What is Geodynamics?

Geodynamics is a subfield of geophysics dealing with dynamics of the Earth and Planets.

It applies physics, chemistry and mathematics to the understanding of geologic phenomena such as mantle convection, seafloor spreading, mountain building, volcanoes, earthquakes, faulting and so on.

What is special in Geodynamics?

As a scientific discipline, geodynamics is distinguished from other Earth Science disciplines in that it starts from fundamental physical principles to interpret and predict Earth's behavior, rather than working backwards from observations.

Moreover, geodynamics explicitly treats Earth's complex material properties, in addition to its dynamics.

Computational geodynamics

Lectures -- morning, Tutorial-Training -- afternoon

13.03 15.00 Lecture by Prof. Trond Torsvik in GFZ

14.03 Visit to the Geodynamic Modeling Section at GFZ

Detailed program and recommended literature at
http://www.dynamicearth.de/fortgeo

"Everything should be made as simple as possible, but not simpler."

A. Einstein

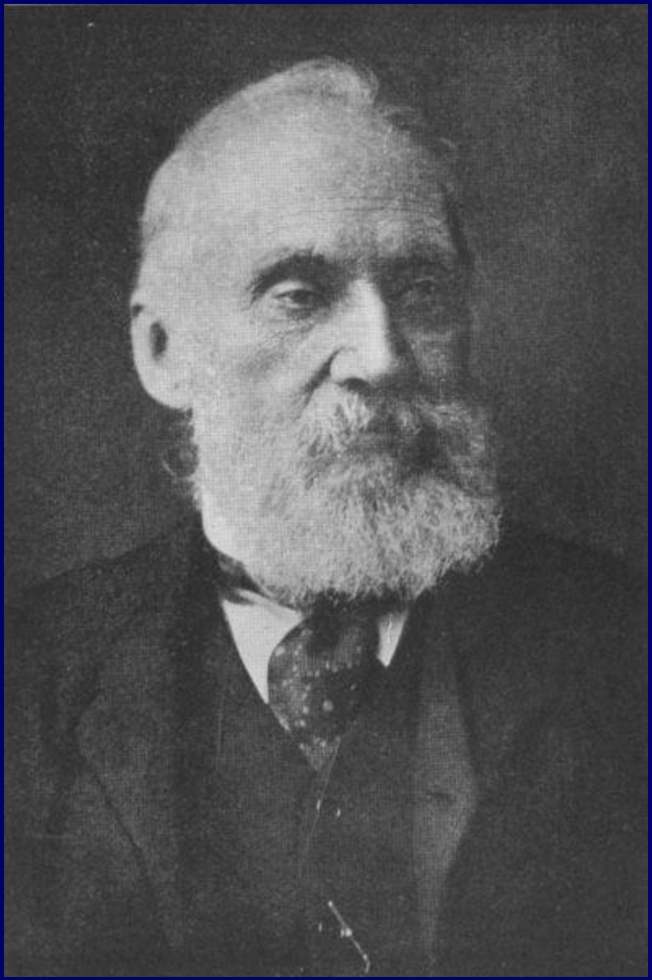
Introduction: historical notes and overview of major challenges in solid Earth dynamics

Outline

- Beginning of geodynamics: Lord Kelvin´s error
- Why plate tectonics at the Earth?
- Key plate-tectonic challenges and mysteries
- Beyond the plate tectonics

Lord Kelvin error

1862- age of the Earth is between 20 and 400 Mln yrs



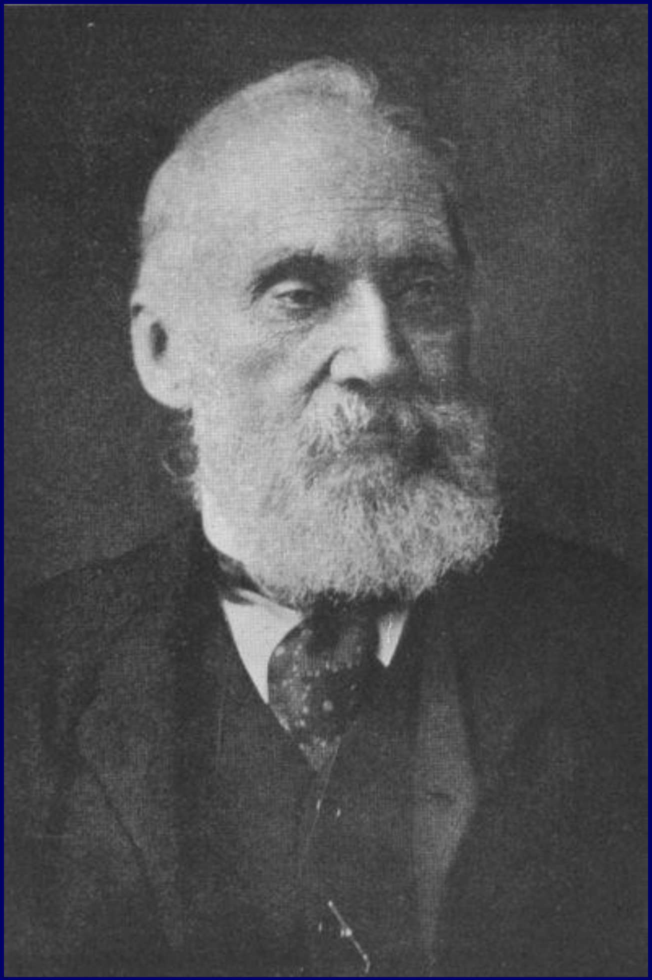
$$\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial z^2}$$

$\kappa = \lambda/\rho C$ -thermal diffusivity

William Thomson, Lord Kelvin (1824–1907)

Lord Kelvin error

1862- age of the Earth is between 20 and 400 Mln yrs



William Thomson, Lord Kelvin (1824–1907)

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

$\kappa = \lambda/\rho C$ -thermal diffusivity

Solution

$$T = T_0 \operatorname{erf}\left(\frac{z}{2\sqrt{\kappa t}} \right)$$

Lord Kelvin error

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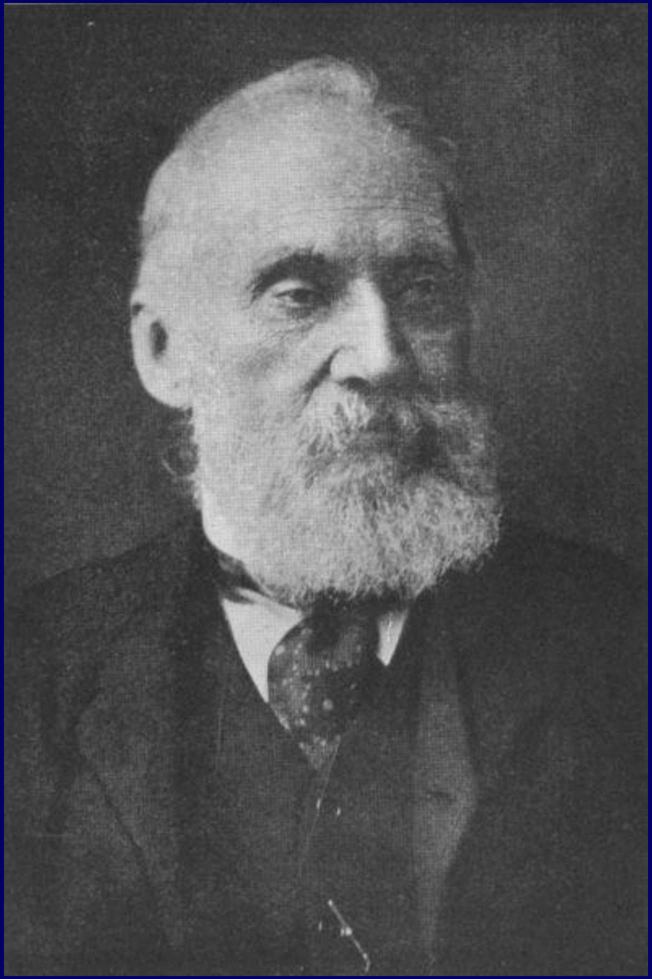
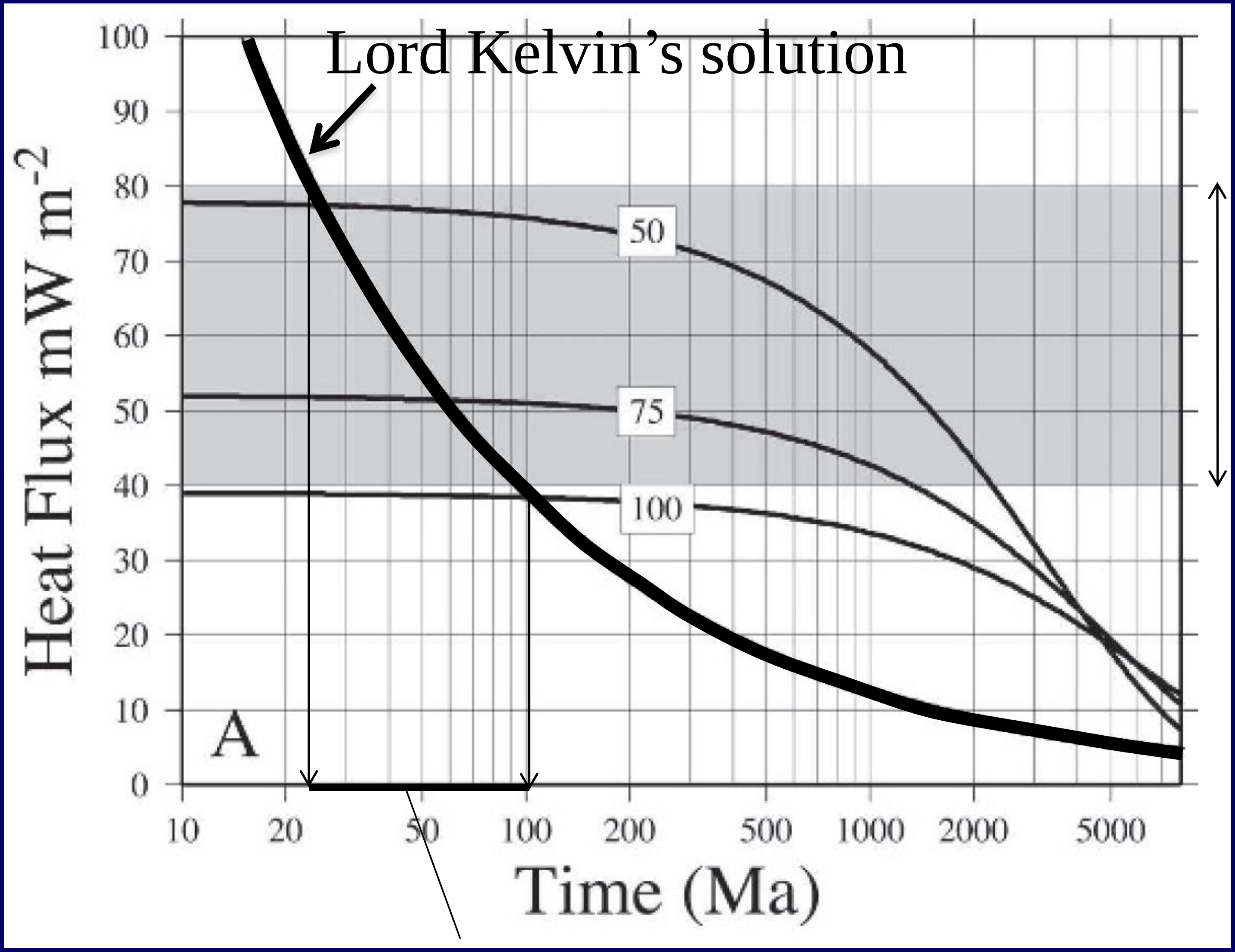


Solution

$$\frac{\partial T}{\partial z}\bigg|_{z=0} = \frac{T_0}{\sqrt{\pi k t}}$$

$$t = \frac{1}{\pi k}\left(T_0 \Big/ \frac{\partial T}{\partial z}\bigg|_{z=0}\right)^2$$

William Thomson, Lord Kelvin (1824–1907)

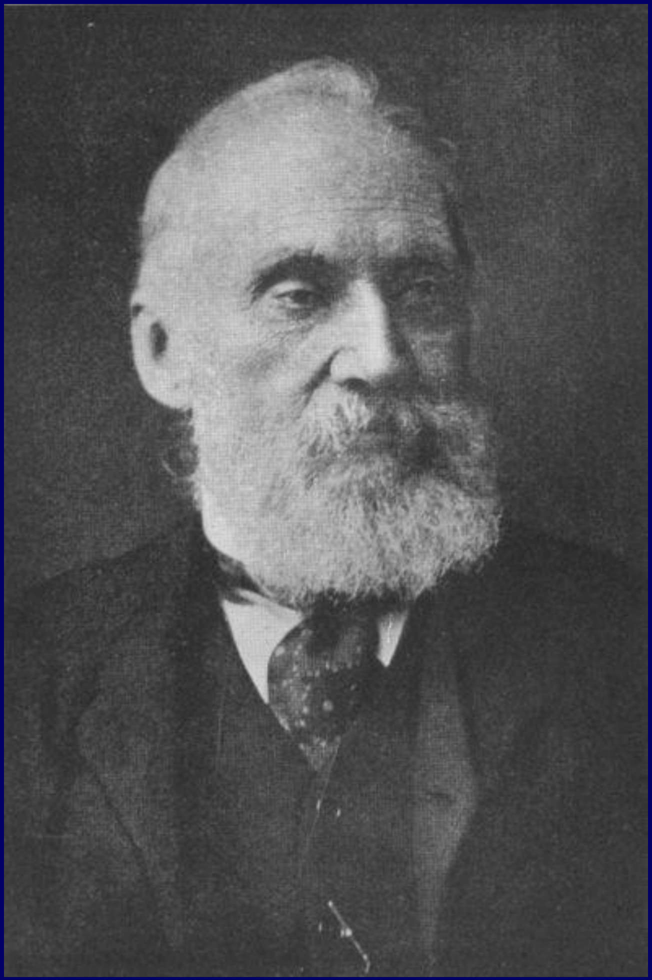


Lord Kelvin's solution
Heat Flux mW m^{-2}
100
90
80
70
60
50
40
30
20
10
0
50
75
100
A
Observed range
10
20
50
100
200
500
1000
2000
5000
Time (Ma)

Age=25-100 Ma

Lord Kelvin error

1862- age of the Earth is between 20 and 400 Mln yrs



Geologists were strongly against such short time, but could not find physical objections !

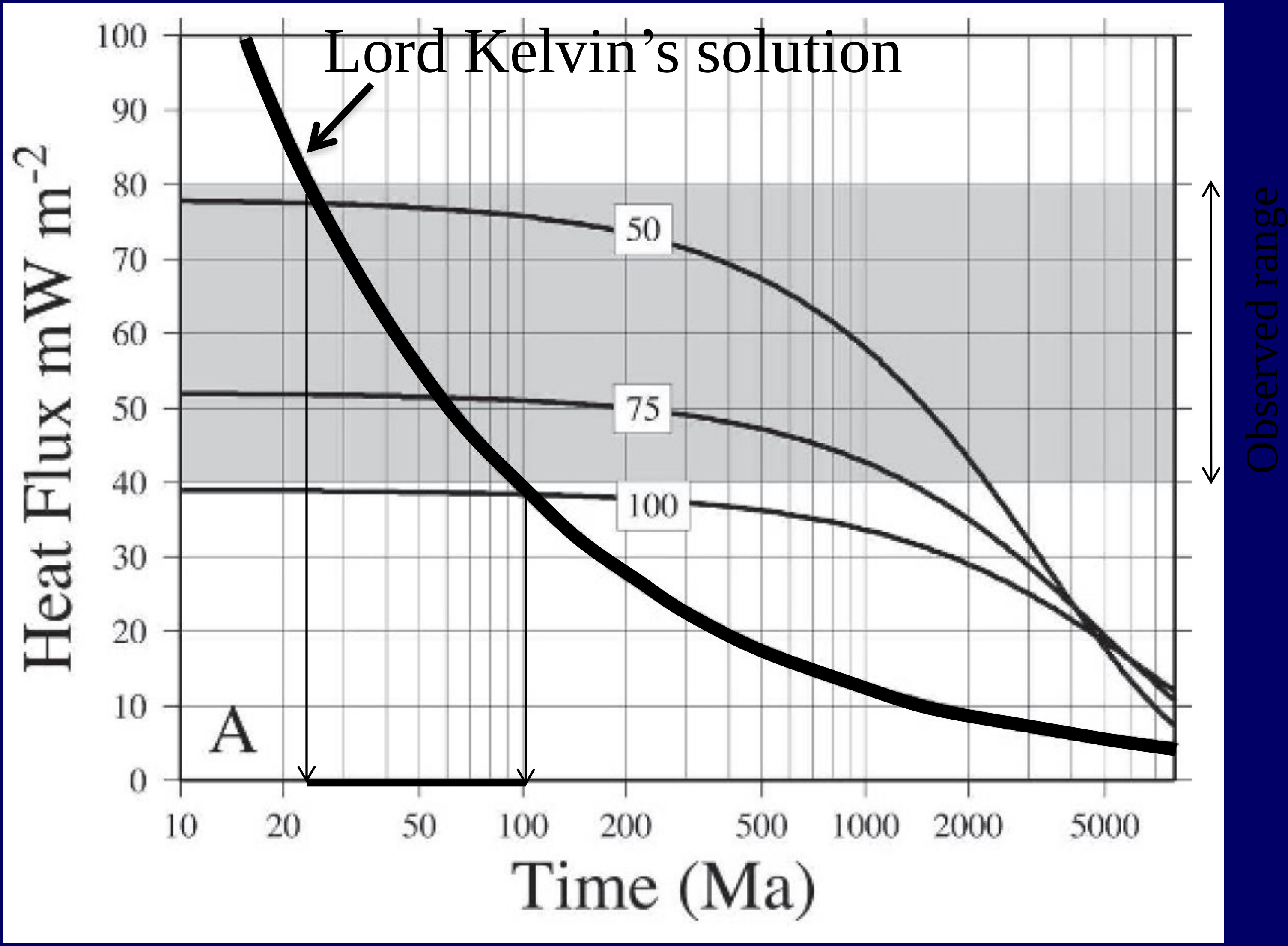
William Thomson, Lord Kelvin (1824–1907)

Does consideration of radioactivity help?

Entire radiogenic heat production for the Earth is about $2*10^{13}$ W

If distributed in the Earth homogeneously it gives volumetric heat production rate of $A=2*10^{-5}$ mW/m^3

Surface layer of thickness H will generate heat flow J=H*A. For H=100 km, **J=2 mW/m^2**



Lord Kelvin's solution
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100
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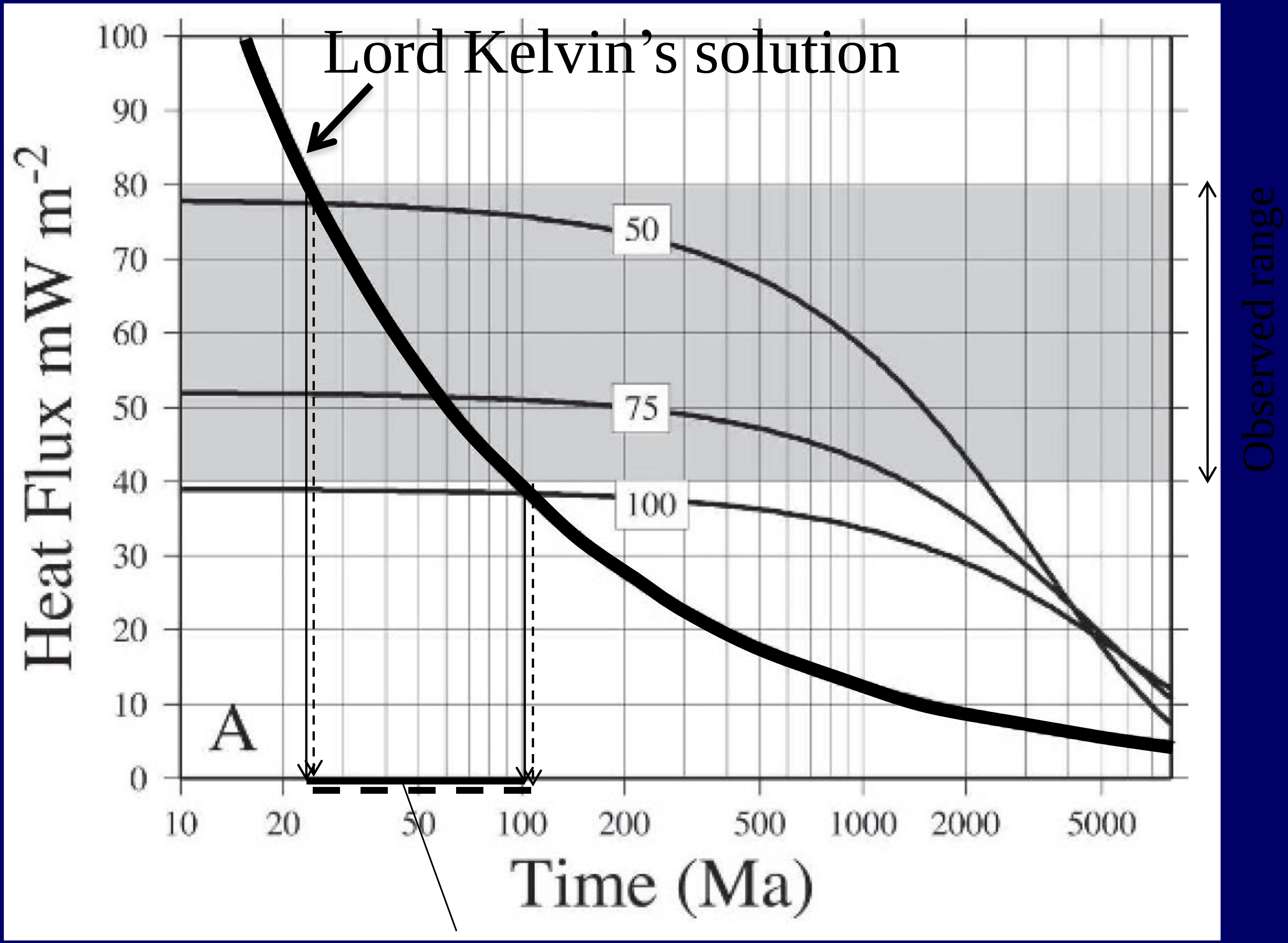
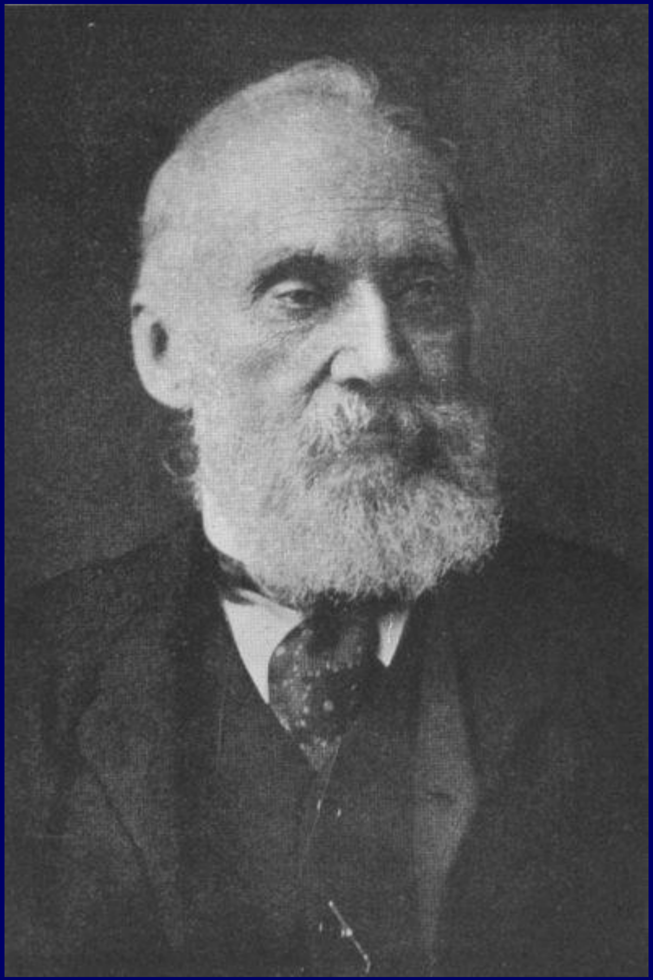
20
50
100
200
500
1000
2000
5000
Time (Ma)
Observed range



Correction is much too small!

Lord Kelvin error

1862- age of the Earth is about 20 Mln yrs

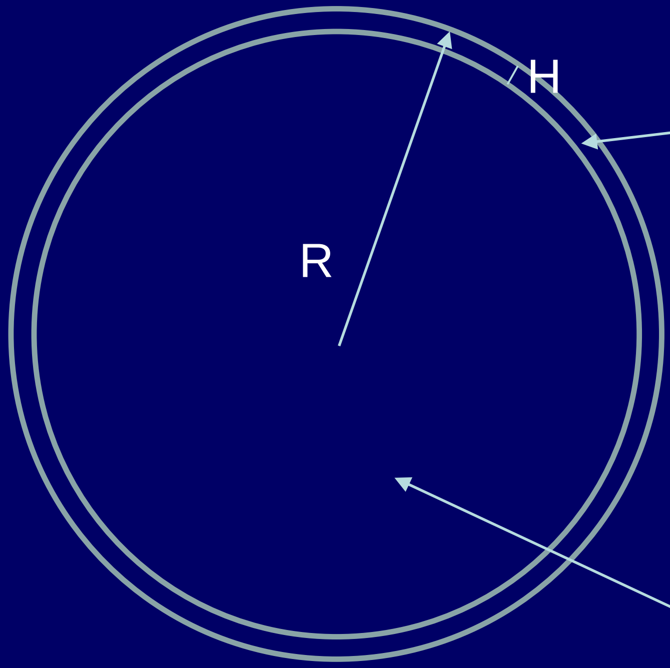


1895- age of the Earth increases to few Bln. Yrs

William Thomson, Lord Kelvin (1824–1907)

John Perry (1850-1920)

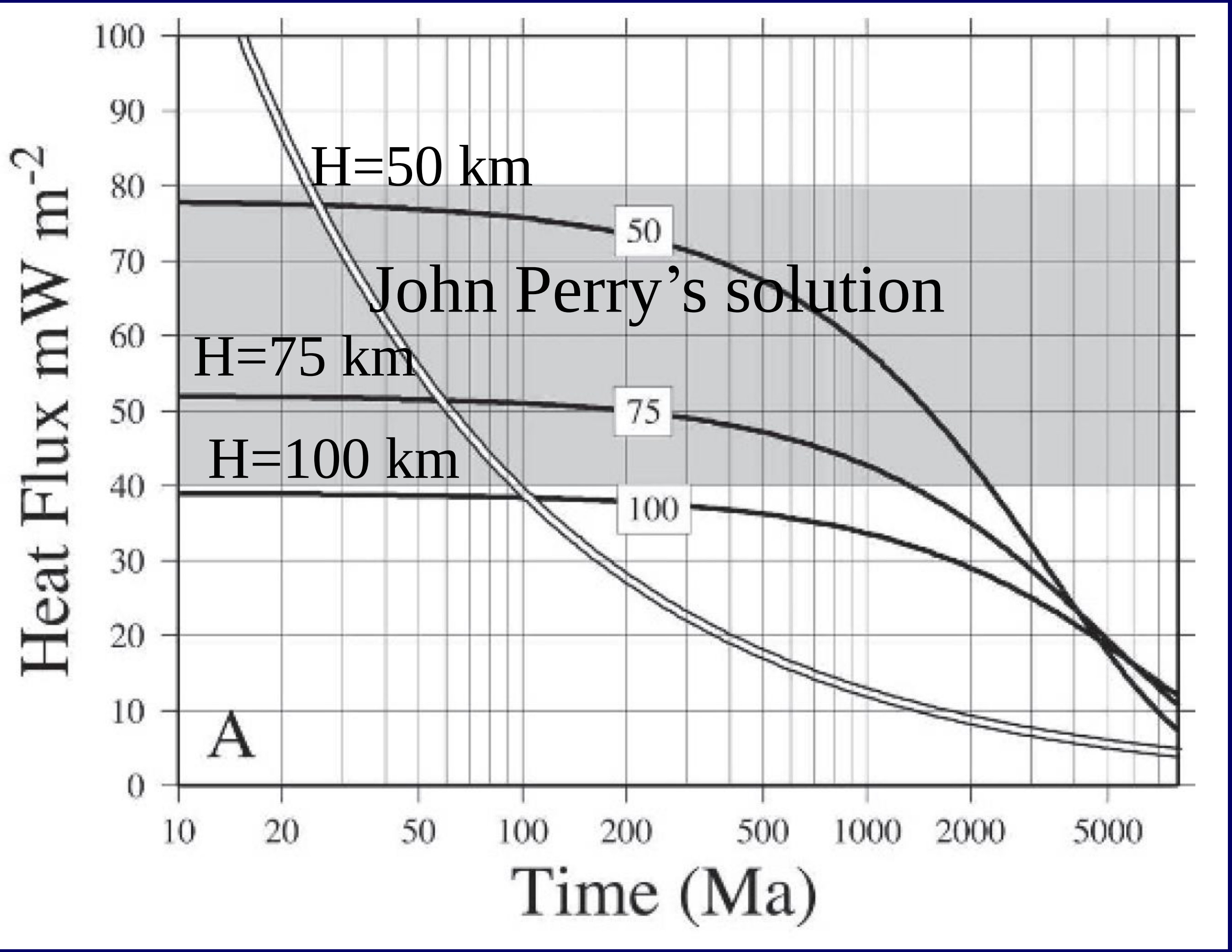
Perry assumed that inner part of the cooling Earth beneath the shell with thickness H was/is vigorously convecting. In this case heat from the deep Earth is efficiently transmitted to the surface



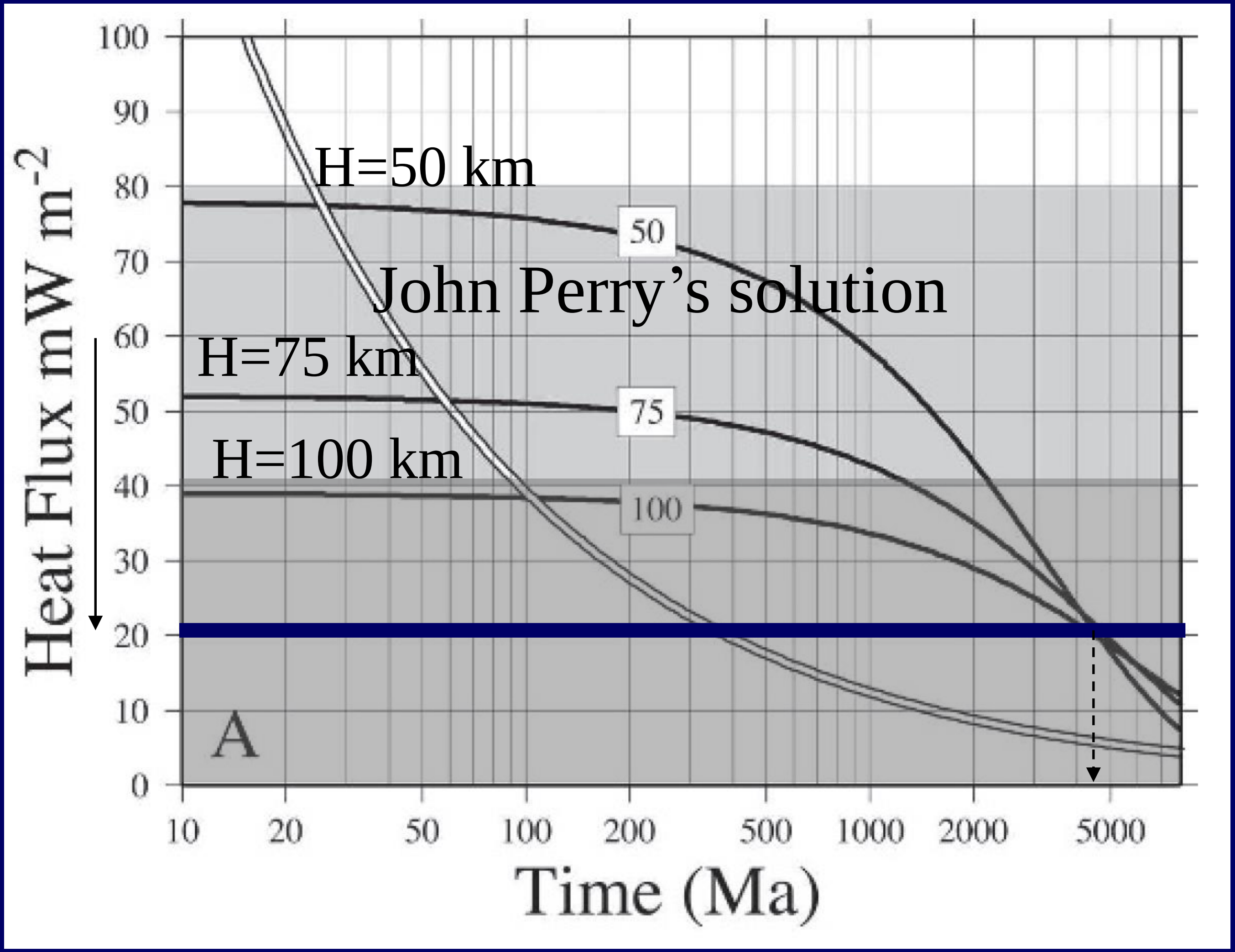
Thermal conduction, heat flow $Q=\lambda*(T_m-T_{surf})/H$

Vigorous convection, homogeneous temperature (T_m)

Perry's solution



When we add radiogenic heat production of the entire Earth, that gives 40 mW/m2 heat flux; then Perry’s model must explain surface heat flux reduced by 40 mW/m2



Lord Kelvin errors:

1. **Assumed conductive (slow) heat transfer in the entire Earth= ignored convection in the Earth (Major error)**
2. Did not consider radiogenic heat production (not known at that time)- less important error

If Lord Kelvin respected the intuition of geologists and supported John Perry, geophysicists would invent mantle convection already in year 1895!

If Lord Kelvin respected the intuition of geologists and supported John Perry, geophysicists would invent mantle convection already in year 1895!

That would bring closer and make much easier establishment of the Earth-Science main theory—Plate Tectonics
and Alfred Wegener's idea would be much better recognized during his life!

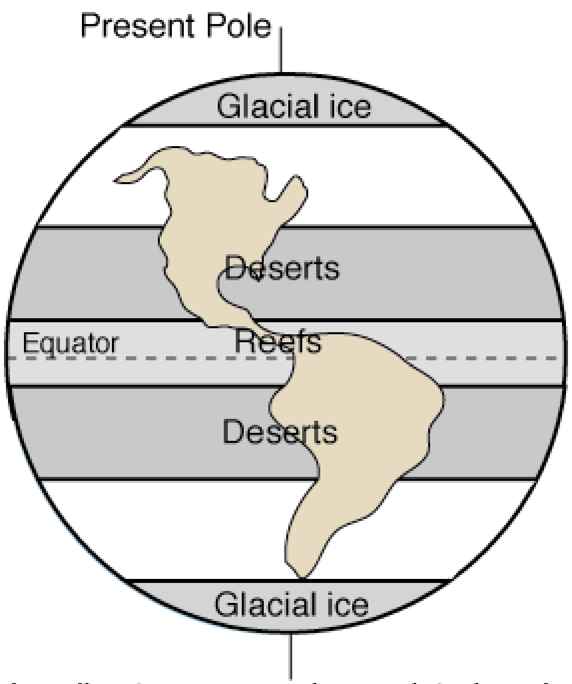
From Continental Drift to Plate Tectonics

<u>1915</u> first edition of book

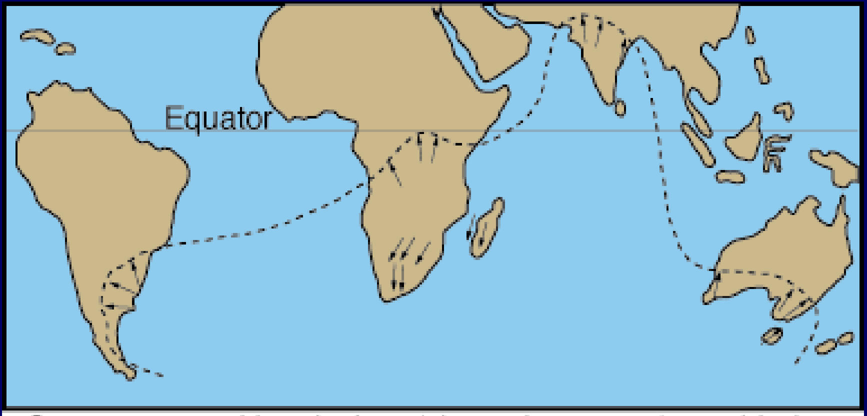
"*Die Enstehung der Kontinente und Ozeane*"

Alfred Lothar Wegener (1880 –1930)

Paleoclimate argument



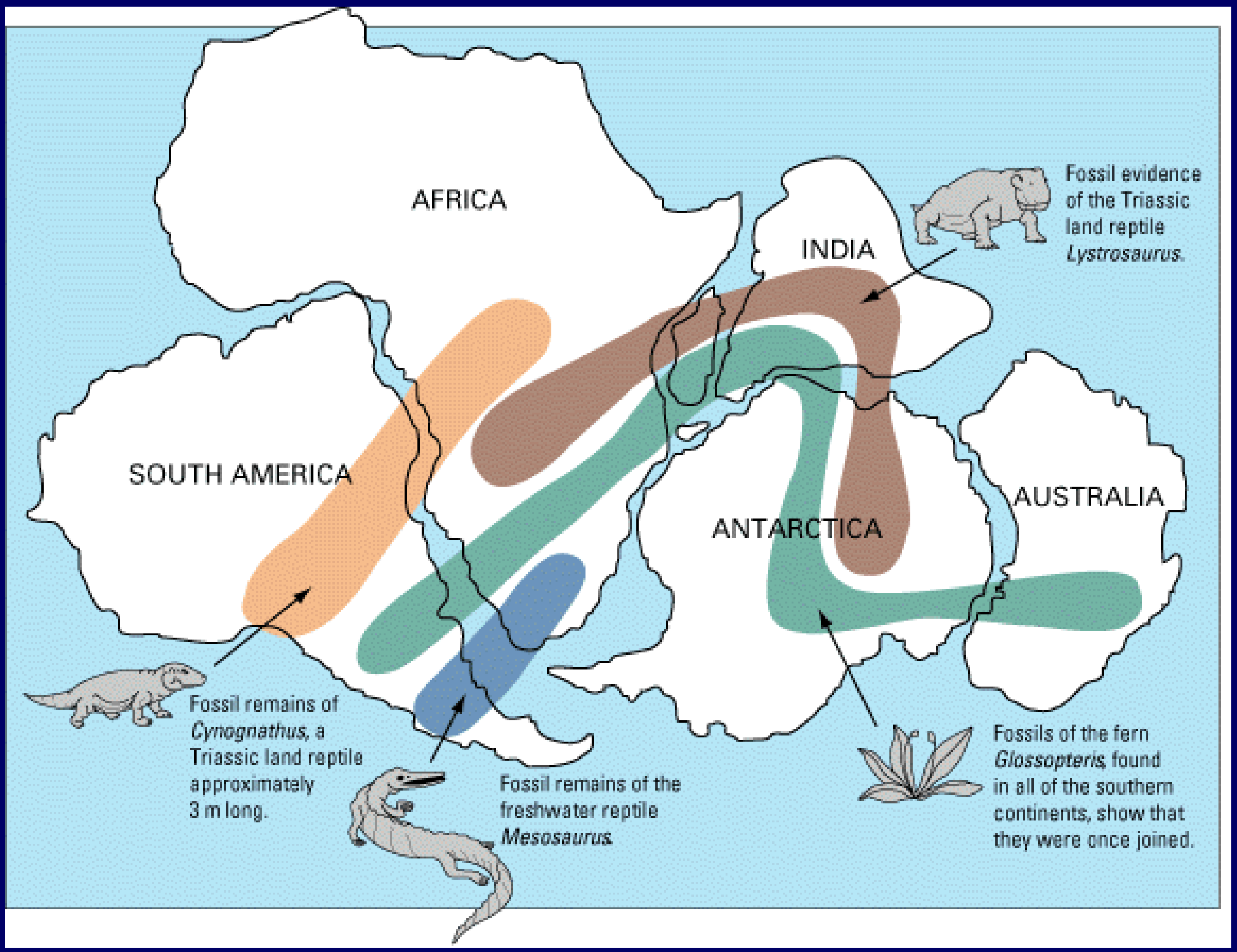
Present-day climate zones and associated geologic features define a pattern relative to the pole of rotation.



Grooves carved by glaciers (shown by arrows) provided evidence for continental drift. This diagram assumes the continents were in their present-day locations.

The distribution of glacial features can be best explained if the continents were part of Pangaea.

Fossils distribution argument



Wegener suggested that continents moved by thousands of km based on large range of various observations: very valuable approach in geodynamics

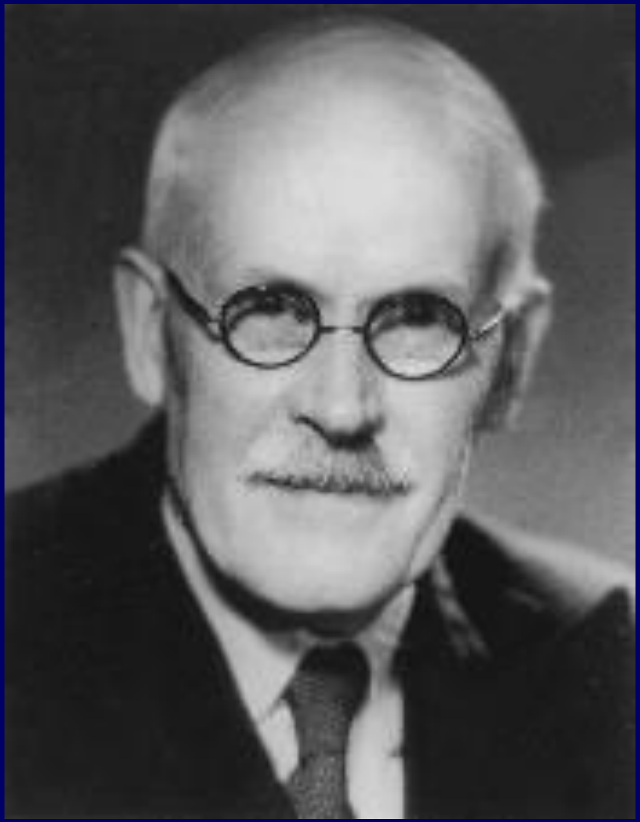
The next step should be recognition of reasons, i.e. origin of forces required to move the continents

Wegener suggested <u>rotational</u> and <u>tidal forces</u> as a possible driver

It was soon recognized that rotational and tidal forces are insufficient

From Continental Drift to Plate Tectonics

1912- Continental Drift hypothesis



Alfred Lothar Wegener (1880 –1930)

Sir Harold Jeffreys (1891 – 1989)

Fatal argument against continental drift :

most of the crust and mantle is solid and elastic (elastic shear waves pass through), ***hence continents can not drift by 1000 km***

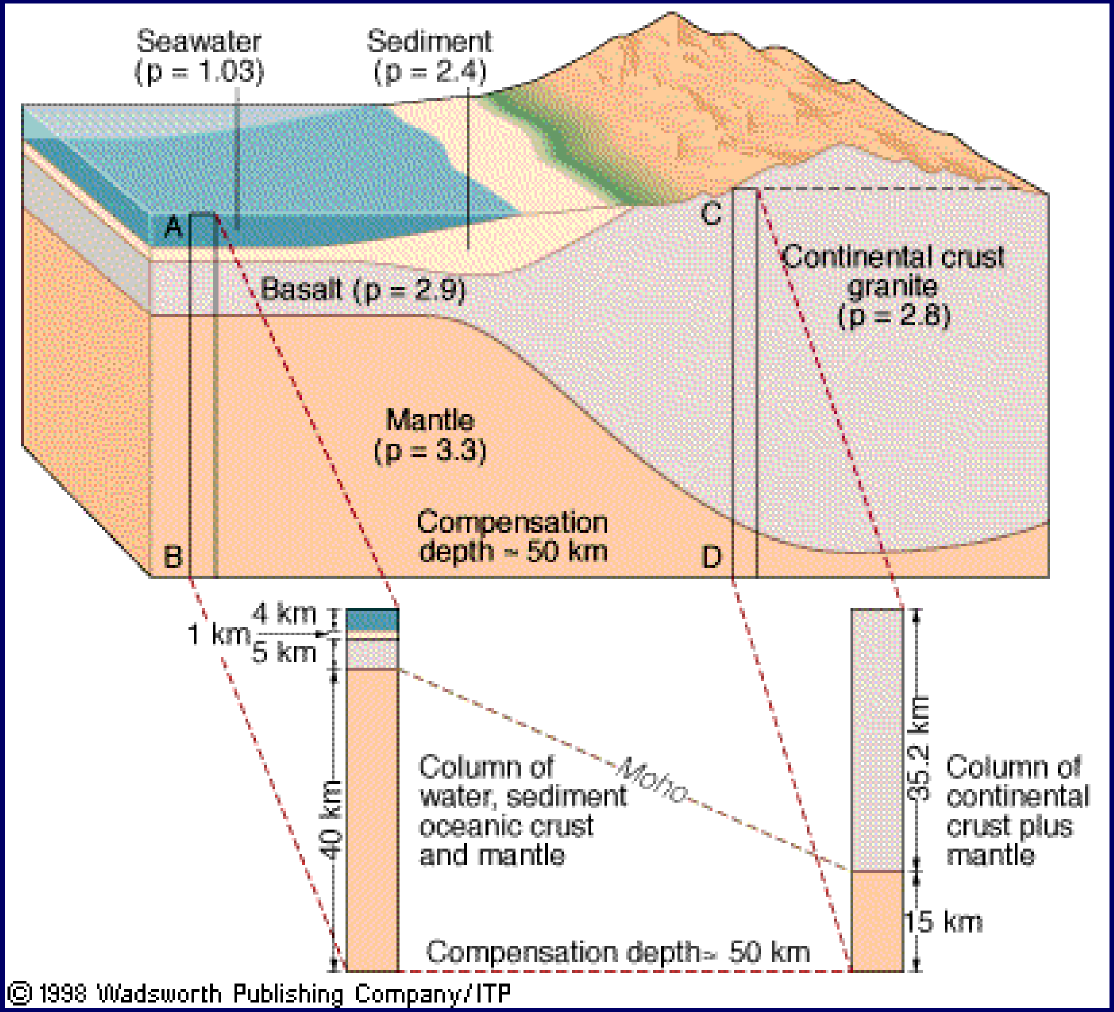
Contra-argument:

solid-flow is possible at geological time scale - ductile rheology

Isostasy was already known since 1885!

isostasy:
columns of mass must be the same at a certain depth (compensation depth) ~ 50 km

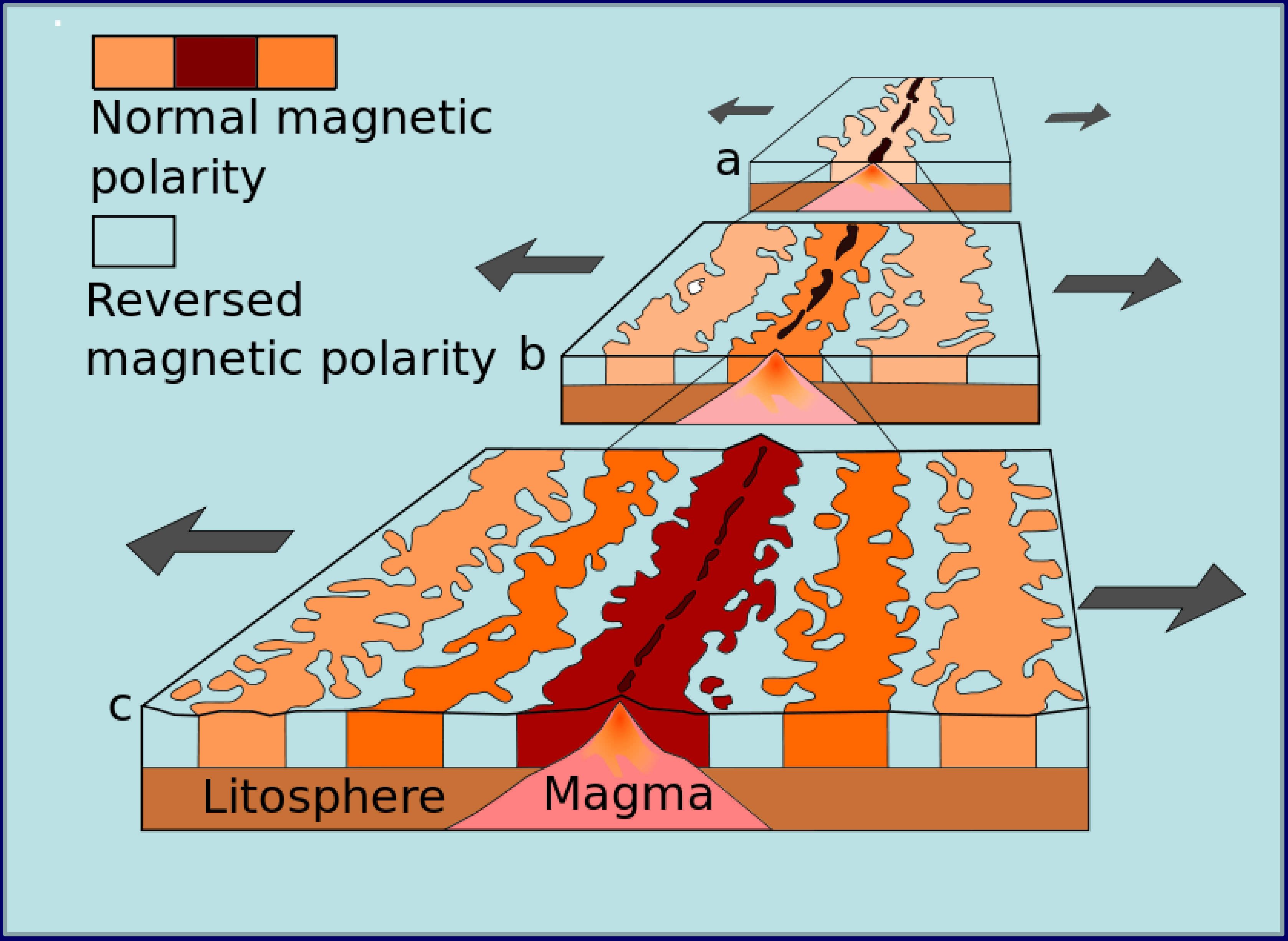
continents have roots and stick-up



1928- Mantle convection as a driver of continental drift

Arthur Holmes (1891 – 1989)

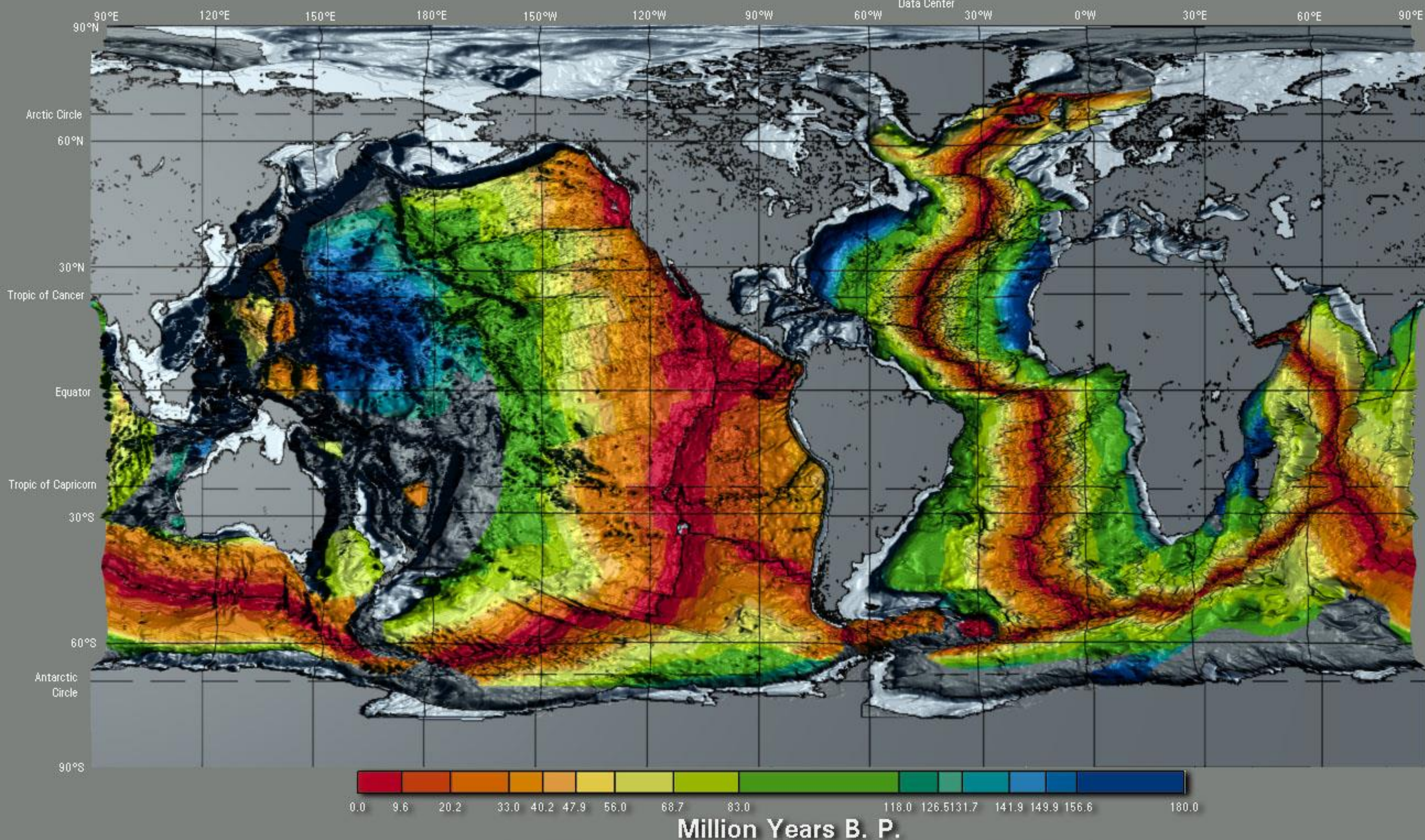
Great 1960s!



Vine and Matthews (1963)

Crustal Age

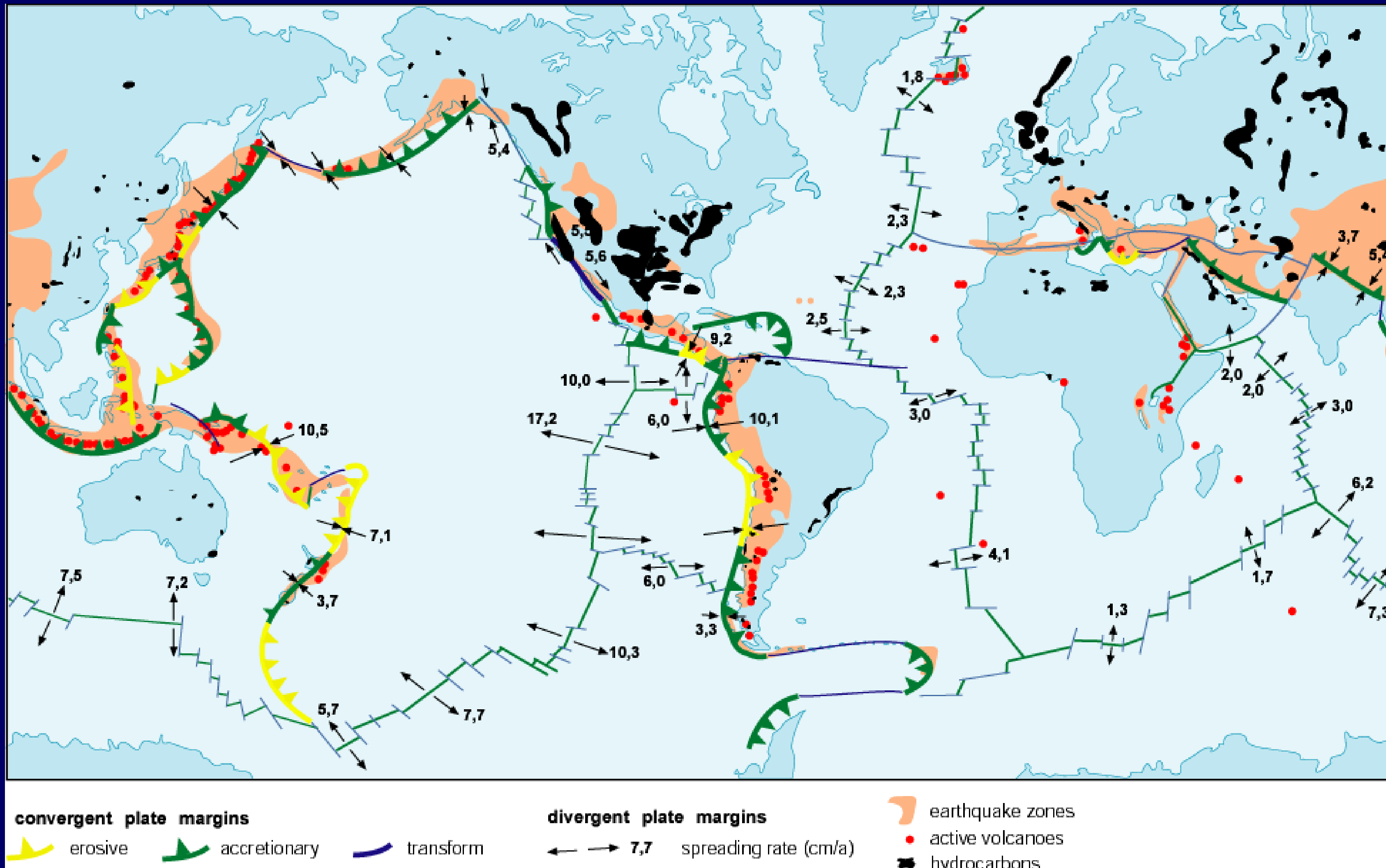
National Geophysical Data Center



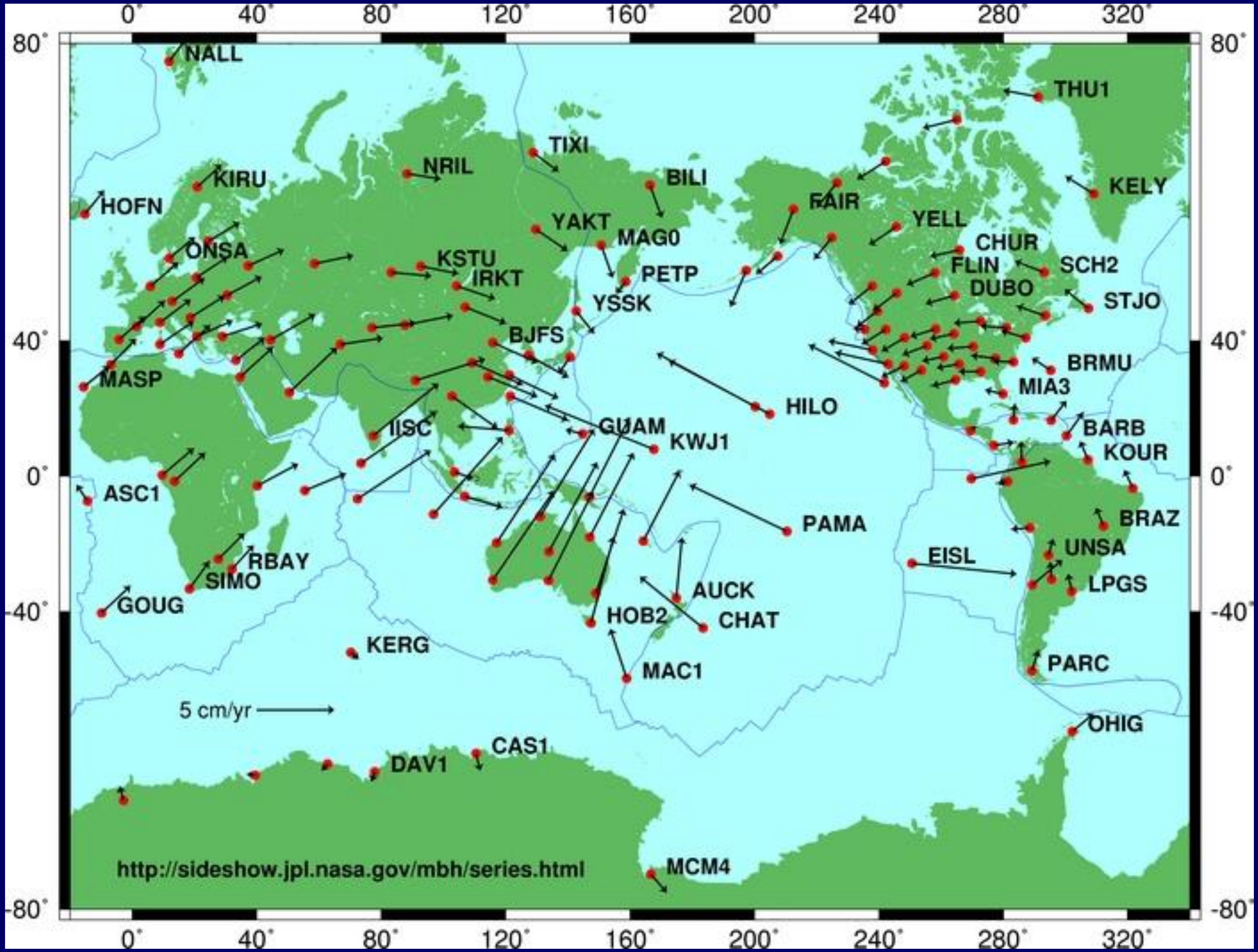
Data for the image from "Digital Age Map of the Ocean Floor" by Müller, Roest, Royer, Gahagan, and Schlater, Scripps Institution of Oceanography Ref. Series No. 93-30

For information on this and other images produced by NGDC's Marine Geology and Geophysics Division, contact Peter Sloss at plsoss@ngdc.noaa.gov

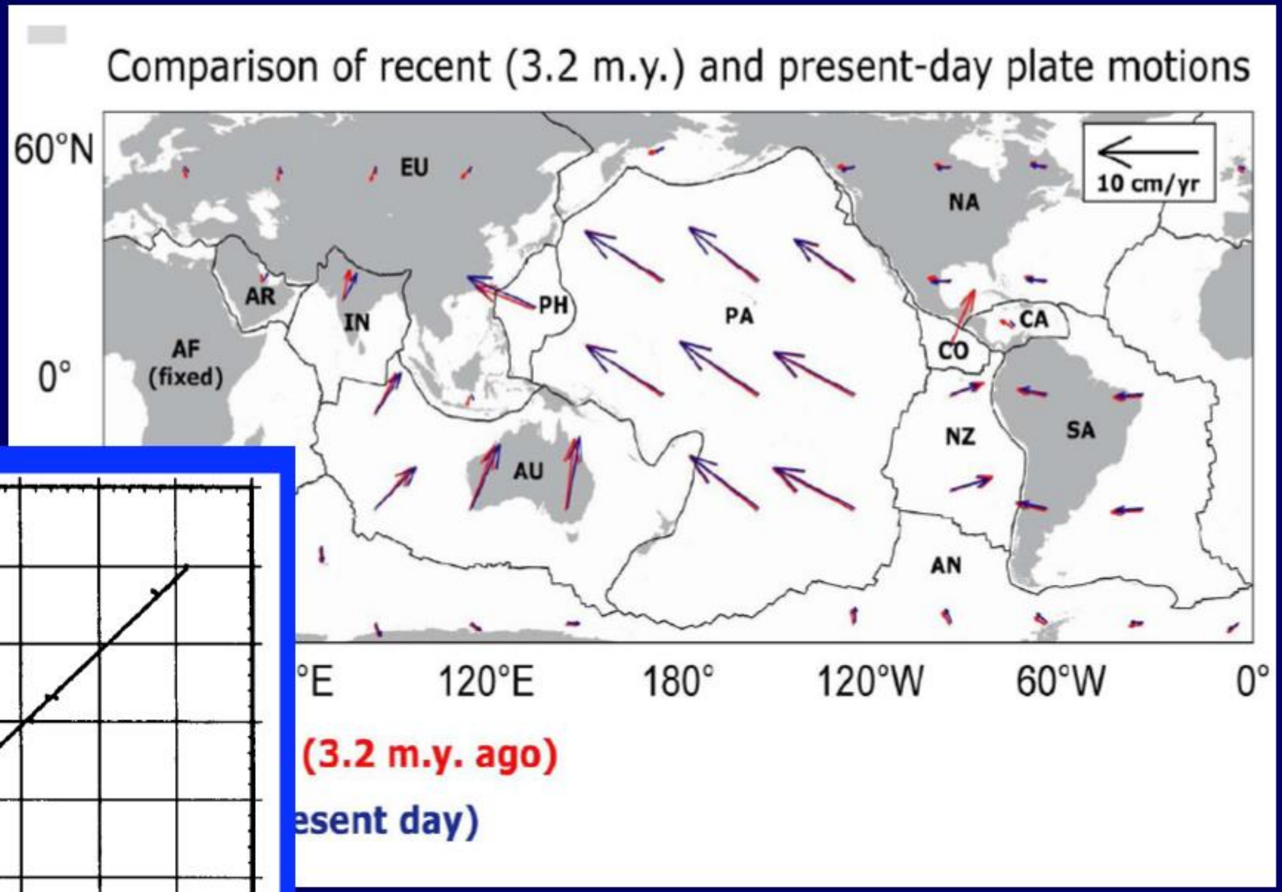
Plates

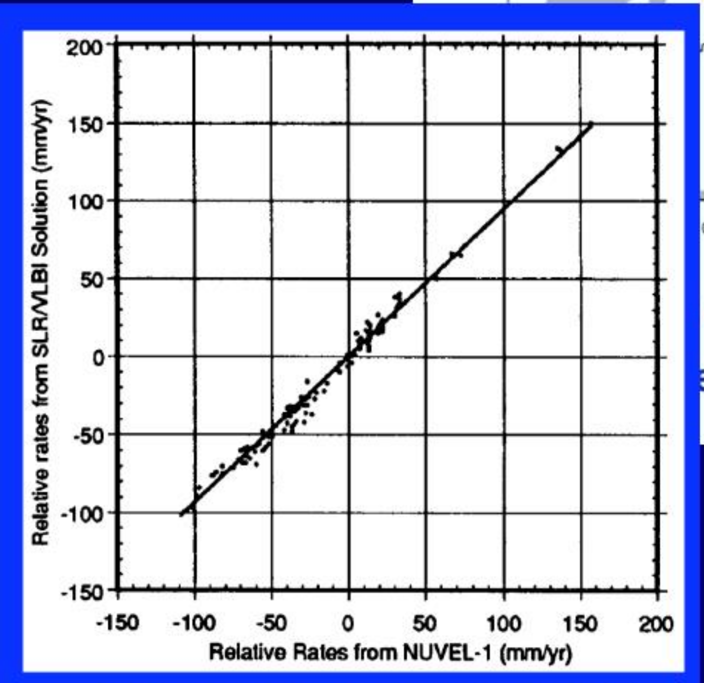

1,8
2,3
2,3
2,5
3,0
4,1
1,3
1,7
2,0
2,0
3,0
6,2
7,3
3,7
5,4
5,4
5,6
9,2
10,0
17,2
6,0
10,1
6,0
3,3
10,3
7,7
5,7
10,5
7,1
3,7
7,5
7,2
convergent plate margins
erosive
accretionary
transform
divergent plate margins
7,7 spreading rate (cm/a)
earthquake zones
active volcanoes
hydrocarbons

GPS-revolution



GPS revolution





3 Myr average plate motion model

Plate tectonics model is verified !

What causes plate tectonics?

Google search top:

How Do Plates Move?
Plates at our planet's surface move because of the intense heat in the Earth's core that causes molten rock in the mantle layer to move. It moves in a pattern called a convection cell…

Source:
http://www.windows2universe.org/earth/interior/how_plates_move.html

What causes plate tectonics?

Google search top:

- **Q:** What causes tectonic plates to move?
- **A:QUICK ANSWER**
- The three primary causes for tectonic plate movement are the convection of material in the mantle, gravity and the rotation of the planet.

Source:
https://www.reference.com/science/causes-tectonic-plates-move-974f091e6fc56047

Is convection in the mantle sufficient to produce plate tectonics?

What kind of tectonics should be expected with "normal" mantle convection?

$$\eta \approx exp(H_a/nRT)$$

Stagnant-lid tectonics→ convection beneath the outer shall (lid) and no much deformation near the surface

NOT Plate Tectonics!

Surface would not move by 1000 km.

Additional ingredient is required.

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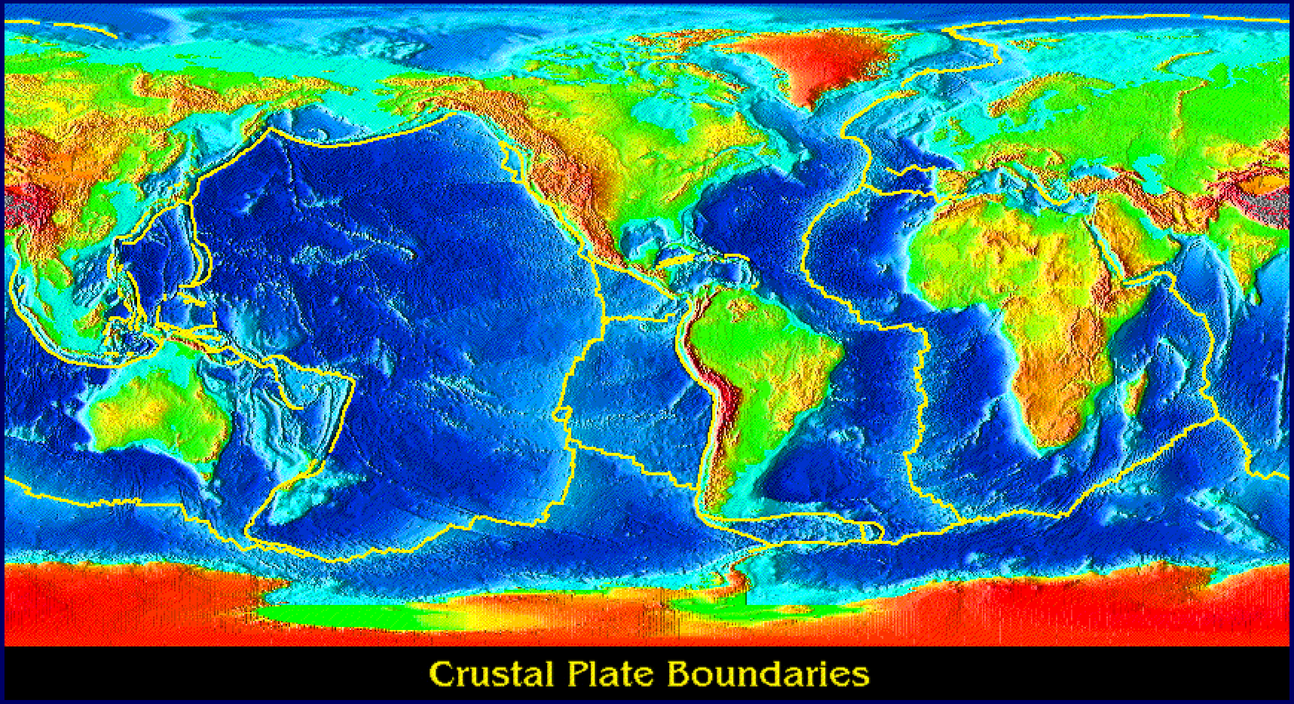
Surface would not move by 1000 km.

Additional ingredient is required.



Weak plate boundaries

Key factors for plate tectonics

1. Mantle convection
2. Weak plate boundaries, and particularly, weak interfaces of subducting slabs making subduction interfaces the weakest faults

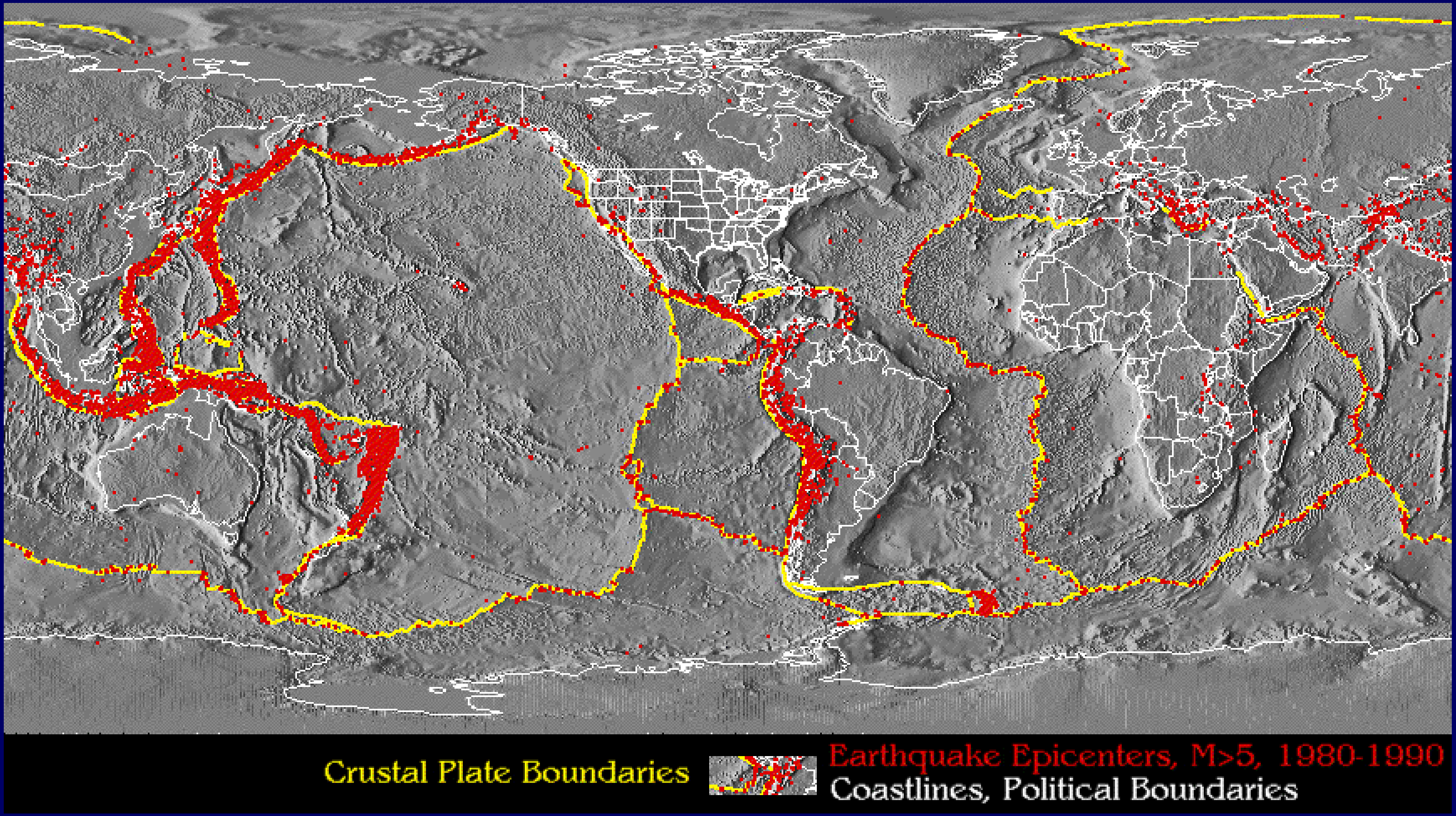
Is "weakness" of plate boundaries consistent with appearance there greatest earthquakes?

Plate tectonics and great earthquakes

At geological-time scale (10-1000 Mln.y) signatures of Plate Tectonics are 1000 km -scale plate motions, large deformations at plate boundaries like mountain belts, rift zones and transform faults or Wilson Cycle

At time-scale of less than 1000 years signatures of Plate Tectonics are earthquakes at plate boundaries

Earthquakes and plate tectonics



The greatest earthquakes occur in subduction zones

Great Earthquakes challenges

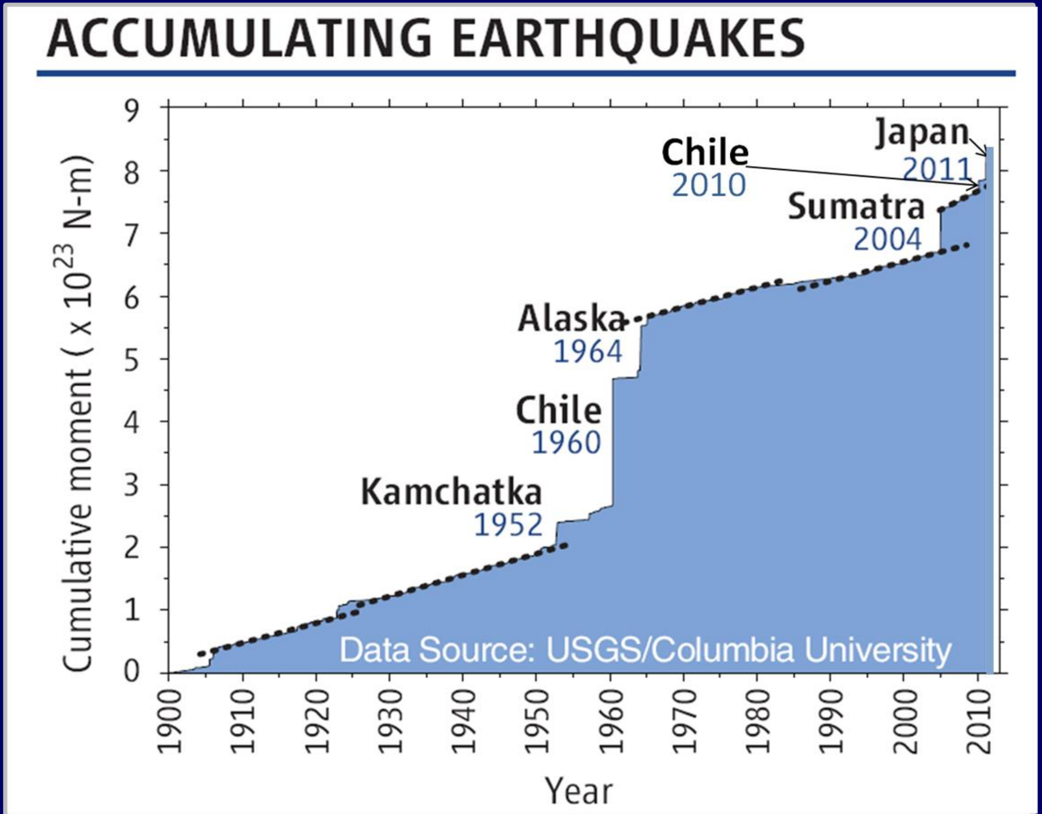
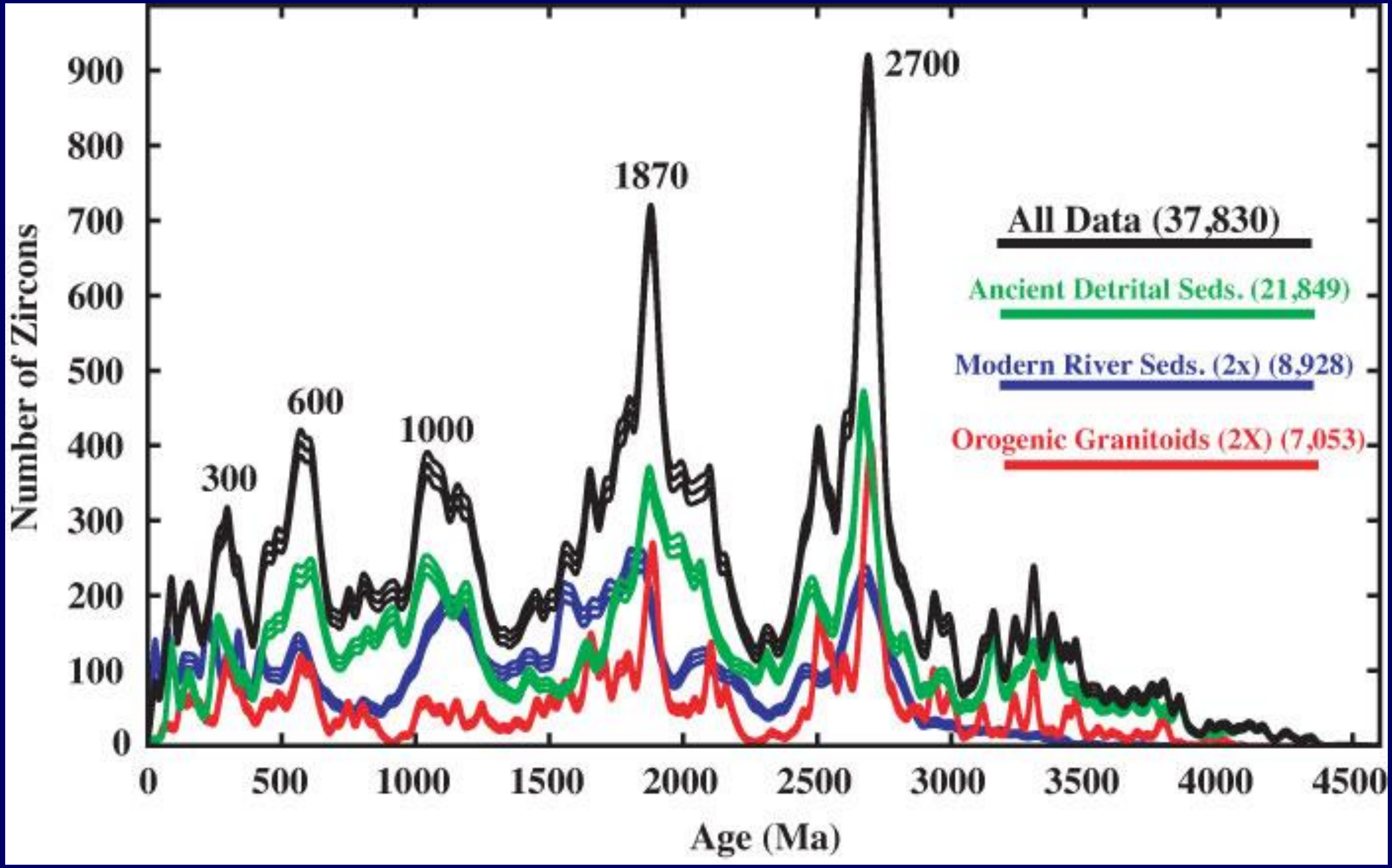


Figure 1. Cumulative seismic moment versus time. Modified from [Kerr, 2011]

Why the greatest earthquakes occur in the weakest zones? Do they indeed cluster?

How and when the plate tectonics started at Earth?

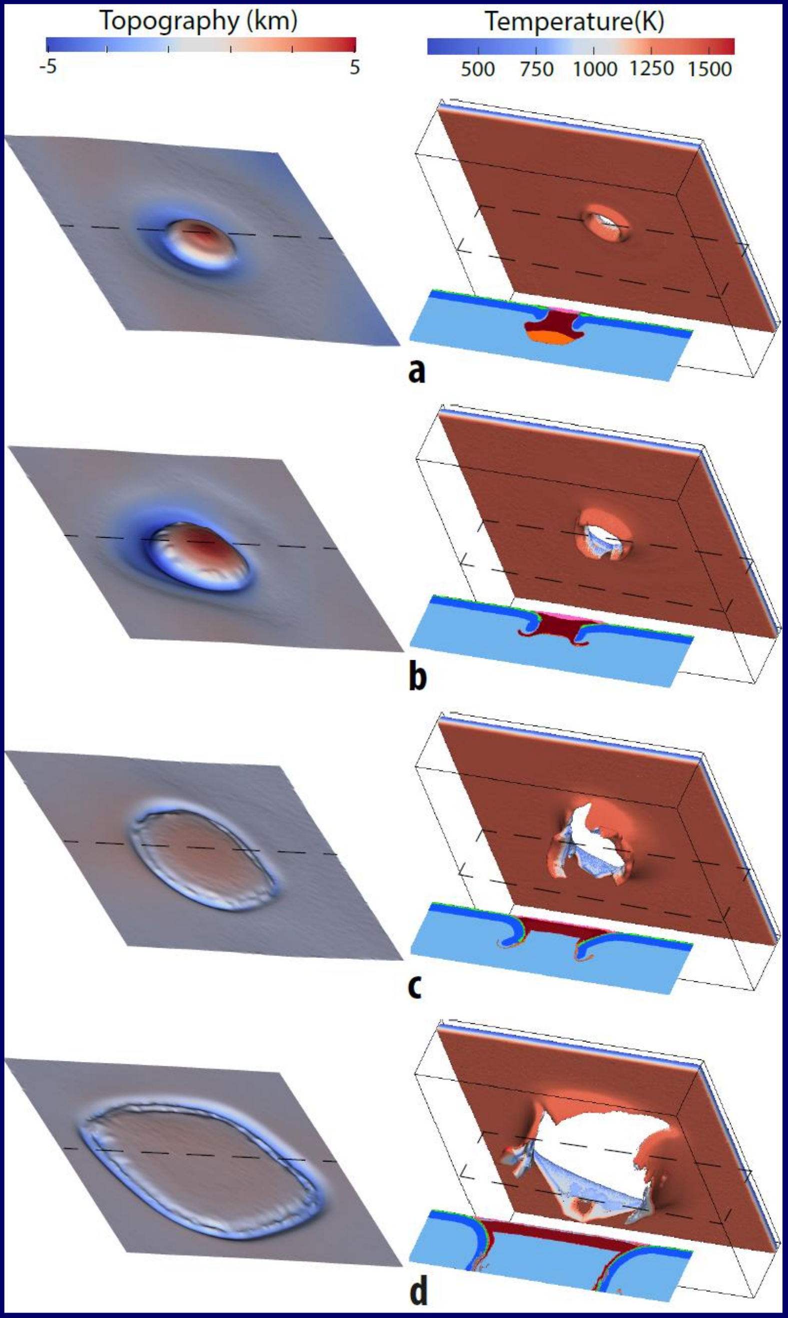
Zircon Age Distribution through time. Monitor of Continental Crust growth



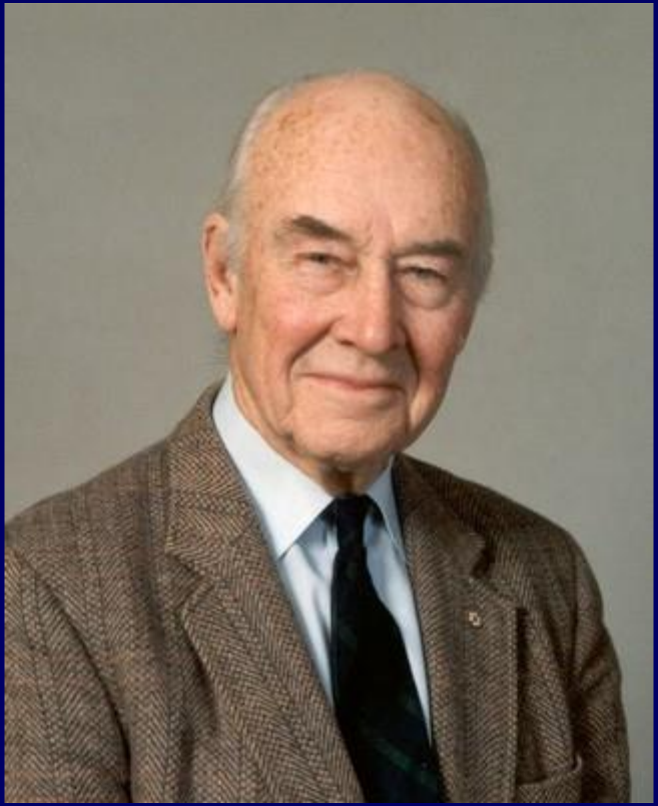
Condie & Aster, 2009

How and when the plate tectonics started at Earth?

Brand-new 3D model for initiation of plate tectonics by mantle plume



Mysteries of Wilson cycle



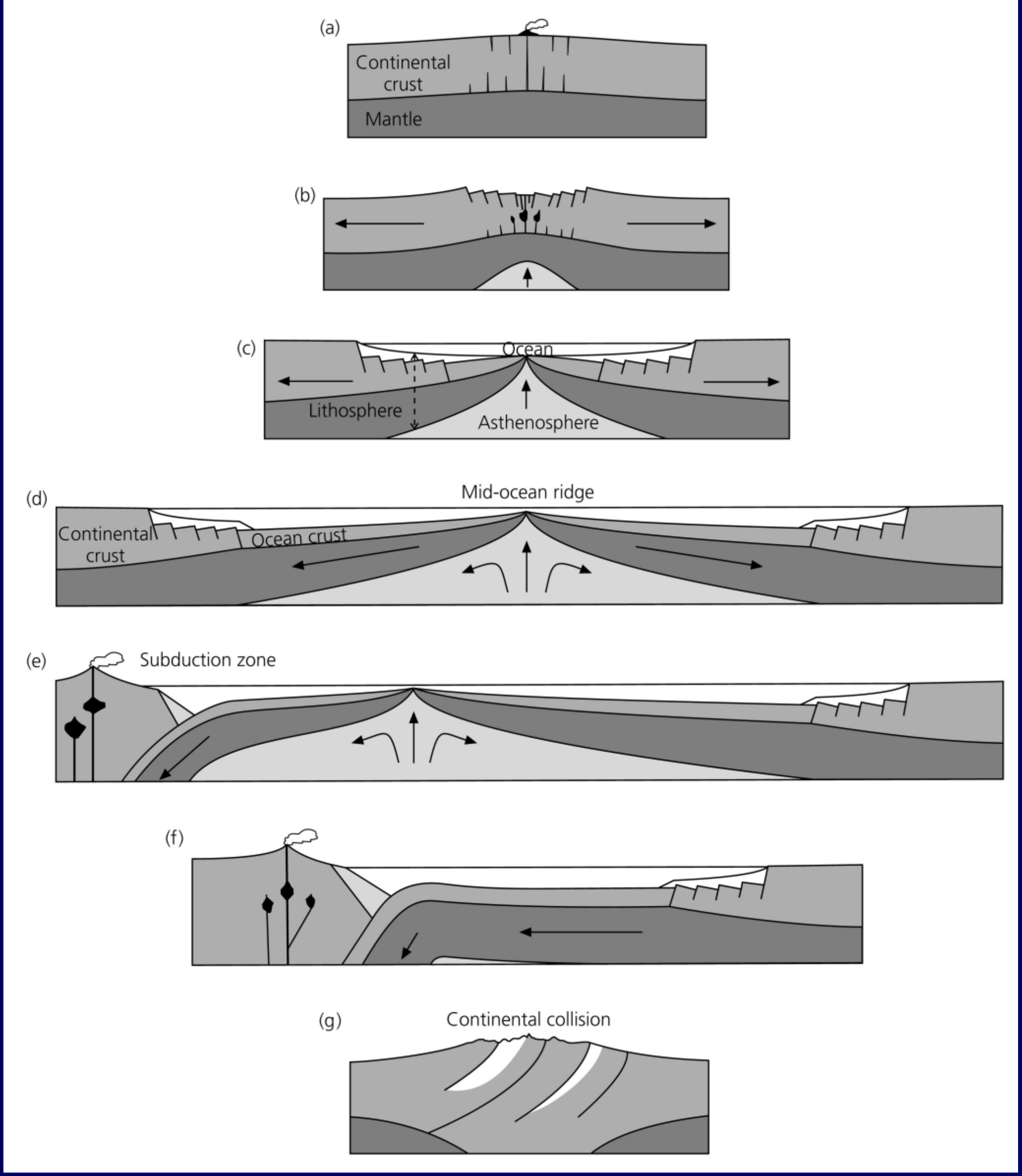
John Tuzo Wilson (1908–1993)

Wilson cycle

Physically difficult

No known examples

Physically very difficult



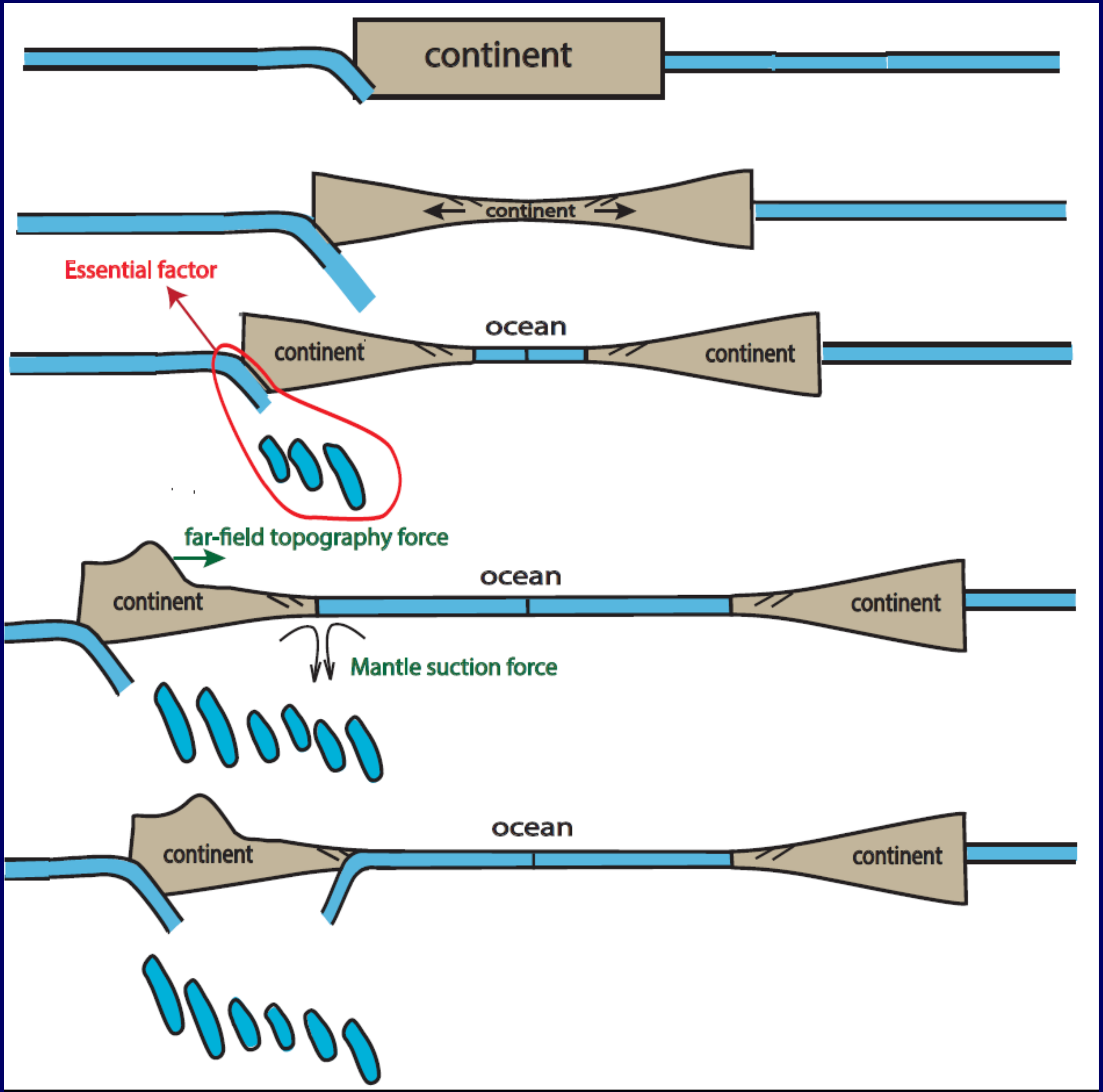
Wilson Cycle challenges

How do the continents break up?

How do passive margins convert into active (subduction) margins?

How do passive margins convert into active (subduction) margins?

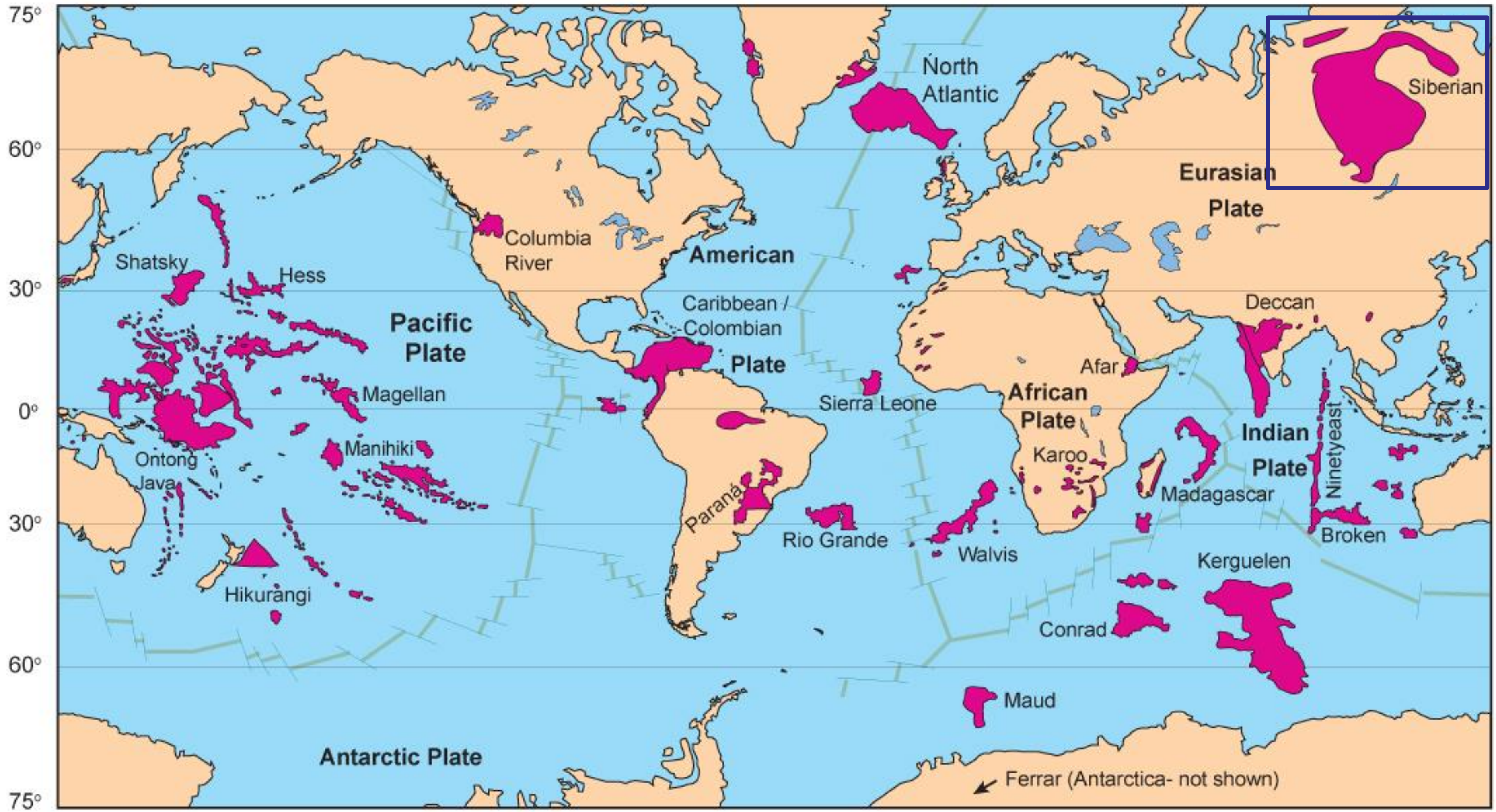
Brand-new model for initiation of subduction at passive margins



In our course we will see ideas and models attempting to resolve these and other key problems of plate tectonics

Beyond the plate tectonics

Large Igneous Provinces (LIPs)



After Saunders et al. (1992)

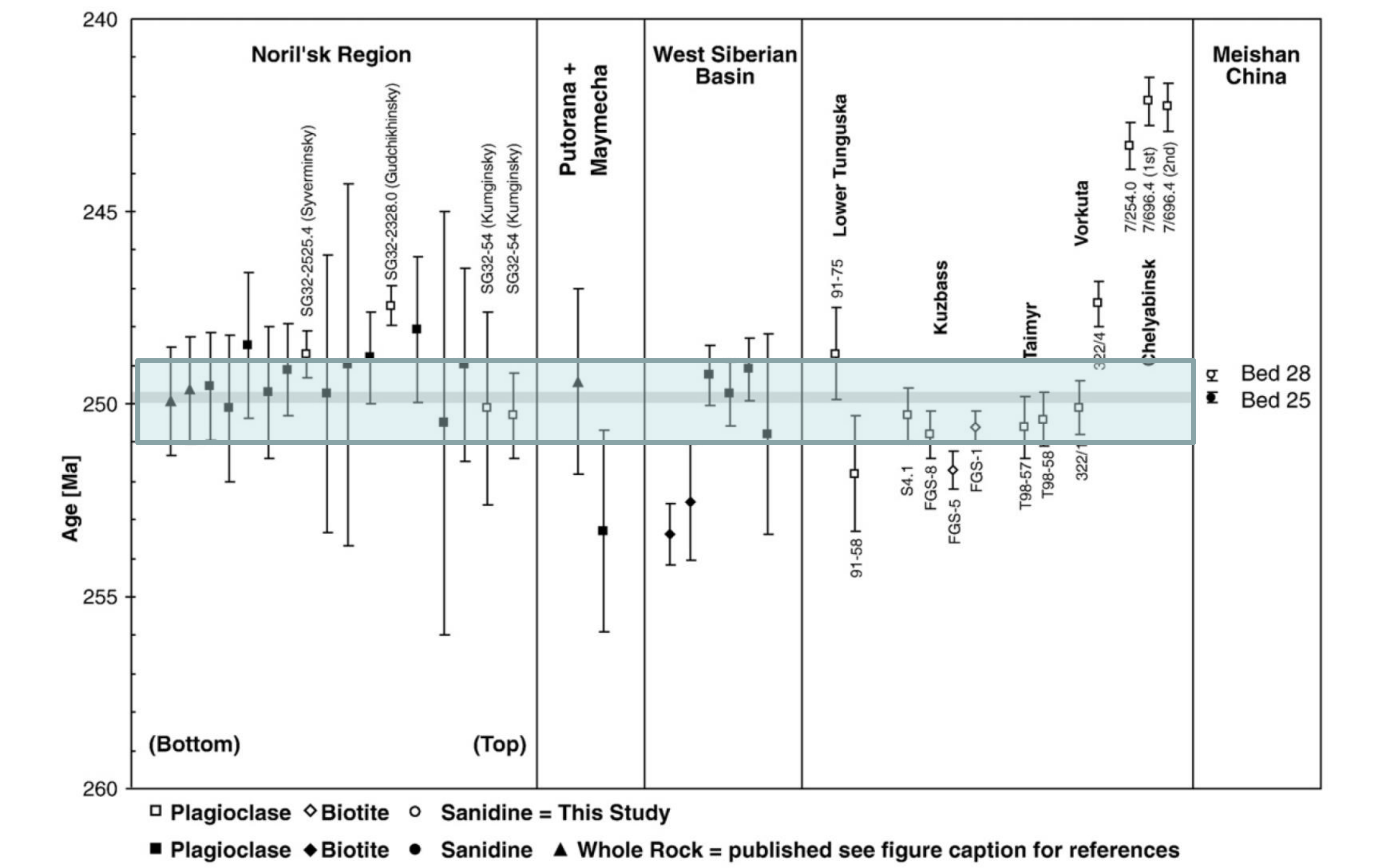
Siberian LIP

- Over <u>**4 mln. km^3**</u> of magmas produced in less than **1 ma**

Siberian LIP

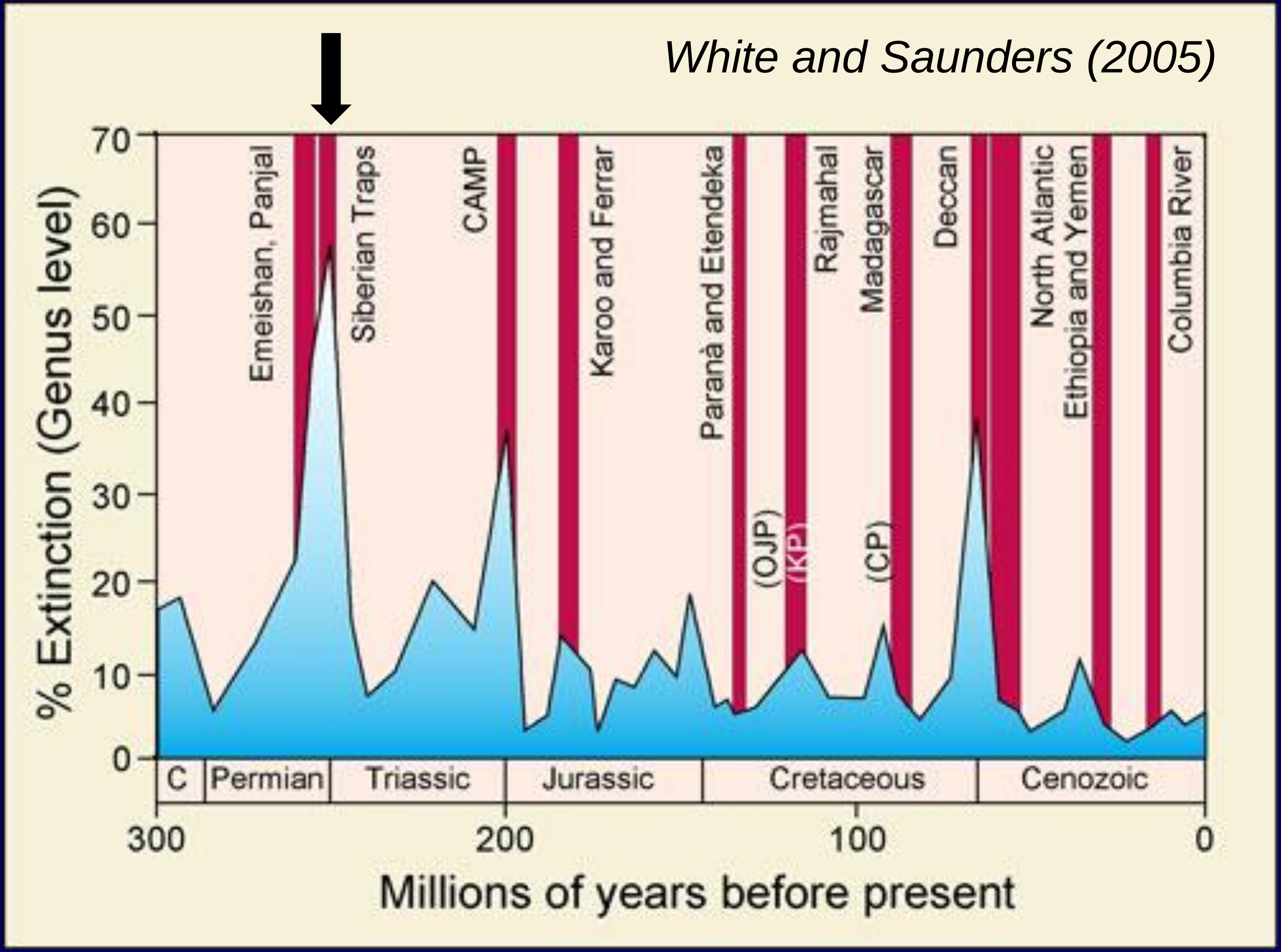
- Over **<u>4 mln. km^3</u>** of magmas produced in less than **1 ma**

Ar-Ar age of Siberian Flood Basalts 250±1.1 Ma



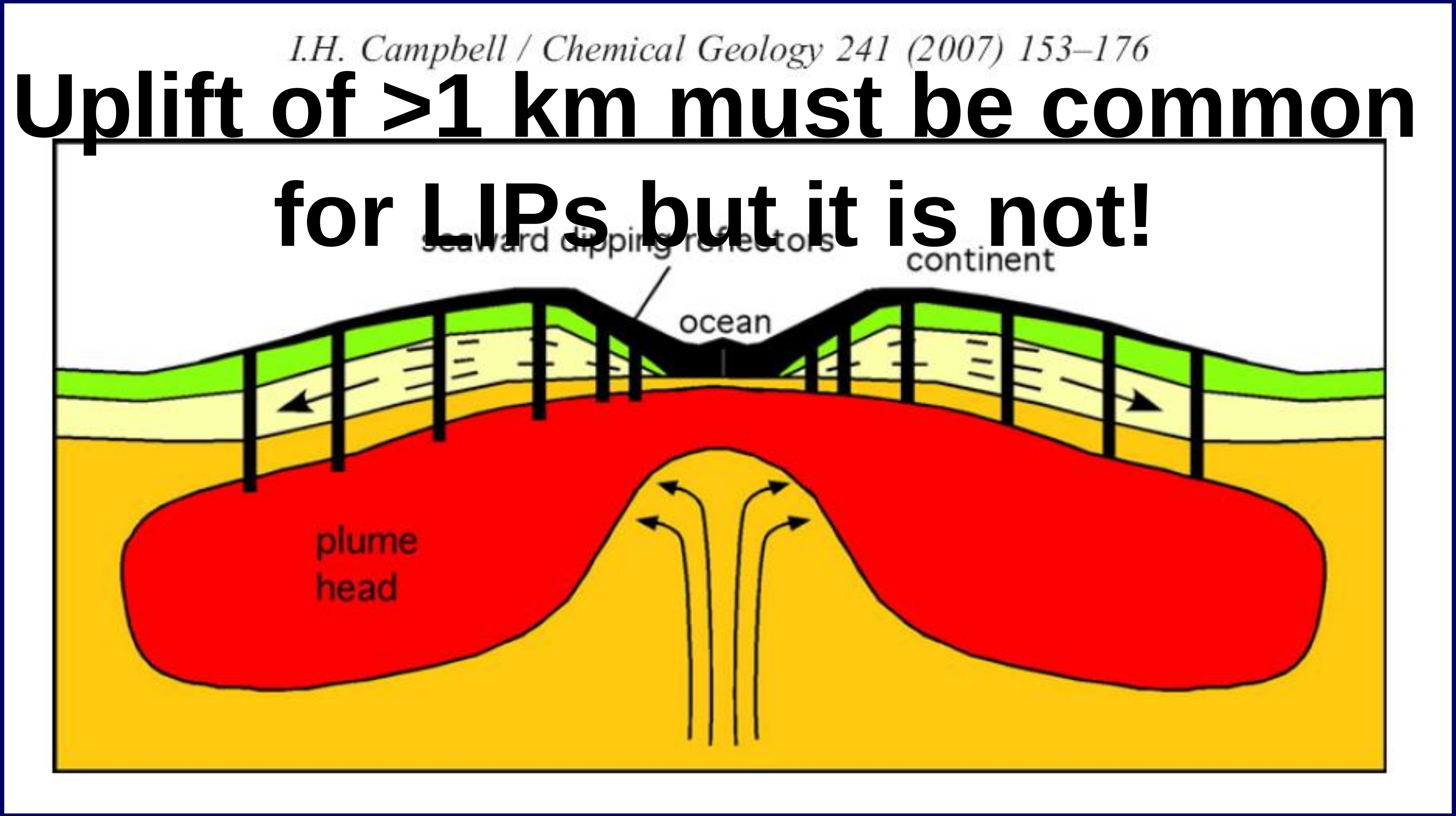
Reichow et al, 2009

LIPs correlate with mass extinction events



Plume head model of LIPs

White and McKenzie, 1989; Richards et al.,1989,
Campbell and Griffiths, 1990



How do LIPs form and how do they relate to plumes and plate tectonics?

Why in some cases LIPs are associated with mass extinctions and in other not?

In our course we will see ideas and models attempting to solve key problems of LIPs

Equations

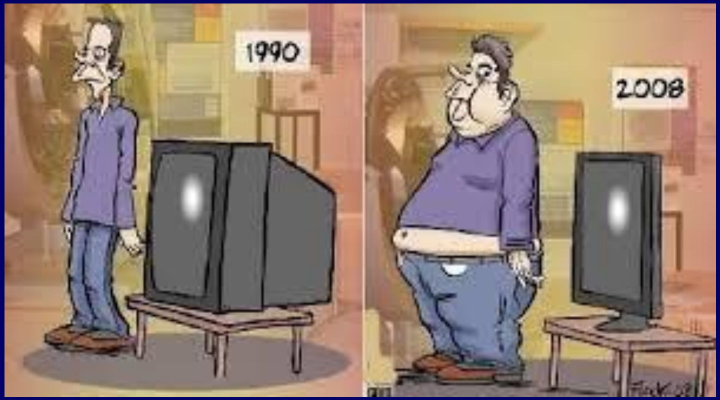
Geodynamic modelling

Basic conservation laws

Geodynamic modelling

Basic conservation laws

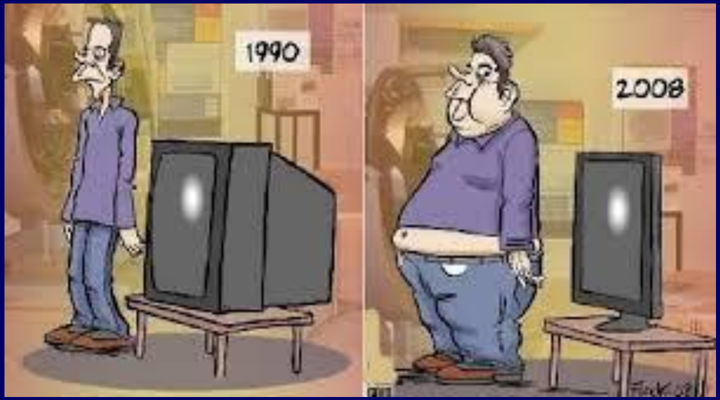
Mass conservation law:



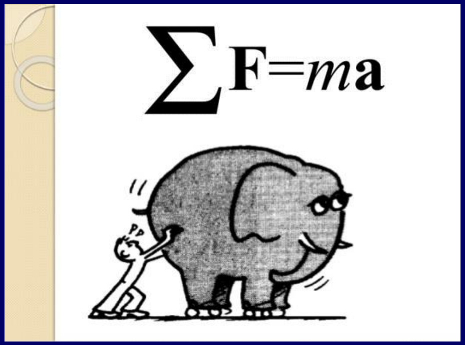
Geodynamic modelling

Basic conservation laws

Mass conservation law:



Momentum conservation law:



Geodynamic modelling

Basic conservation laws

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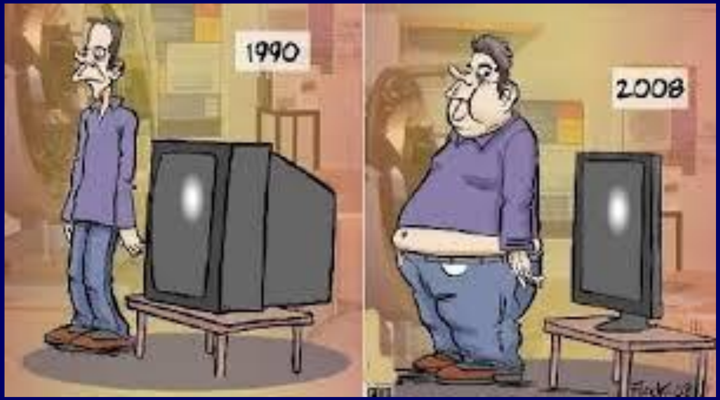

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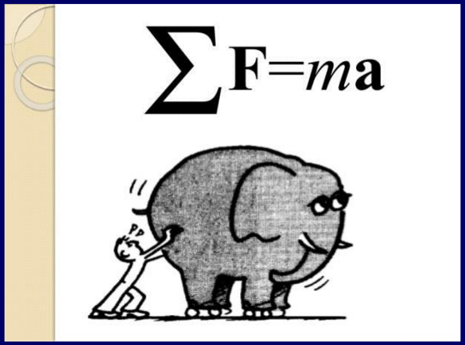
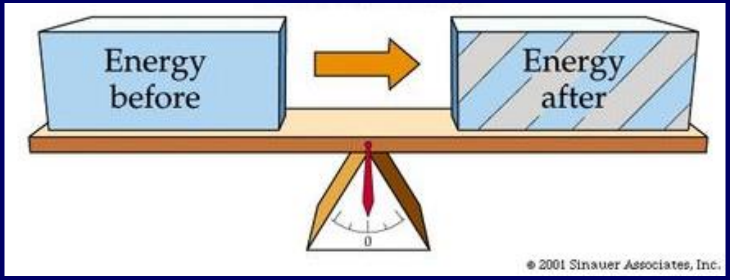


Energy conservation law:



Geodynamic modelling

Basic conservation laws

Mass conservation law:

$$\frac{1}{K}\frac{DP}{Dt} - \alpha\frac{DT}{Dt} + \frac{\partial v_i}{\partial x_i} = 0$$

Momentum conservation law:

$$-\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i = \rho\frac{Dv_i}{Dt}$$

Energy conservation law:

$$\rho C_p\frac{DT}{Dt} = \frac{\partial}{\partial x_i}\left(\lambda\frac{\partial T}{\partial x_i}\right) + \frac{1}{\eta_{eff}}\tau_{ij}\tau_{ij} + \rho A + \Delta H_{chem}$$

Geodynamic modelling

Basic conservation laws

Mass conservation law:

1 equation

$$\frac{1}{K}\frac{DP}{Dt} - \alpha\frac{DT}{Dt} + \frac{\partial v_i}{\partial x_i} = 0$$

Momentum conservation law:

3 equations

$$-\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i = \rho\frac{Dv_i}{Dt}$$

Energy conservation law:

1 equation

$$\rho C_p\frac{DT}{Dt} = \frac{\partial}{\partial x_i}\left(\lambda\frac{\partial T}{\partial x_i}\right) + \frac{1}{\eta_{eff}}\tau_{ij}\tau_{ij} + \rho A + \Delta H_{chem}$$

Geodynamic modelling

Basic conservation laws

Mass conservation law:

1 equation

$$\frac{1}{K}\frac{DP}{Dt} - \alpha\frac{DT}{Dt} + \frac{\partial v_i}{\partial x_i} = 0$$

Momentum conservation law:

Only 5 equations for 11 unknowns!

3 equations

$$-\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i = \rho\frac{Dv_i}{Dt}$$

Energy conservation law:

1 equation

$$\rho C_p \frac{DT}{Dt} = \frac{\partial}{\partial x_i}\left(\lambda\frac{\partial T}{\partial x_i}\right) + \frac{1}{\eta_{eff}}\tau_{ij}\tau_{ij} + \rho A + \Delta H_{chem}$$

Geodynamic modelling

Rheological (constitutive) equations

Equation of state for density:

1 equation

$$\rho = F(P,T)$$

Deformation mechanisms:

5 equations

$$\dot{\varepsilon}_{ij} = \frac{1}{2}\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right) = \Phi(P,T,\tau_{ij})$$

Geodynamic modelling

Rheological (constitutive) equations

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1 equation

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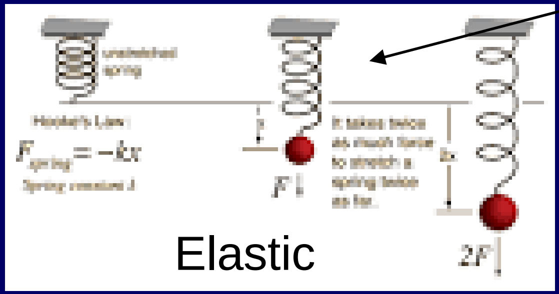
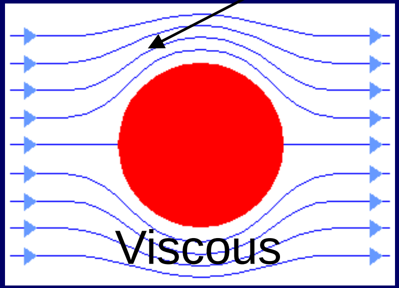
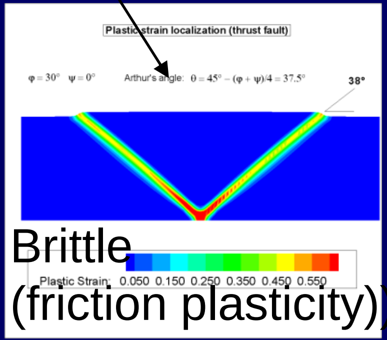
5 equations

$$\dot{\varepsilon}_{ij} = \frac{1}{2}\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right) = \Phi(P,T,\tau_{ij})$$







Major numerical challenges

Handle large non-linearity

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Handle extreme variations of viscosity >5 orders of magnitude

Major numerical challenges

Handle large non-linearity

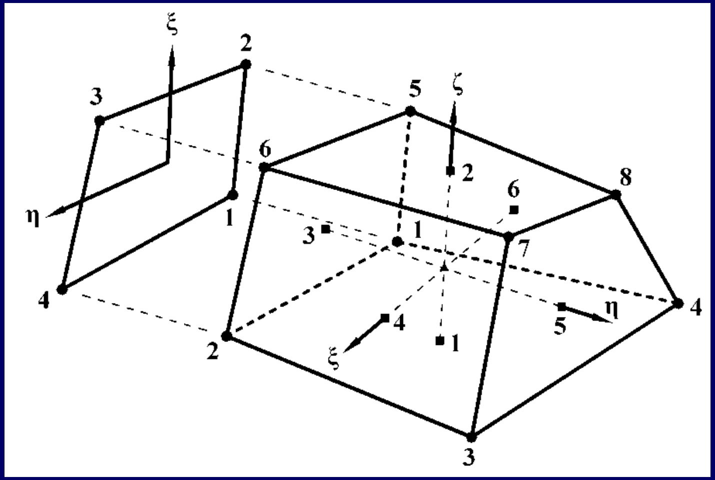
Handle extreme variations of viscosity >5 orders of magnitude

Model strong strain localization = faults

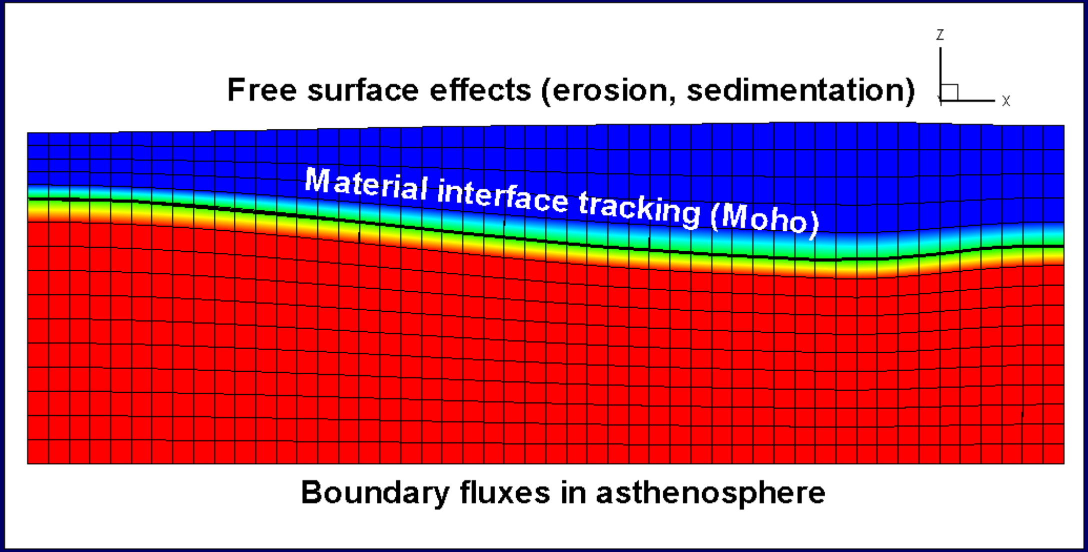
Numerical methods

Numerical FE code SLIM3D

Discretization by Finite Element Method



Arbitrary Lagrangian-Eulerian kinematical formulation



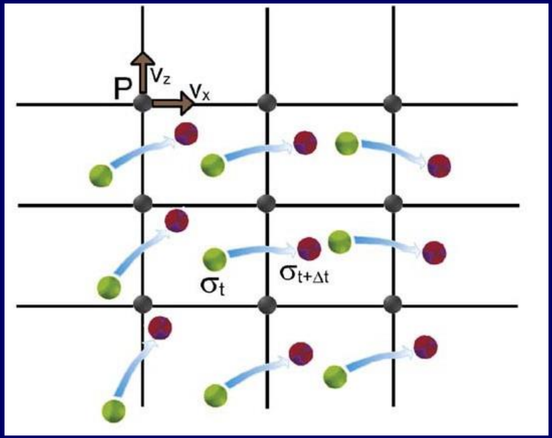
Fast implicit time stepping + Newton-Raphson solver

$$\mathbf{u}_{k+1} = \mathbf{u}_k - \mathbf{K}_k^{-1}\mathbf{r}_k$$

$\mathbf{r}$ – **Residual Vector**

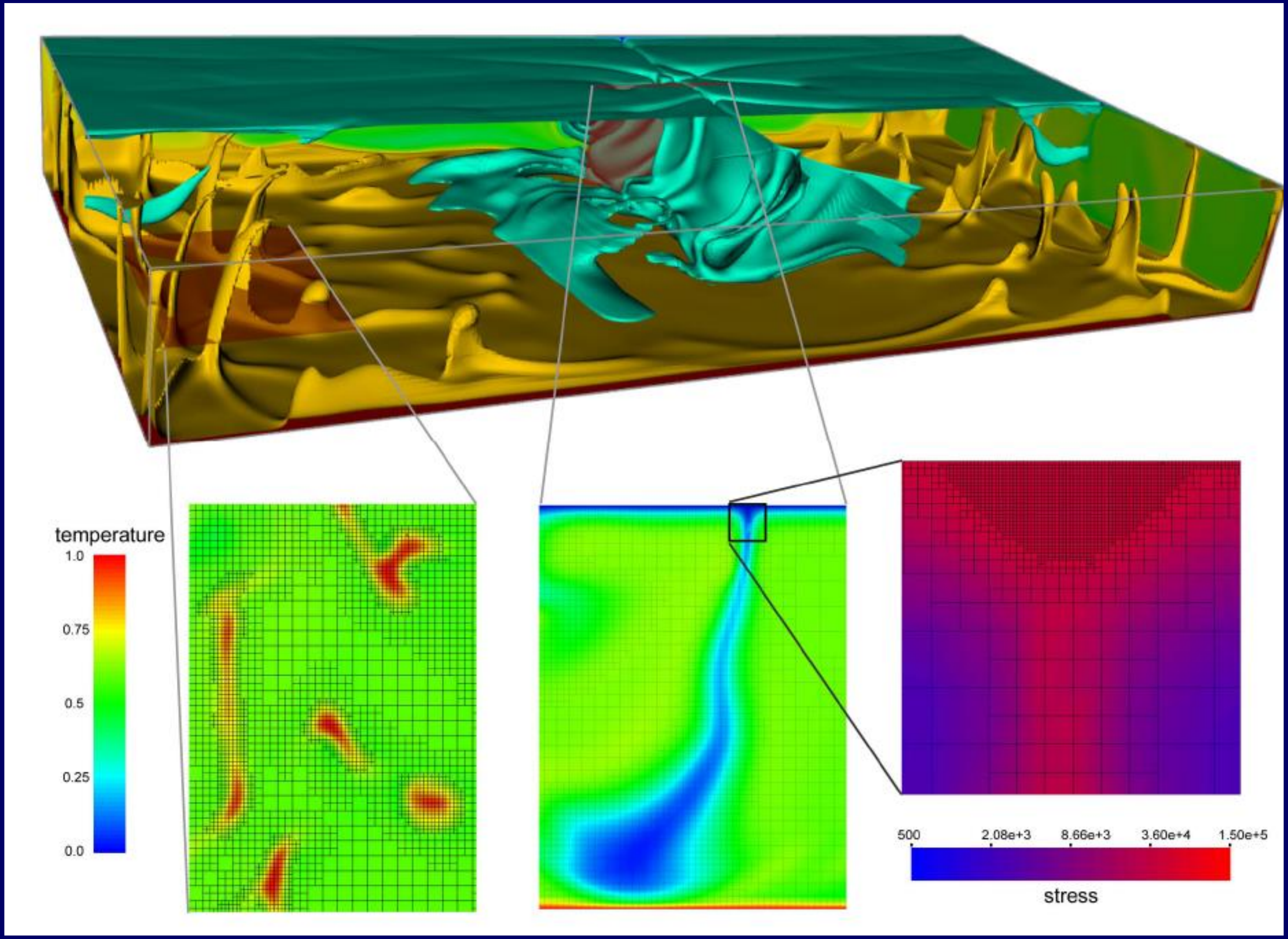
$\mathbf{K} = \dfrac{\partial \mathbf{r}}{\partial \Delta \mathbf{u}}$ – **Tangent Matrix**

Remapping of entire fields by Particle-In-Cell technique



Popov and Sobolev (2008)

Numerical FE code ASPECT

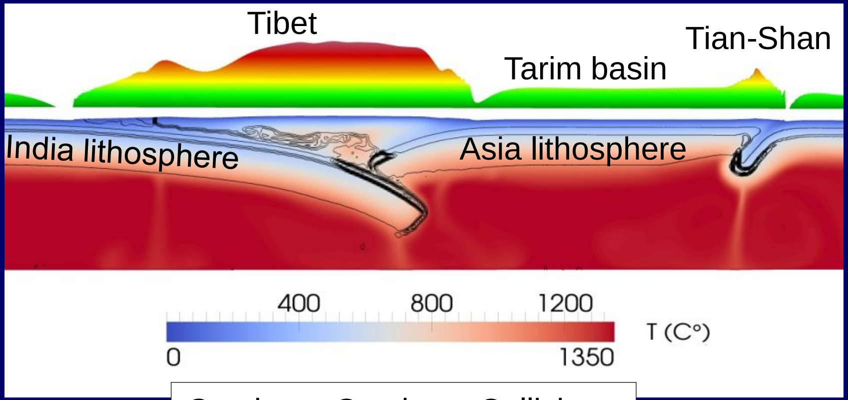


Burstedde et al.,2008-2010

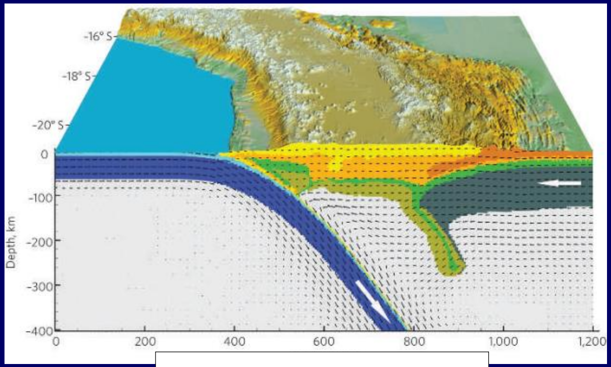
Section on Geodynamic Modeling at GFZ

Lithospheric-scale modeling

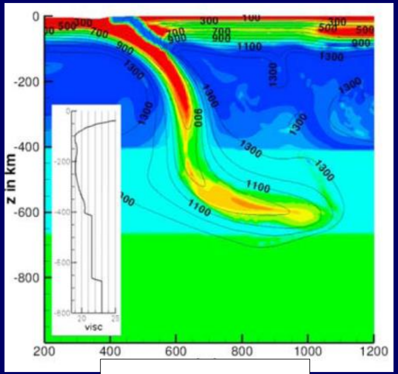
Modeling key geodynamic processes constrained by observations



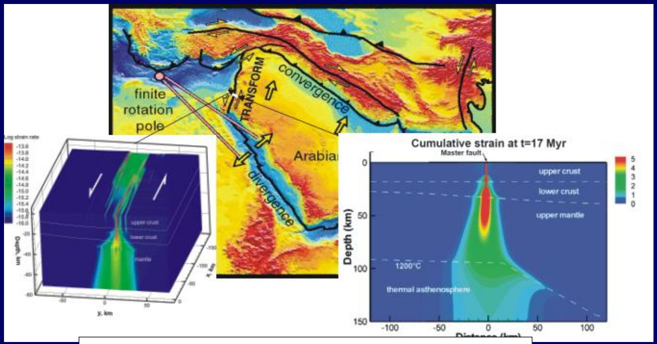
Continent-Continent Collision



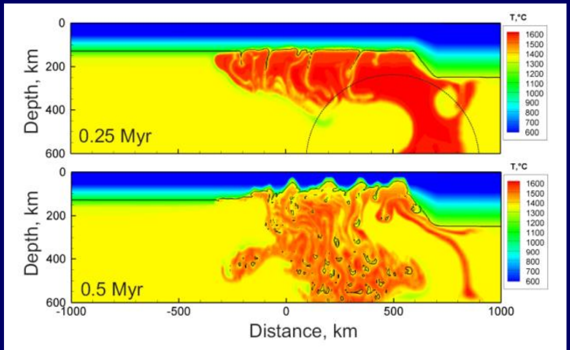
Subduction Orogeny



Subduction



Continental Transform Faults

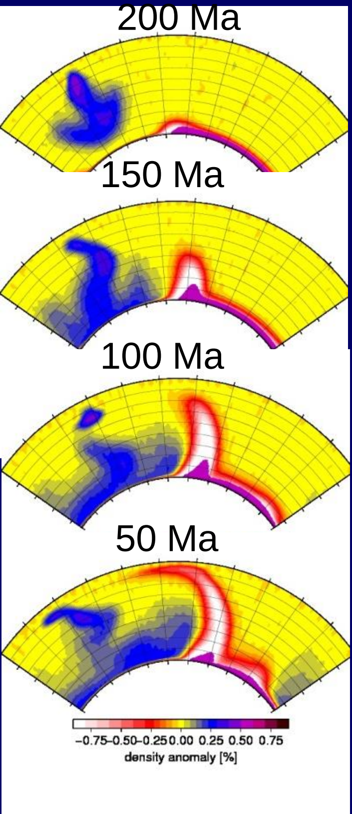


Large Igneous Provinces

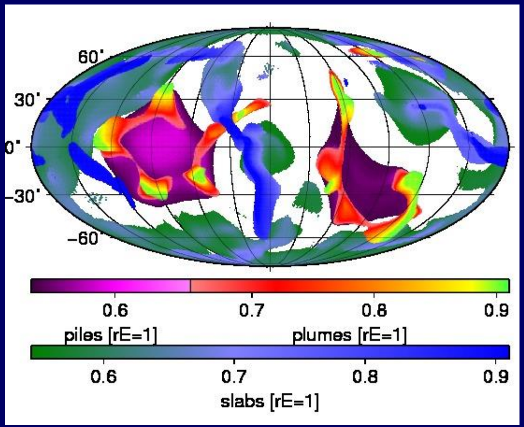
Sektion 2.5 – Geodynamische Modellierung

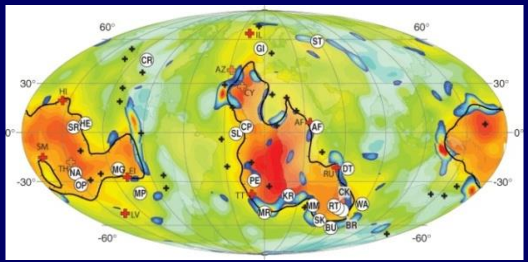
Global-scale modeling

Reconstructing Earth's mantle through geologic time

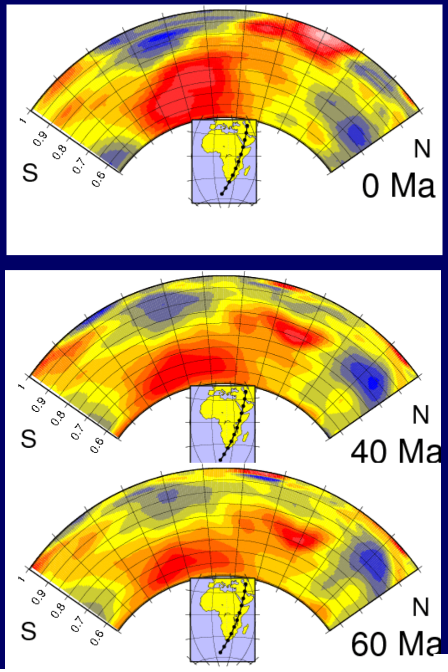


Forward modeling based on subduction history

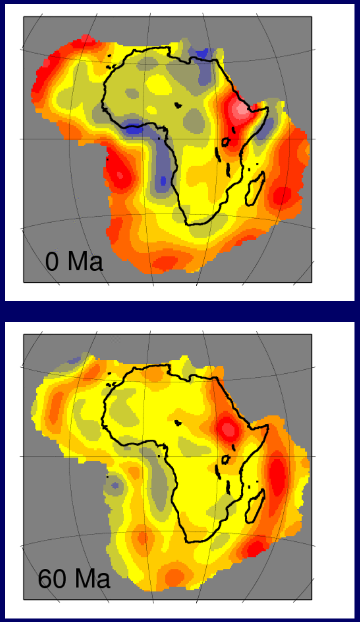


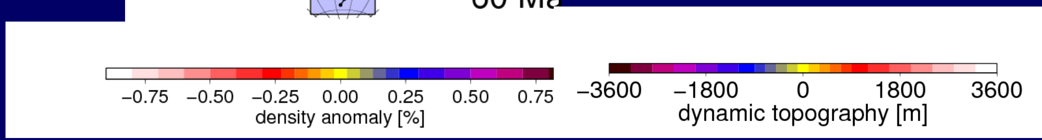


Backward models based on seismic tomography



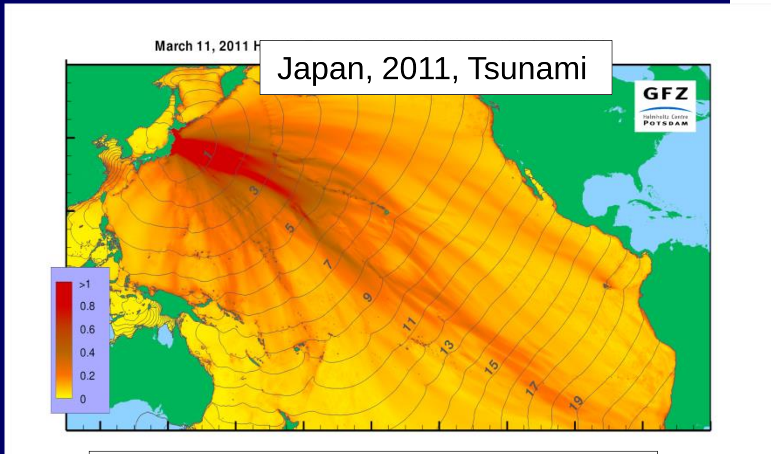
Predicted uplift and subsidence at moving plate



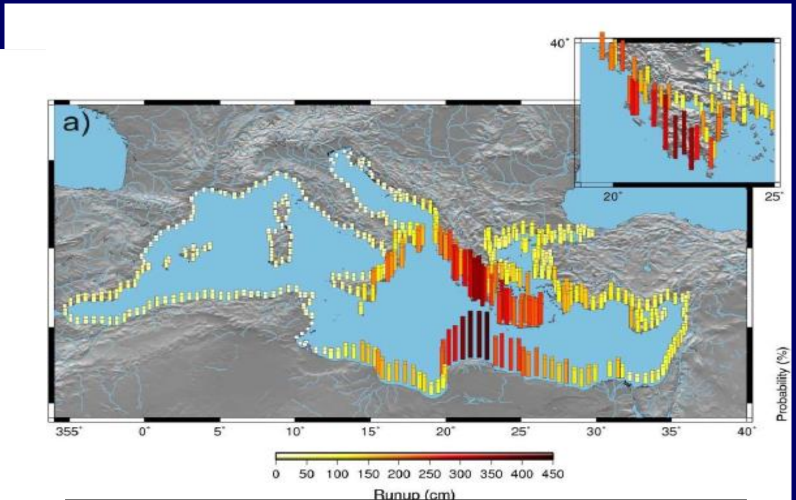


Model and observations: Plumes generated
At the margins of thermo-chemical piles

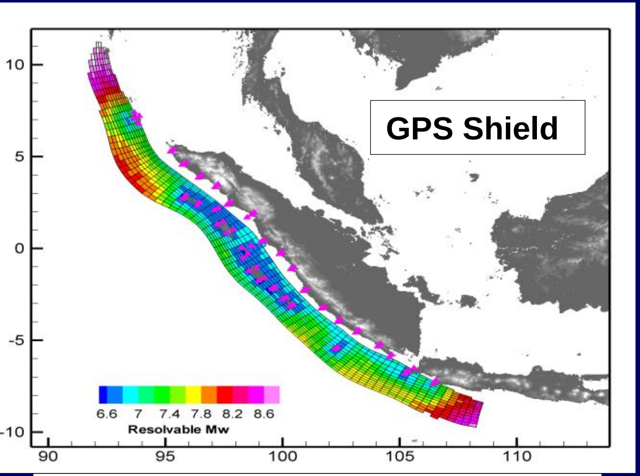
Link to surface processes



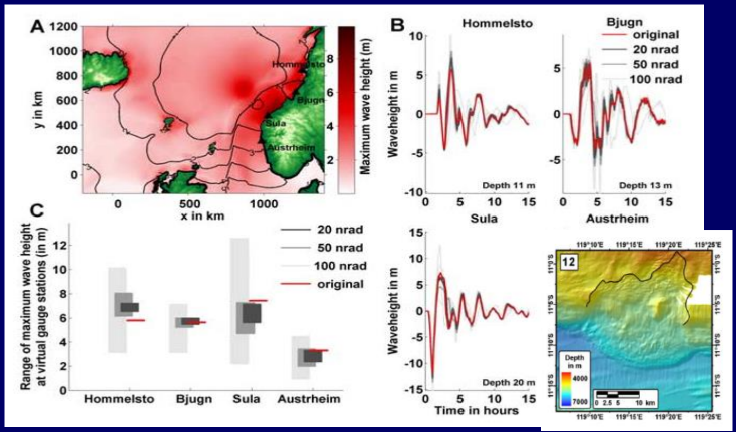
Tsunami and source modeling



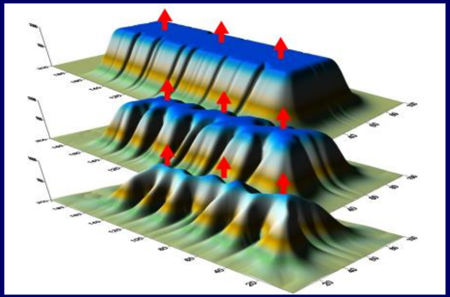
Probabilistic tsunami hazard in Mediterranean



GPS arrays for quick source inversion



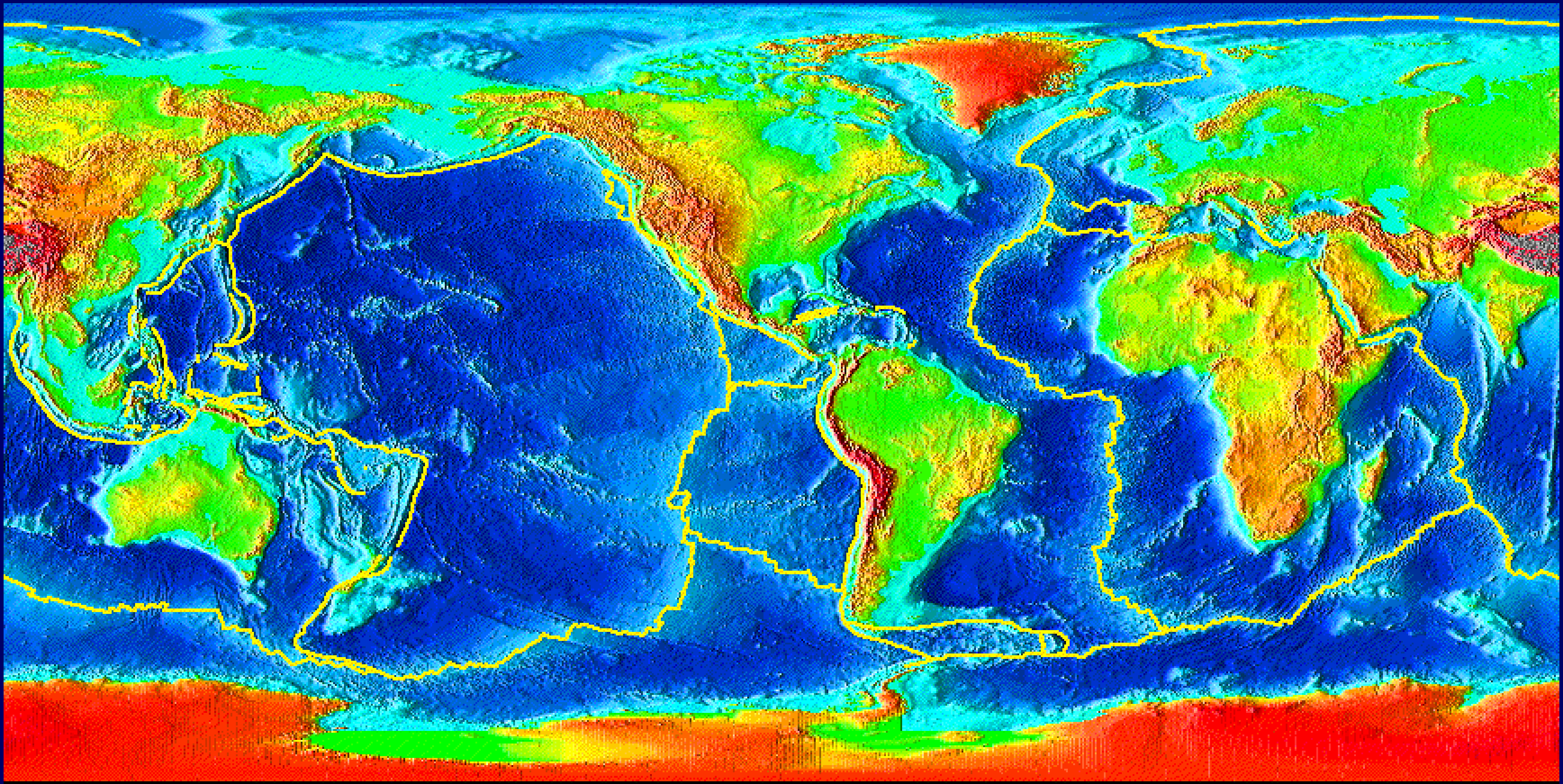
Landslide hazard evaluation and detection



3D Tectonics and erosion

Sektion 2.5 – Geodynamische Modellierung

Why continents?



Crustal Plate Boundaries

oceanic crust:

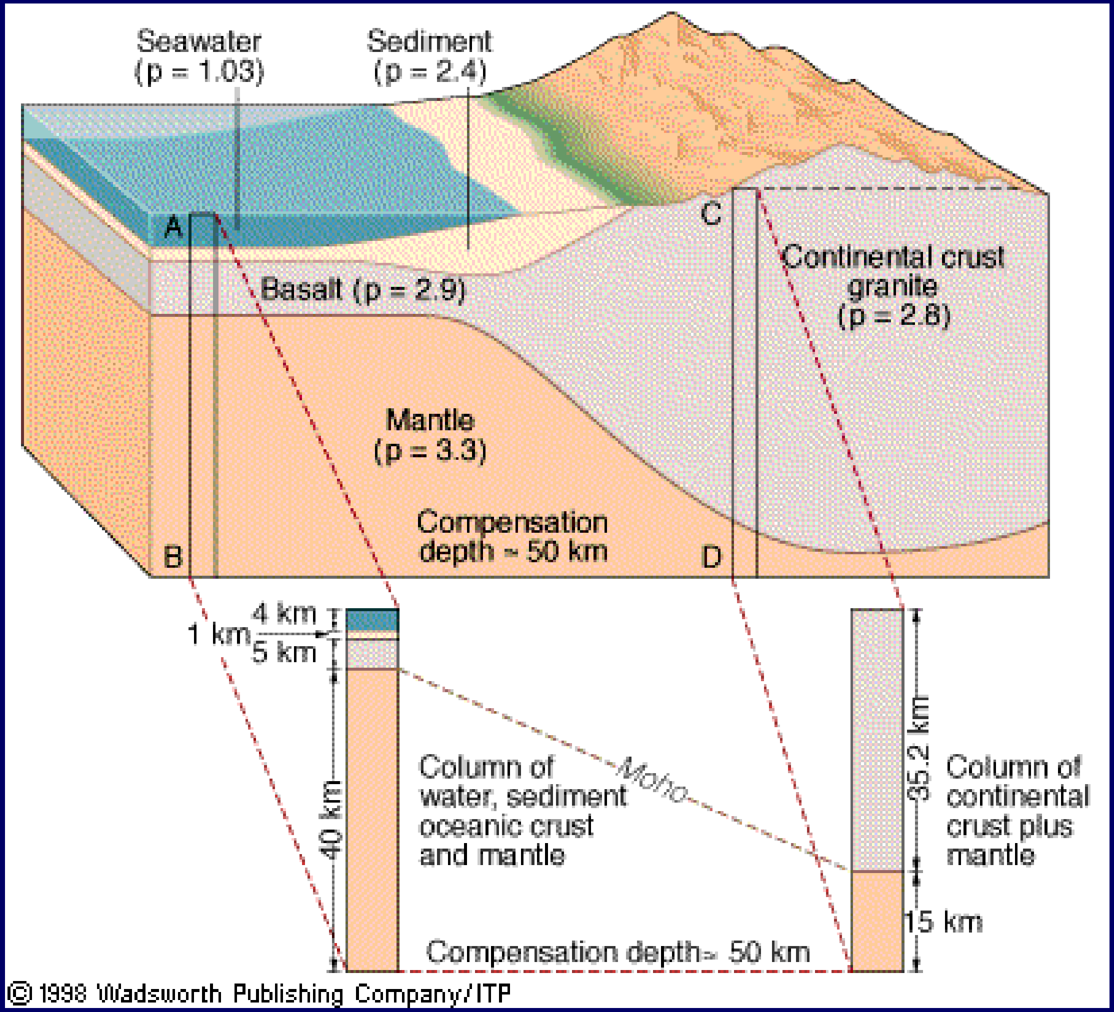
mafic; denser

continental crust:

felsic; less dense

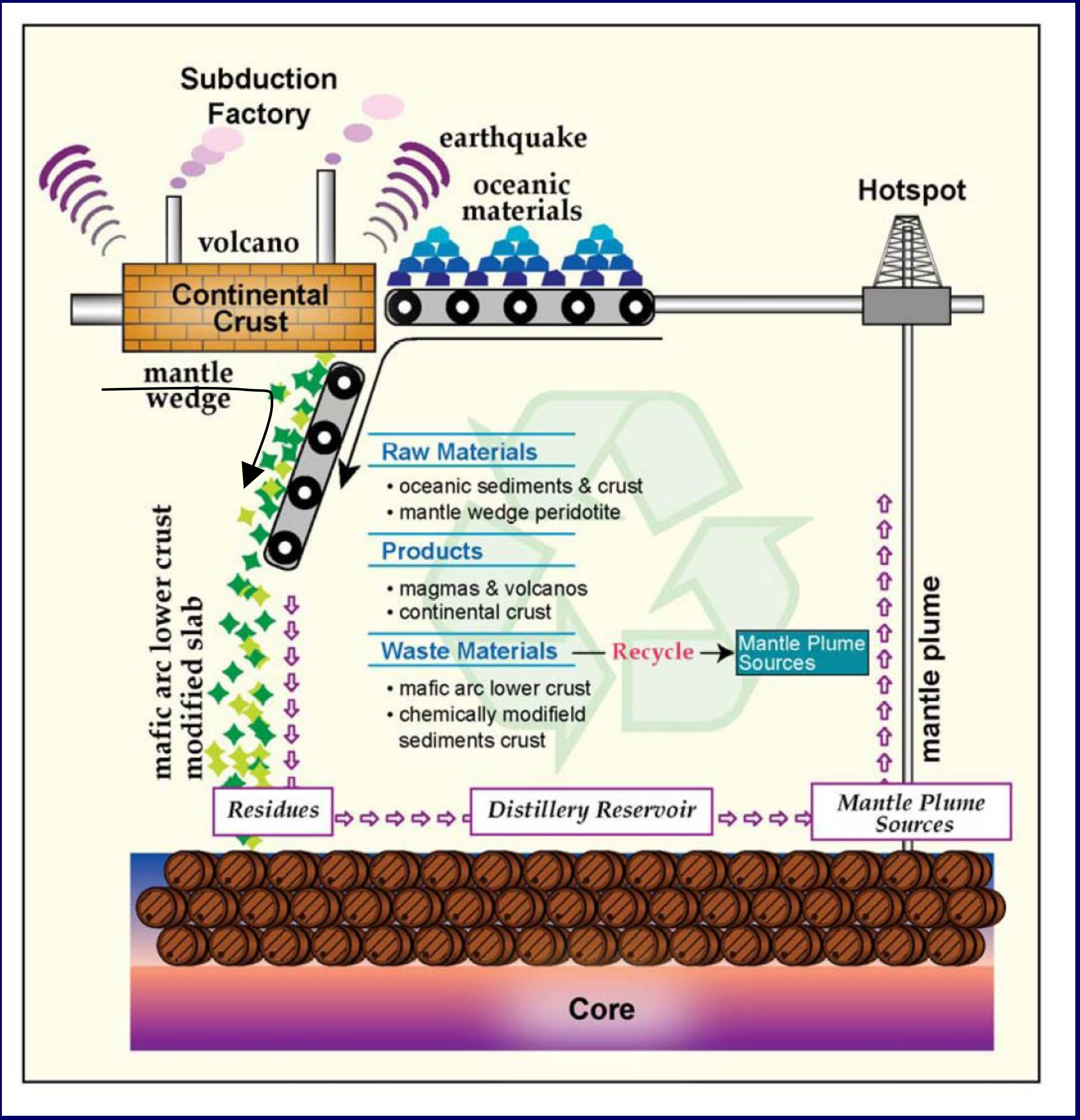
isostasy:

columns of mass must be the same at a certain depth (compensation depth) ~ 50 km

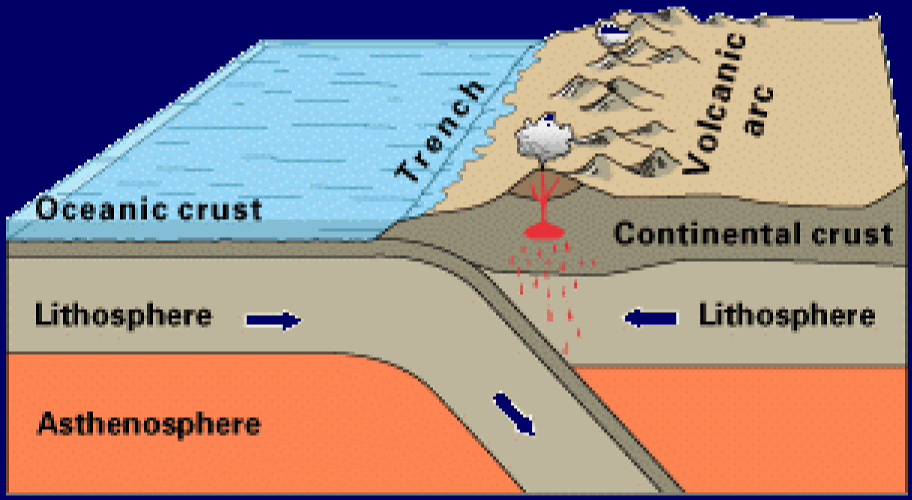


continents have roots and stick-up

Making continental crust

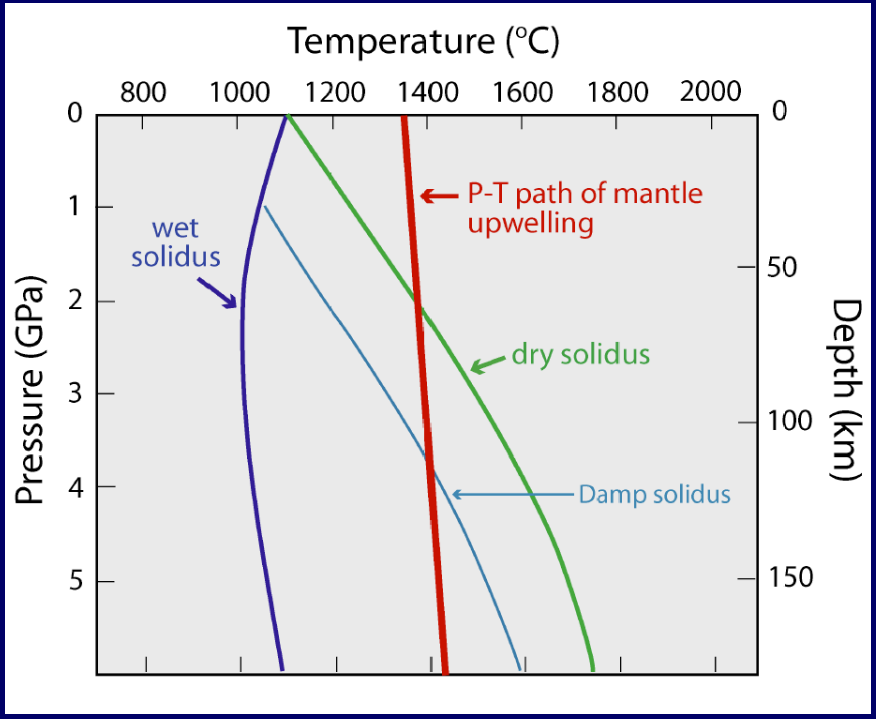


Subduction zone



Because of water

Why volcanoes?



Key factors to make continental crust

1. Permanent inflow of fluids, sediments and oceanic crust
2. Melting of mantle rocks enabled by water-rich fluid
3. Permanent inflow of „fresh“ mantle material = corner flow

Temperature and velocity fields in corner-flow

(Sobolev et al., 2006)

Why corner-flow?