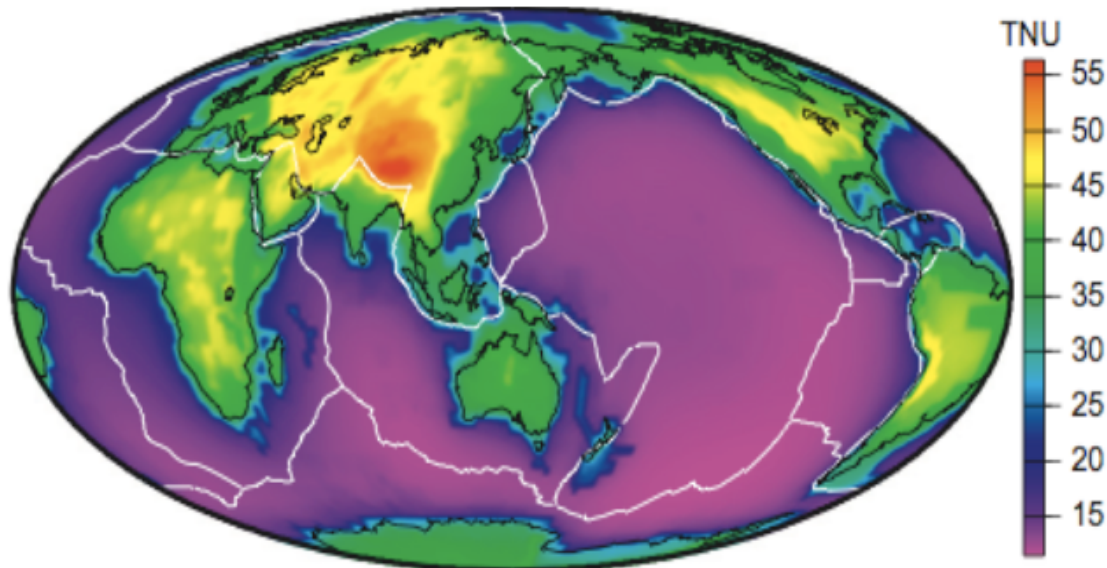
**Come stimare  
il calore radiogenico??**



# Geology and neutrino physics: geoneutrinos



## Crust + mantle geo- $\nu$ signal (U+Th)



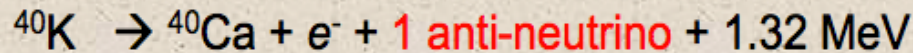
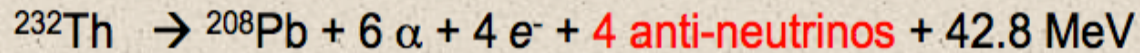
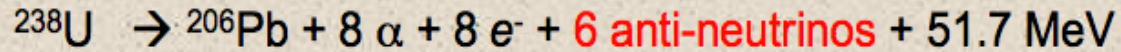
Geochemical BSEA  
&McD DM

1 TNU = 1 event /  $10^{32}$  target protons / year

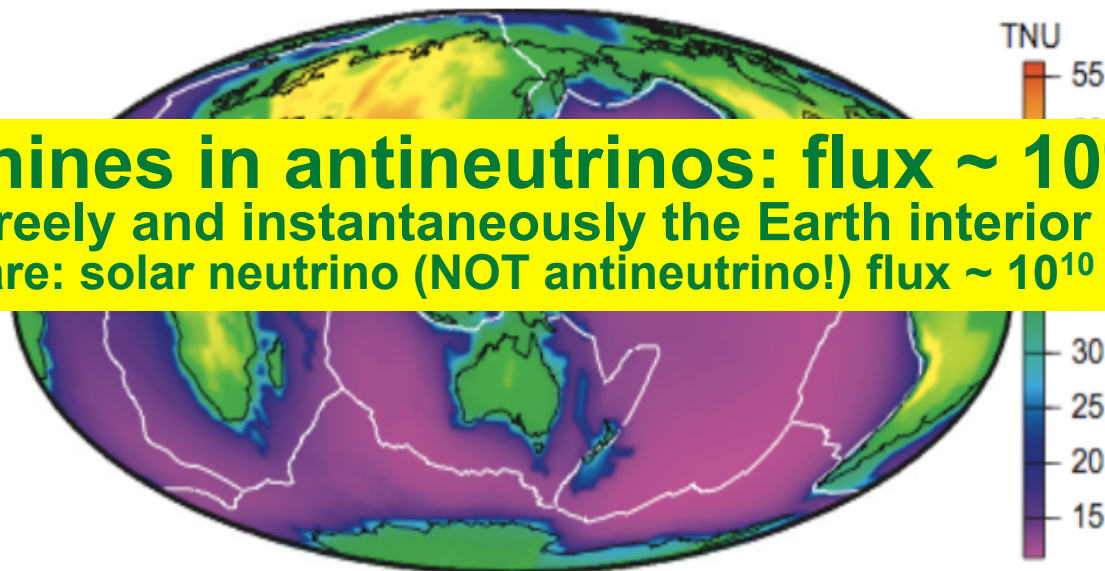
Cca 1 event / 1 kton / 1 year with 100% detection efficiency



# Geology and neutrino physics: goneutrinos



Crust + mantle geo- $\nu$  signal (U+Th)



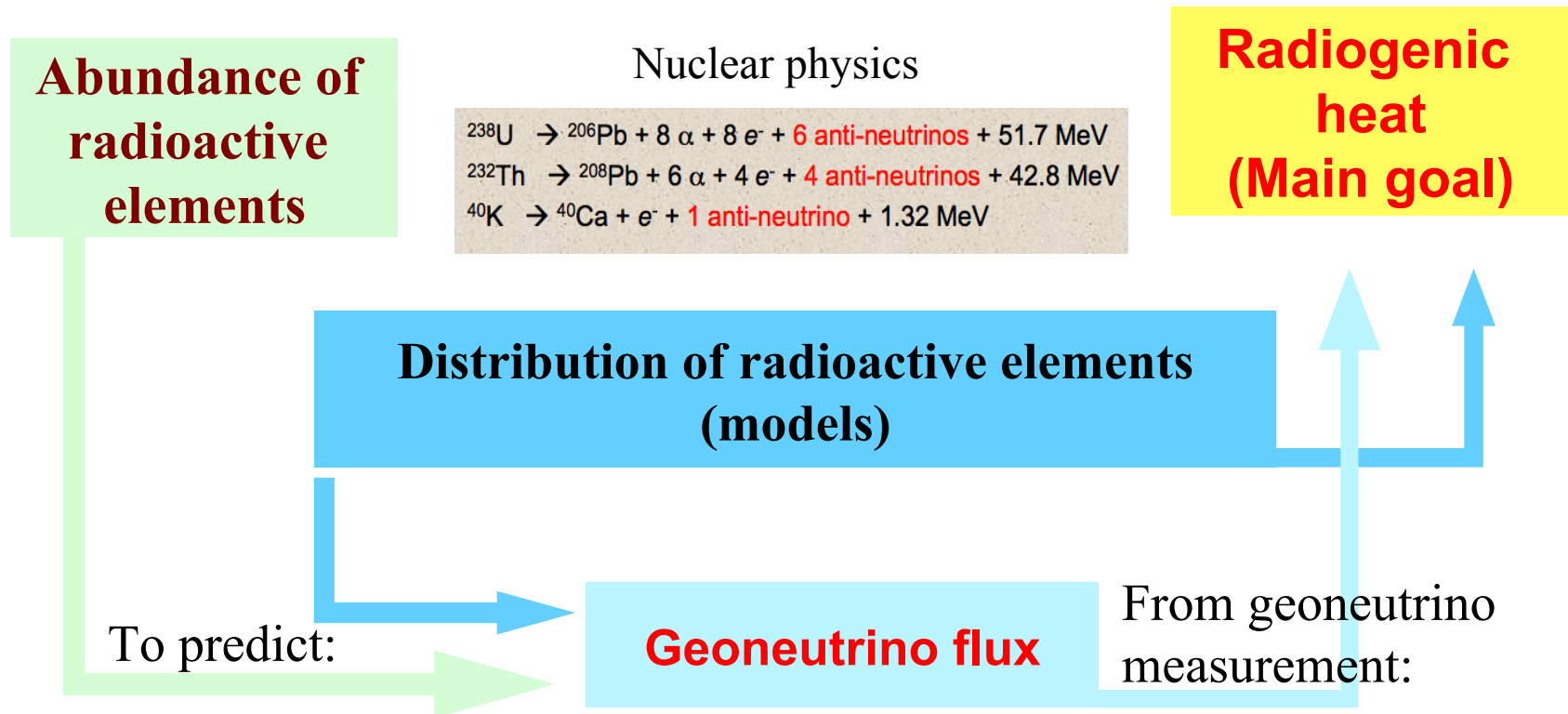
**Earth shines in antineutrinos: flux  $\sim 10^6 \text{ cm}^{-2} \text{ s}^{-1}$**   
 leaving freely and instantaneously the Earth interior  
 (to compare: solar neutrino (NOT antineutrino!) flux  $\sim 10^{10} \text{ cm}^{-2} \text{ s}^{-1}$ )

Geochemical BSEA  
&McD DM

1 TNU = 1 event /  $10^{32}$  target protons / year

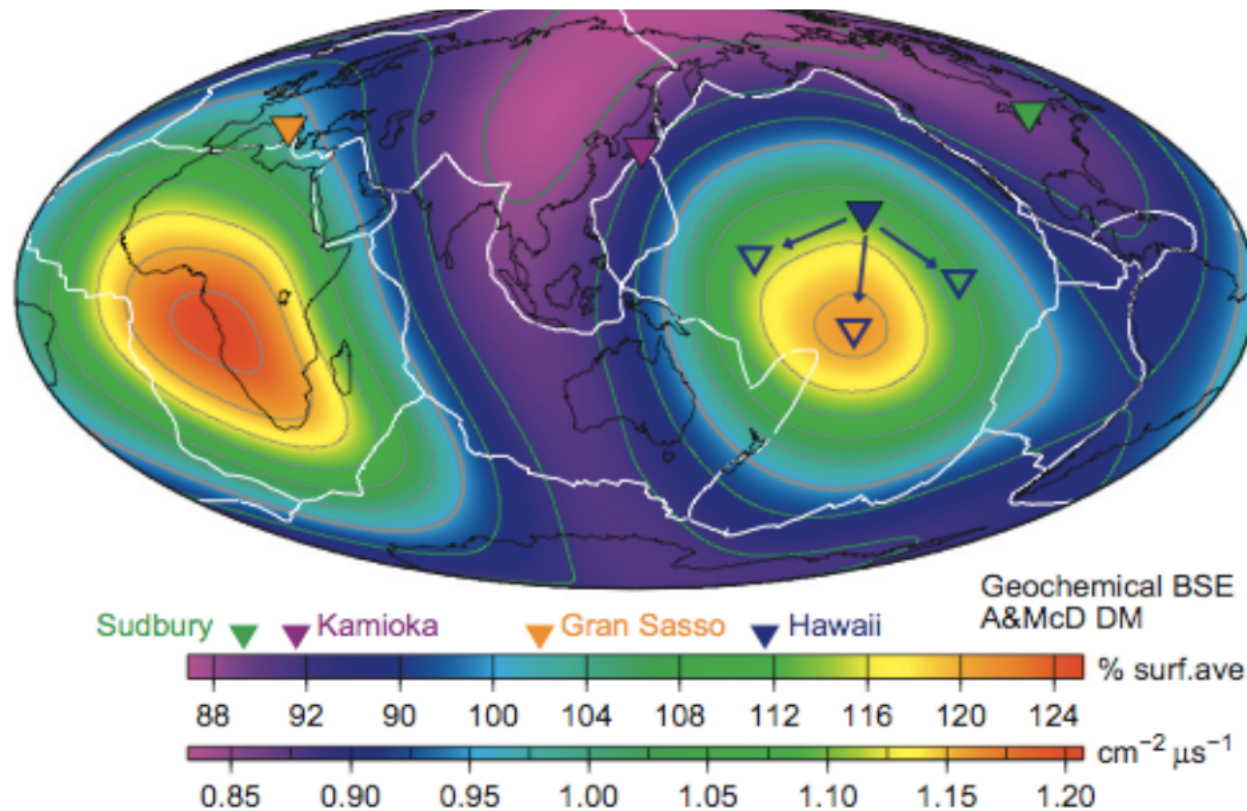
Cca 1 event / 1 kton / 1 year with 100% detection efficiency

# Geoneutrinos: antineutrinos from the decay of $^{238}\text{U}$ , $^{232}\text{Th}$ , and $^{40}\text{K}$ in the Earth



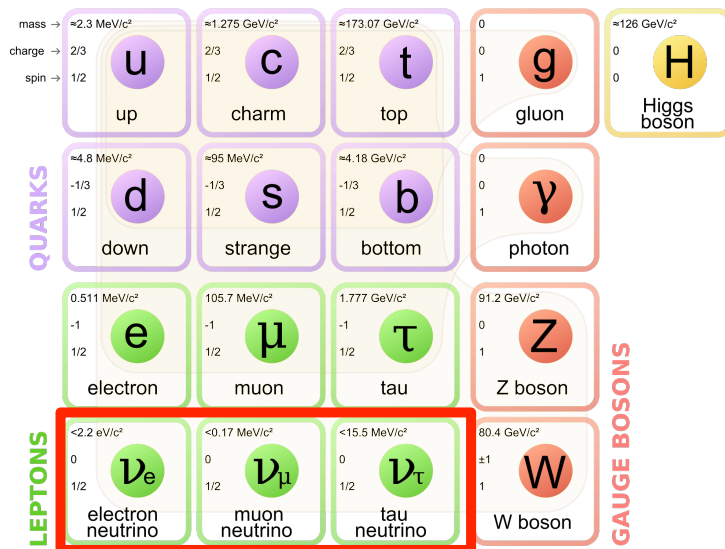
# Is the mantle chemically homogenous? We do not know!!

## Mantle geo- $\nu$ signal in the TOMO model



# What are neutrinos?

## Elementary particles of the Standard Model



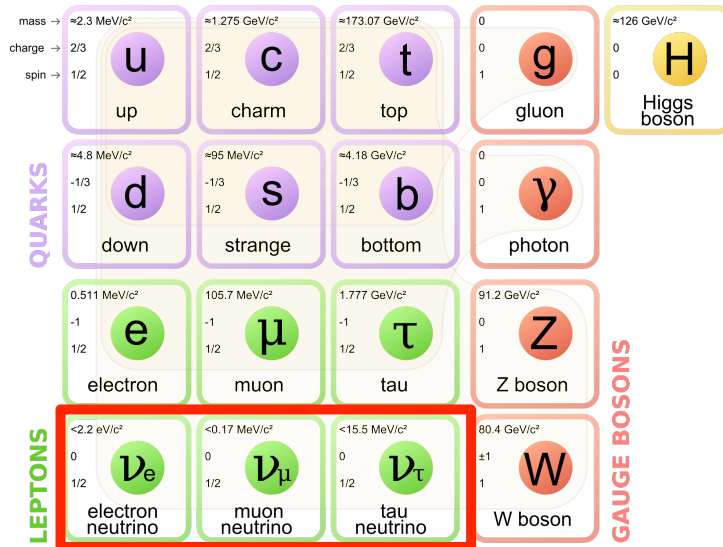
geoneutrinos

- No electric charge  
= no elmag interactions;
- No color  
= no strong interactions;
- Only weak interactions  
= very small cross sections;

- Originally, in the SM neutrinos have exactly zero rest mass;
- Experimental evidences for **neutrino oscillations (change of the flavour during the propagation): non-zero mass** required!

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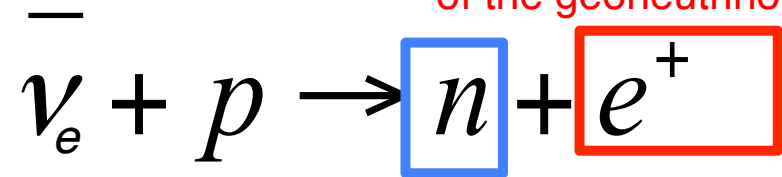
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**Nobel prize for physics in 2015!**

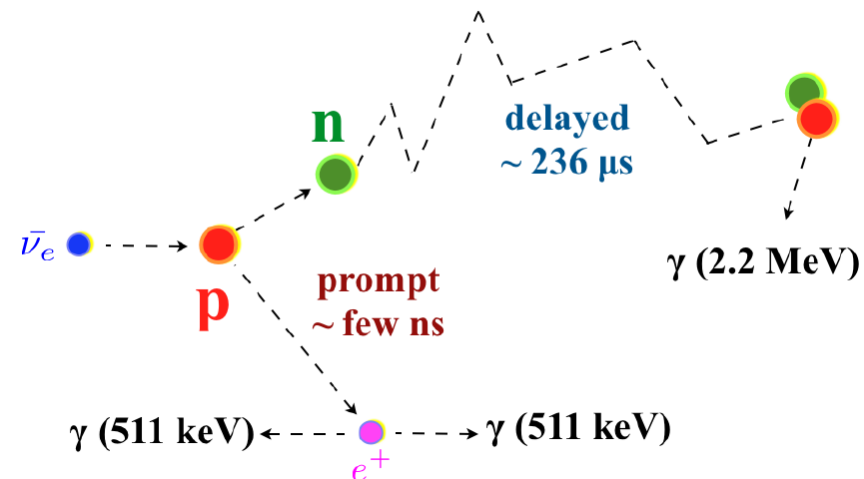
# How to detect geoneutrinos?

- liquid scintillator detectors (charged particle produces light)
- (Anti-)neutrinos have low interaction rates, therefore:
  - Large volume detectors needed (hundreds tons)
  - High radiopurity;
  - Underground labs to shield cosmic radiations

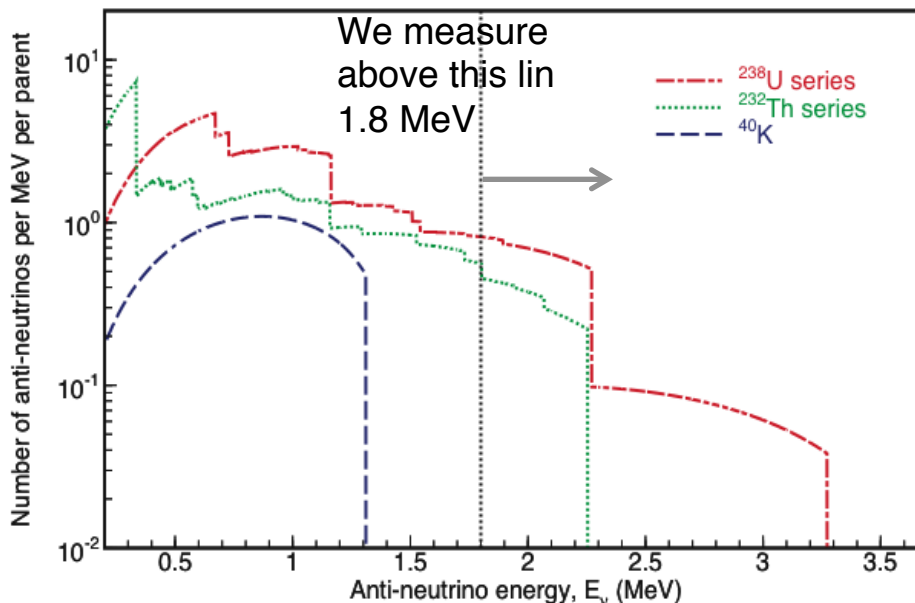
**POSITRON:**  
Tells us  
about the energy  
of the geoneutrino



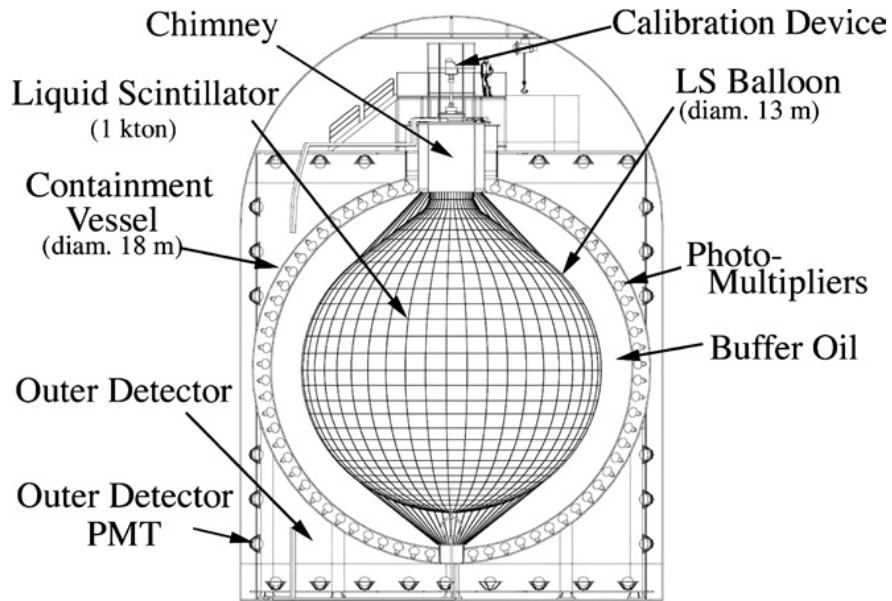
**NEUTRON:**  
Helps us to select positrons  
from reactions of geoneutrinos



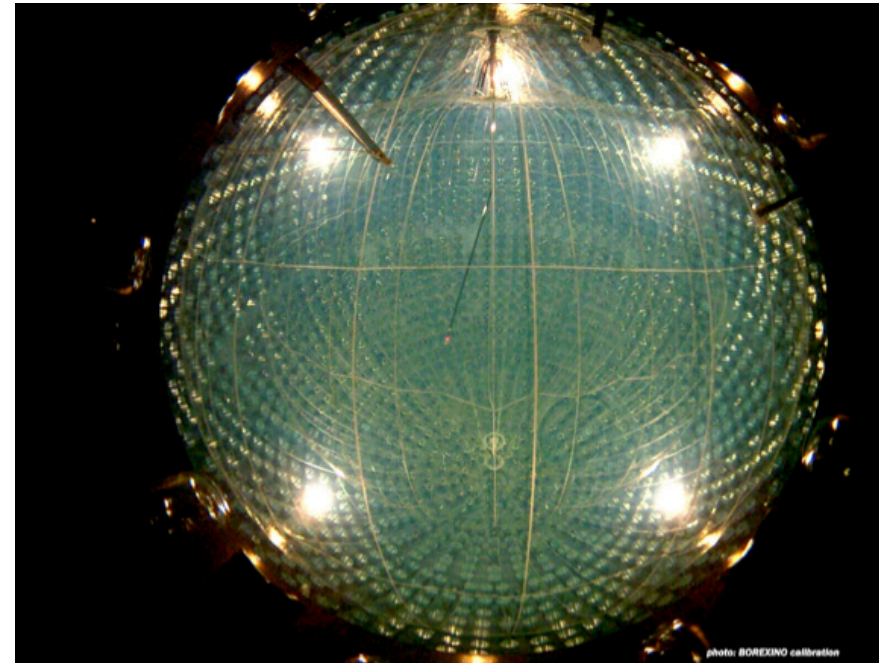
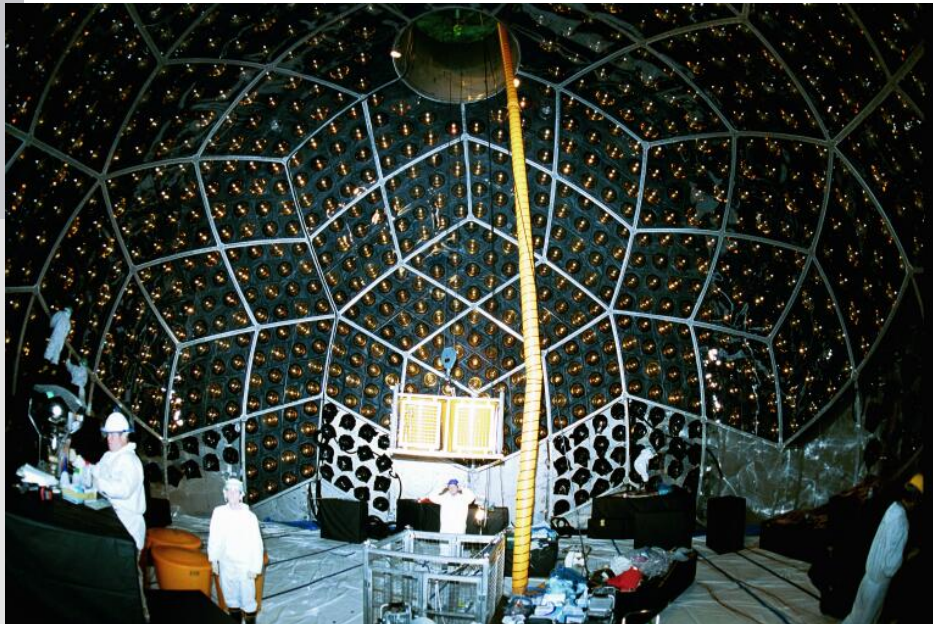
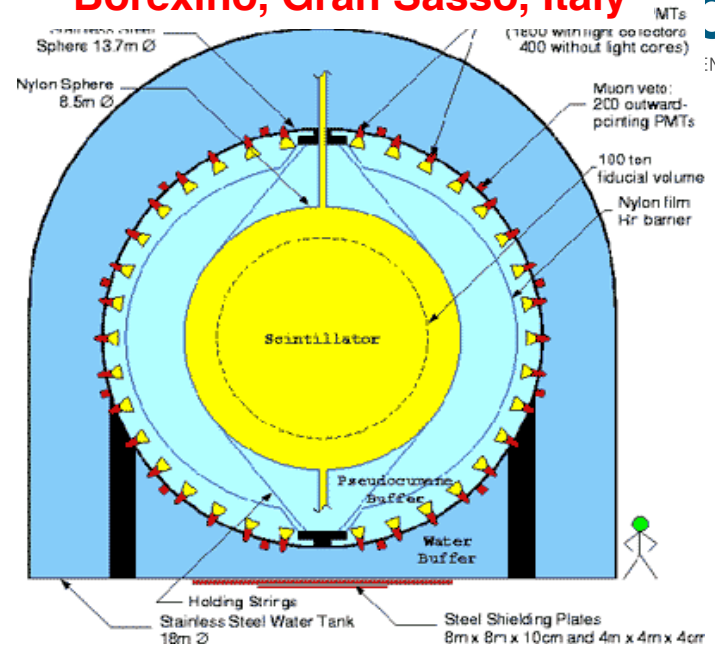
**Energy spectrum of geoneutrinos**



## KamLand, Japan



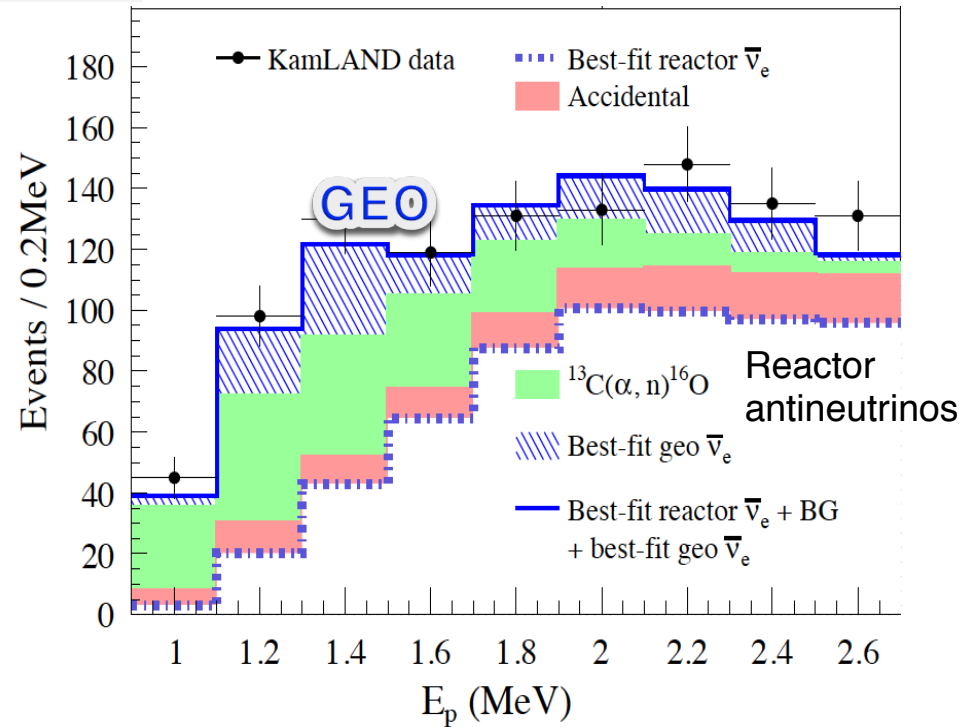
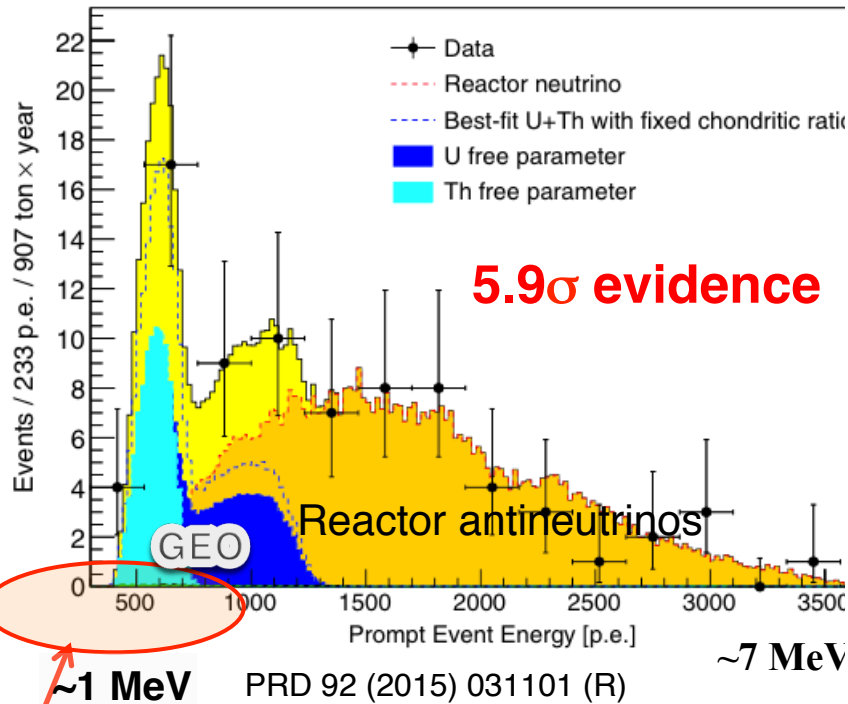
## Borexino, Gran Sasso, Italy



# Latest geoneutrino results

Borexino 2015:  $23.7^{+6.5}$  (stat)  $^{+0.9}$  (sys) geonu's

KamLAND 2013:  $116^{+28}_{-27}$  geonu's



Non antineutrino background almost invisible!

- ✓  $5.5 \times 10^{31}$  target-proton year
- ✓ 0-hypothesis @  $3.6 \times 10^{-9}$

- ✓  $4.9 \times 10^{32}$  target-proton year
- ✓ 0-hypothesis @  $2 \times 10^{-6}$



# What do we learn from these results?

- The current experimental results demonstrate that we can measure geoneutrinos and that their rate is consistent with geological expectation;
- Small number of detected geoneutrinos limits geological predictions:
  - i) The measured Earth radiogenic heat  $(U + Th + K) = 33^{+28}_{-20} T$  to be compared with  $47 \pm 2 TW$  of the total Earth surface heat flux (including all sources)
  - ii) first direct indications of geoneutrinos from the mantle
- Several future projects have geoneutrinos among their aims:
  - SNO+ (1 kton) start soon in Canada
  - JUNO (20 kton) in China to start in 2020

- New interdisciplinary field established: **NEUTRINO GEOSCIENCE** conference every two years
- Power of combined analysis and importance of multi-site measurements at geologically different environments

# Summary



*More we learn about our Earth,  
more fascinating it turns out to be!*

*Thank you!*

