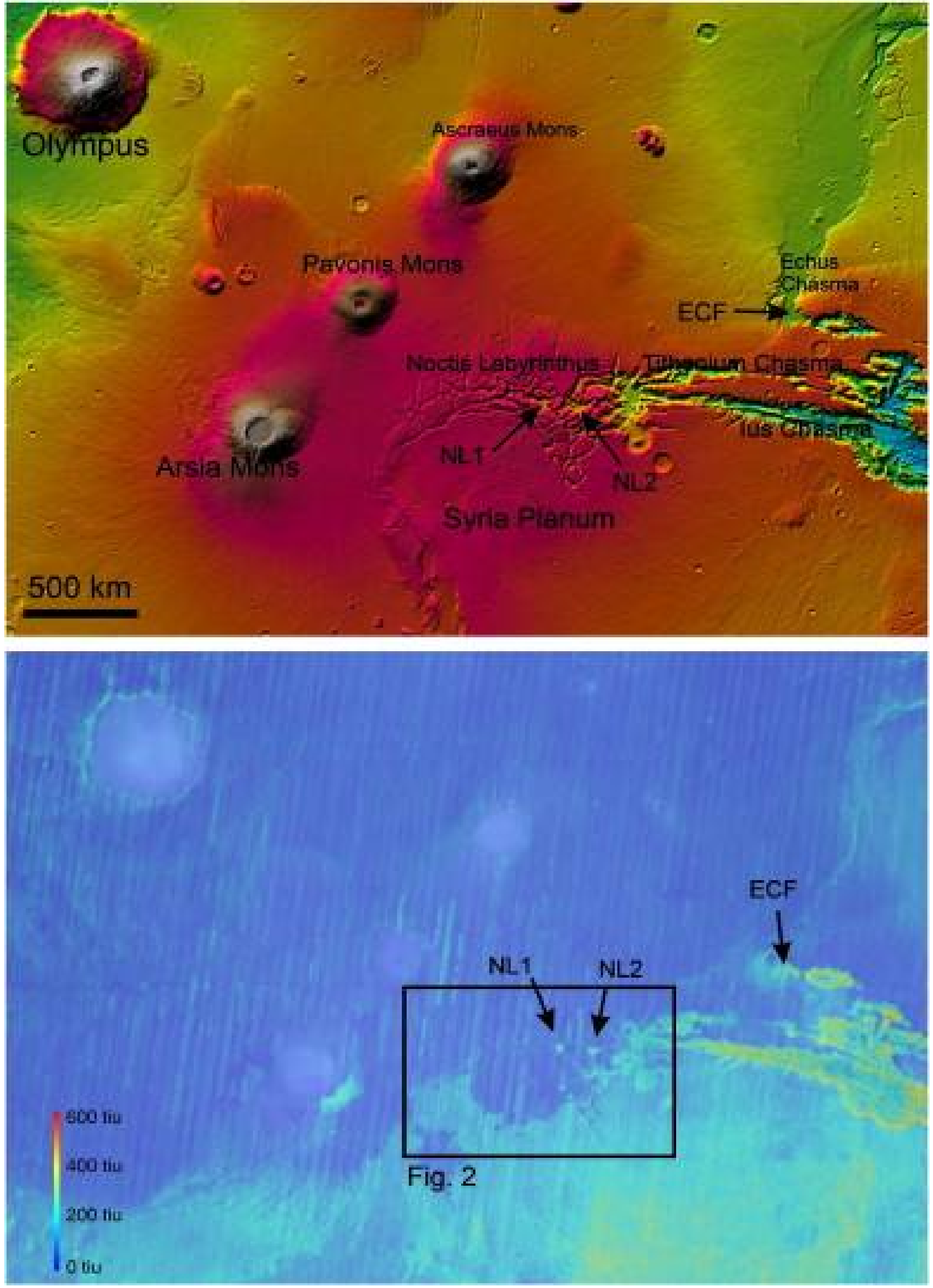


Olympus
Ascraeus Mons
Pavonis Mons
Echus Chasma
ECF
Noctis Labyrinthus
Tithonium Chasma
Ius Chasma
NL1
NL2
Arsia Mons
Syria Planum
500 km
ECF
NL1
NL2
Fig. 2
600 tiu
400 tiu
200 tiu
0 tiu

?

1) Morphology of the Earth: plate tectonics and heat transfer. From Geometrical characteristics to internal structure: Plates, hot spots, mantle convection, the core.

2) conductive behaviour of the lithosphere (matlab ex).

3) Geophysical insight: seismology, gravimetry, magnetism

4) Rheological properties (of the lithosphere, matlab ex).

5) solar system planets geomorphology and tectonics

6) Water effects on rheology, on planetary morphology.

Plate tectonics relate to the state of heat on Earth

La surface terrestre: de grandes structures rectilignes, ou courbes, ou ponctuelles.
Comment les interpréter ?

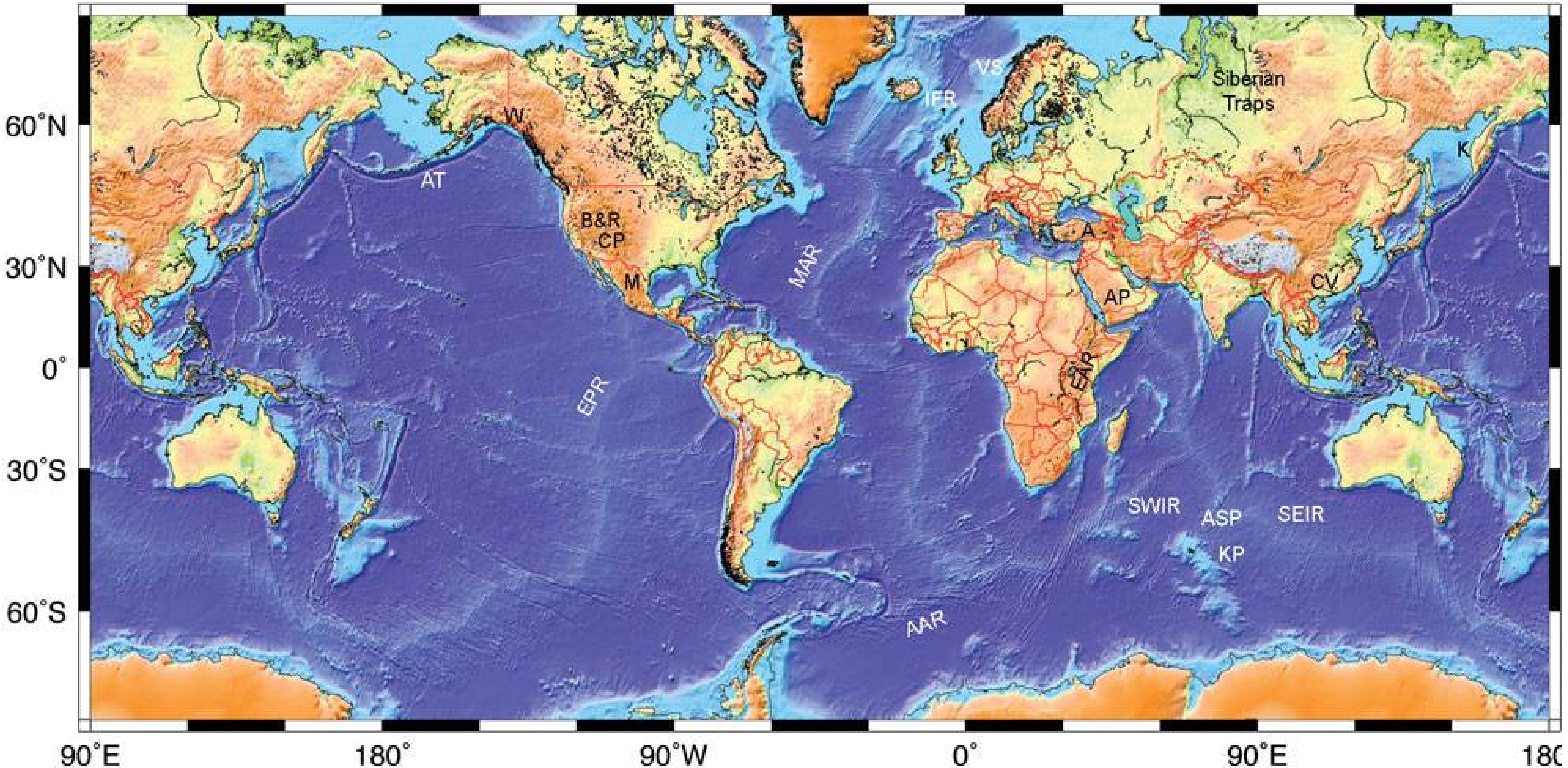
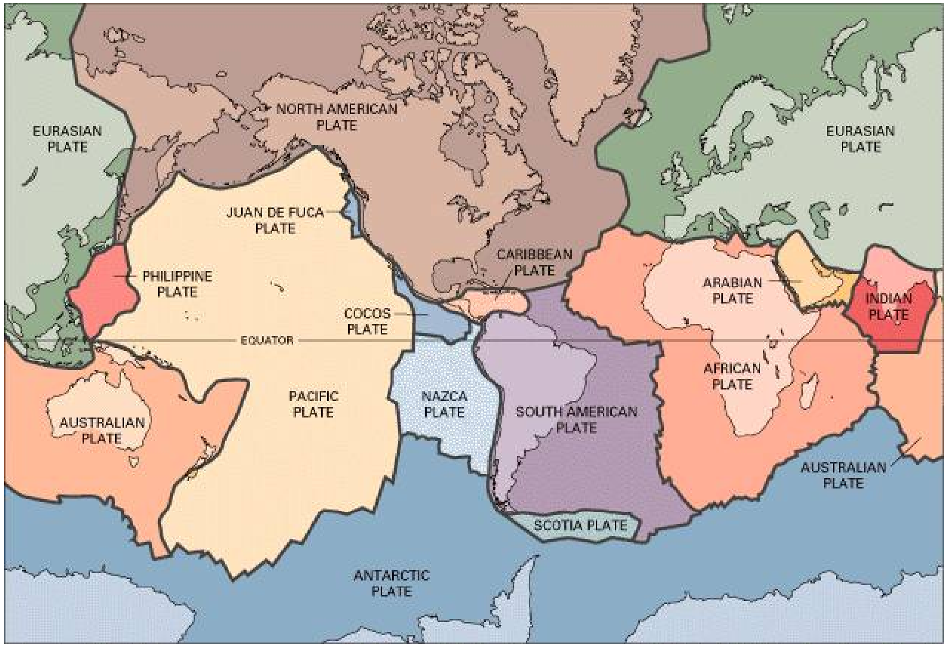


Plate Tectonics

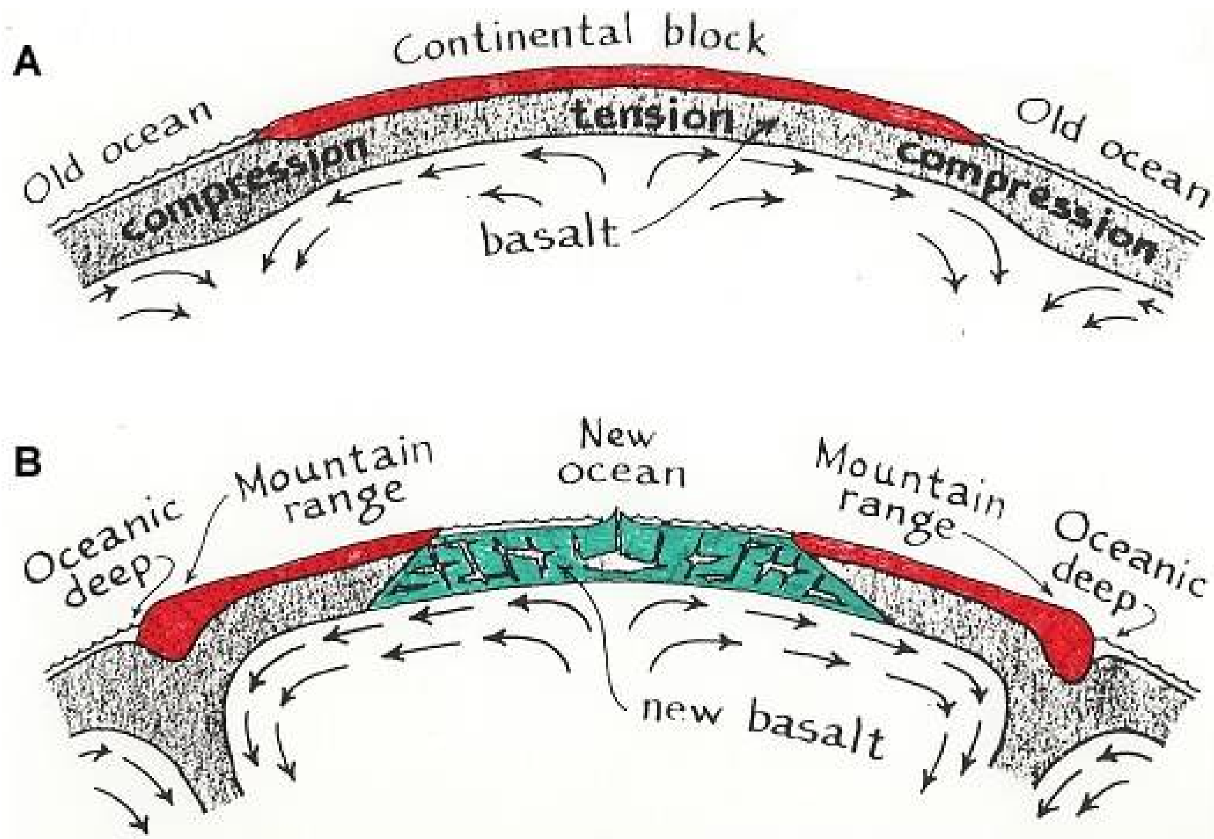
- The Earth's crust is divided into 12 major plates which move in various directions.
- This plate motion causes them to collide, pull apart, or scrape against each other.
- Each type of interaction causes a characteristic set of Earth structures or "tectonic" features (deform)



A short history

The theory of plate tectonics is recent: in 1912, **Alfred Wegener** proposed the idea of continental drift, based on paleontological and morphological evidences, but it started to be accepted only in the end of the 1960 ! one of the flaws of the theory was the lack of a realistic motor entertaining plates movments (Wegener had suggested terrestrial rotation, too weak).

In 1945 **Arthur Holmes** proposed that mantle motion due to global convection drives plate motions; that it is responsible for the creation of oceanic crust from cristallisation of mantle magmas, and that recycling occurs at subduction zones.



Dérive des Continents/ Continental drift Wegener's work

Cartographiques:

- Continuité des ***Cratons***,
- Continuité des ***Zones plissées***
- Continuité des ***Bassins sédimentaires***.

Paléontologiques:

- Apparition de mêmes espèces sur des continents "séparés": Ex: ***Stégocéphales***.

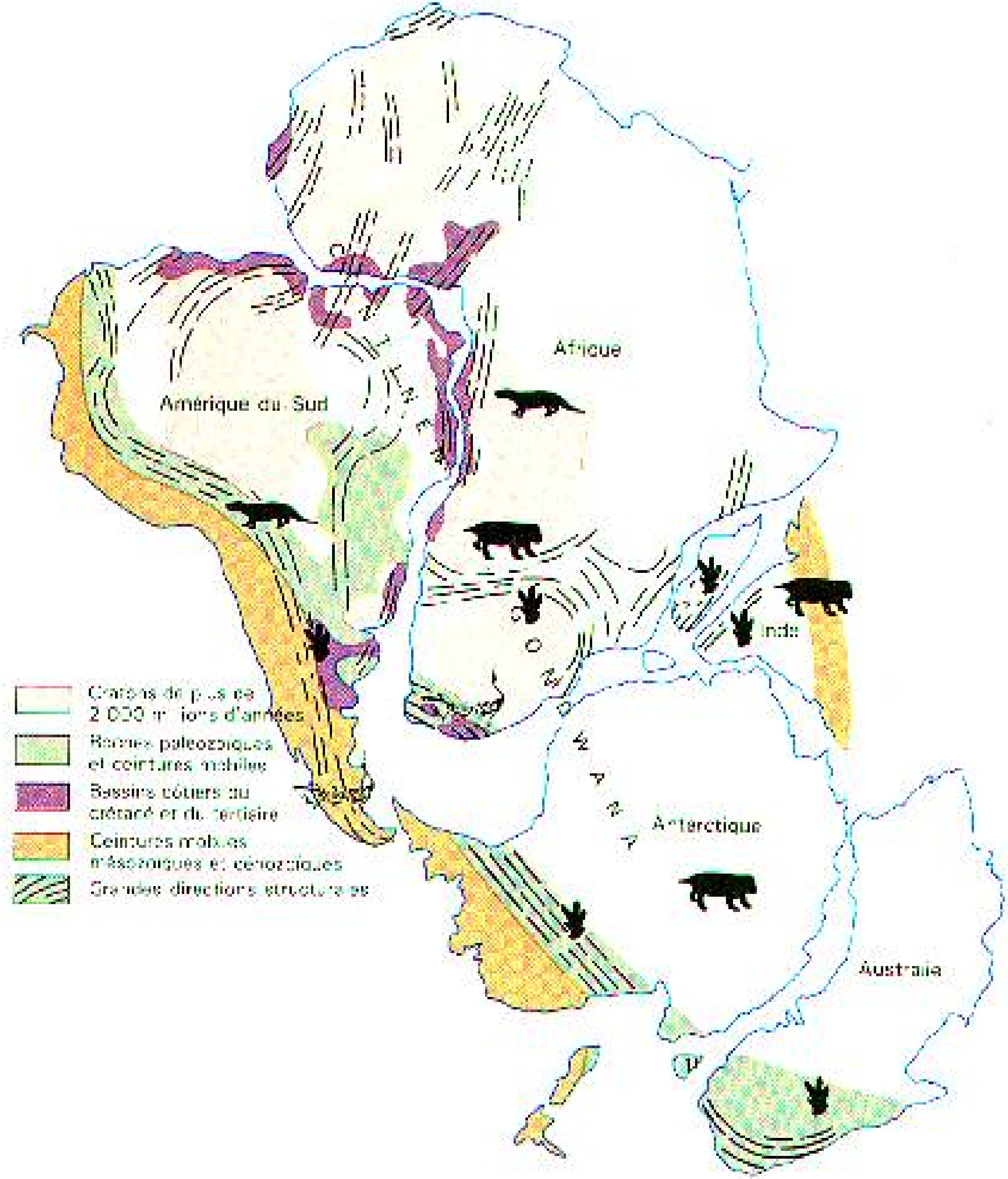
Paléoclimatiques:

- Répartition des ***paléoclimats*** sur les différents continents;

Orogéniques:

- Reprenant les idées d'Argand il jette les bases de la Tectonique Globale actuelle, avec la présence des trois grands types de zones tectoniques, **compression, distension et coulissement**.

C'est le premier modèle Global.

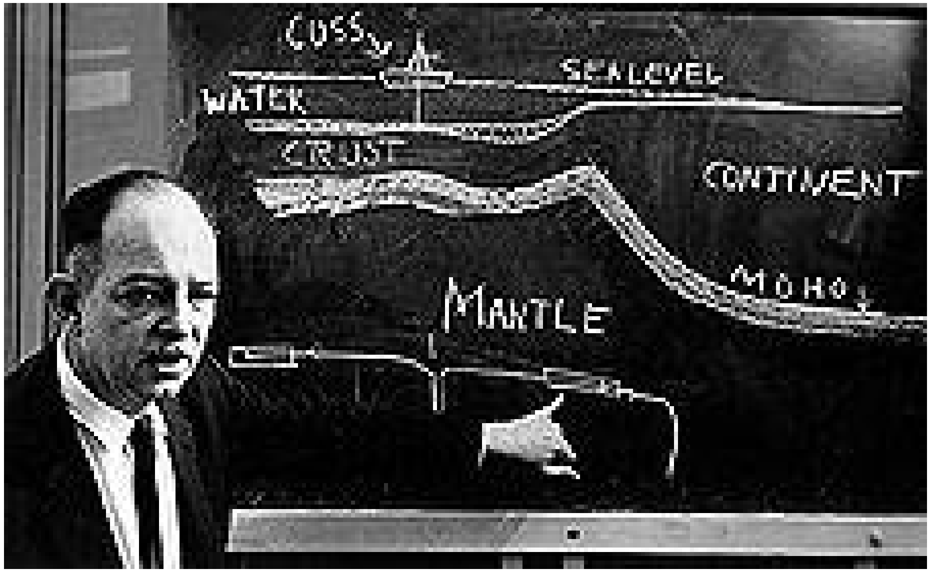


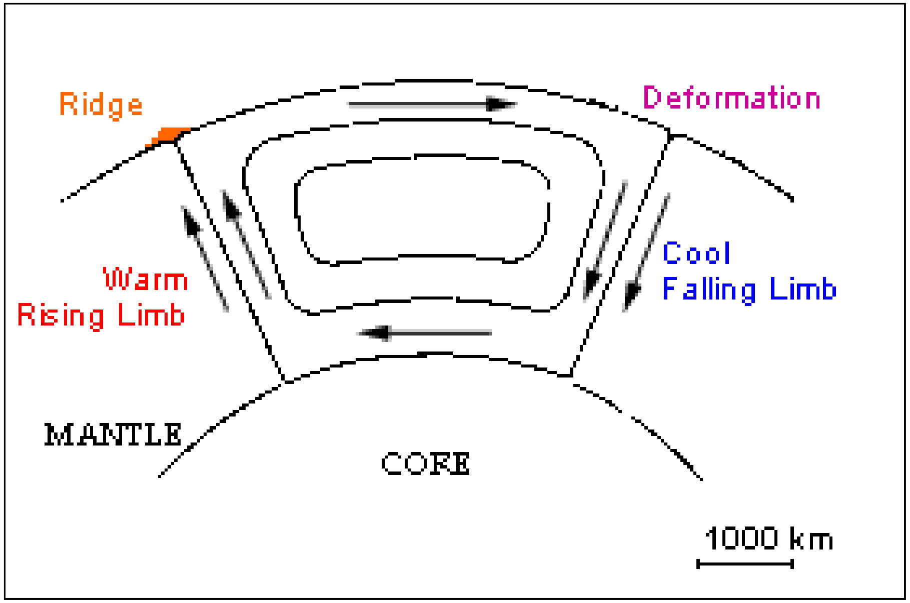
Sea-floor spreading /
Tapis roulant océanique
Hess (1962)

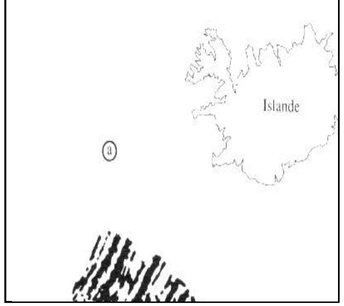
•"Tentative géopoétique" pour expliquer:

- **que les roches draguées ne sont jamais anciennes (maximum Jurassique) ; et qu'il n'existe pas de sédiments correspondant à des milliards d'années d'érosion.**
- **Le manteau est parcouru par de larges mouvements de convection, avec des parties montantes aux dorsales médio-océaniques et des parties descendantes aux fosses;**
- **le plancher océanique se forme aux dorsales, dérive et s'engloutit dans les fosses.**

Théorie qui ne rencontre que scepticisme parmi les non-océanographes.



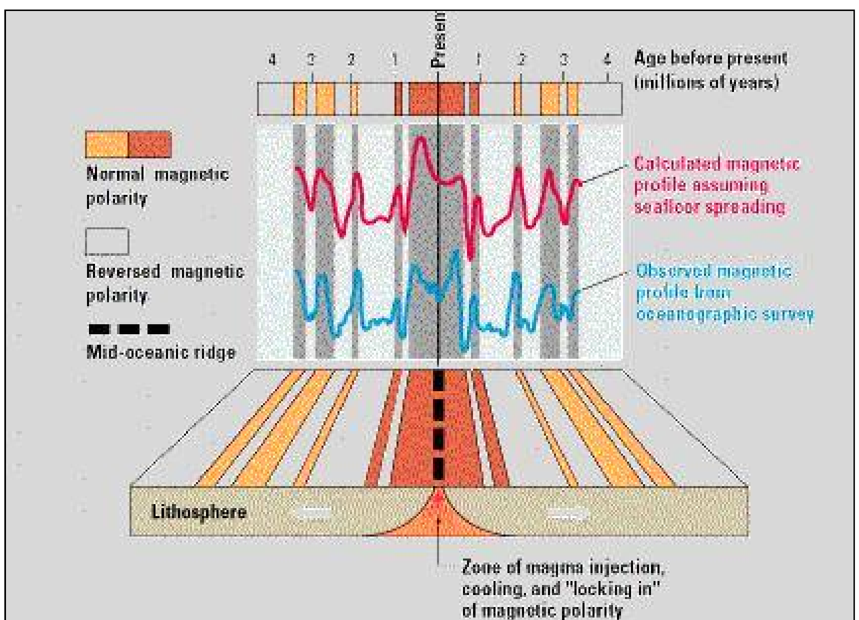


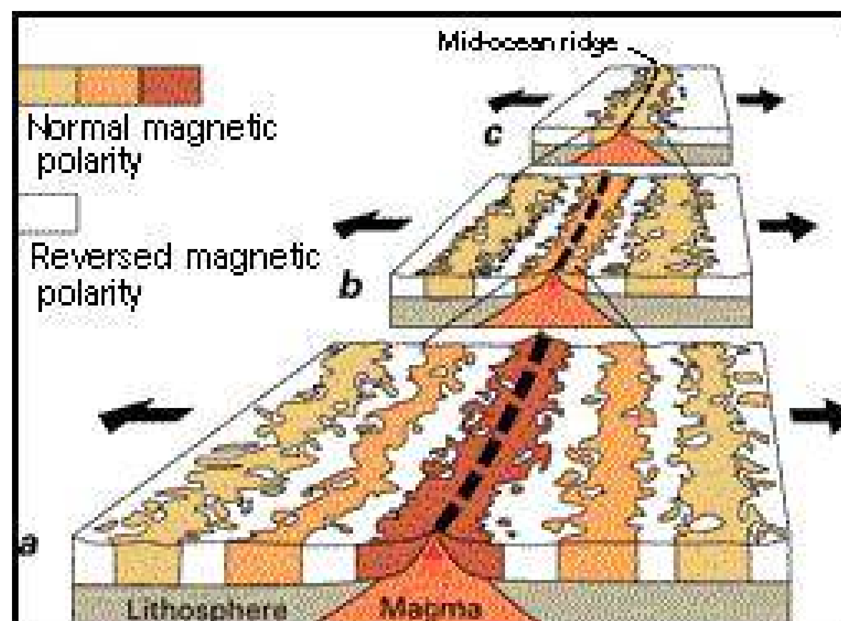


La théorie de l'Expansion des fonds océaniques

(Marley, Vine & Mattews, 1962)

- **Marley, Vine et Mattews rapprochent trois observations::**
  - **Les interprétations de Matuyama des anomalies magnétiques dans les coulées,**
  - **L'échelle des inversions du champ géomagnétique,**
  - **L'hypothèse du "Tapis Roulant" de Hess**
- **Ils concluent à l'extension des fonds océaniques à partir des dorsales par fabrication continue de basalte à partir du manteau et écartement symétrique de part et d'autre de la dorsale.**
- **Il y a disparition de cette lithosphère dans les fosses situées en bordure des océans.**





Interprétation d'un fond océanique

(Dorsale de Juan de Fuca)

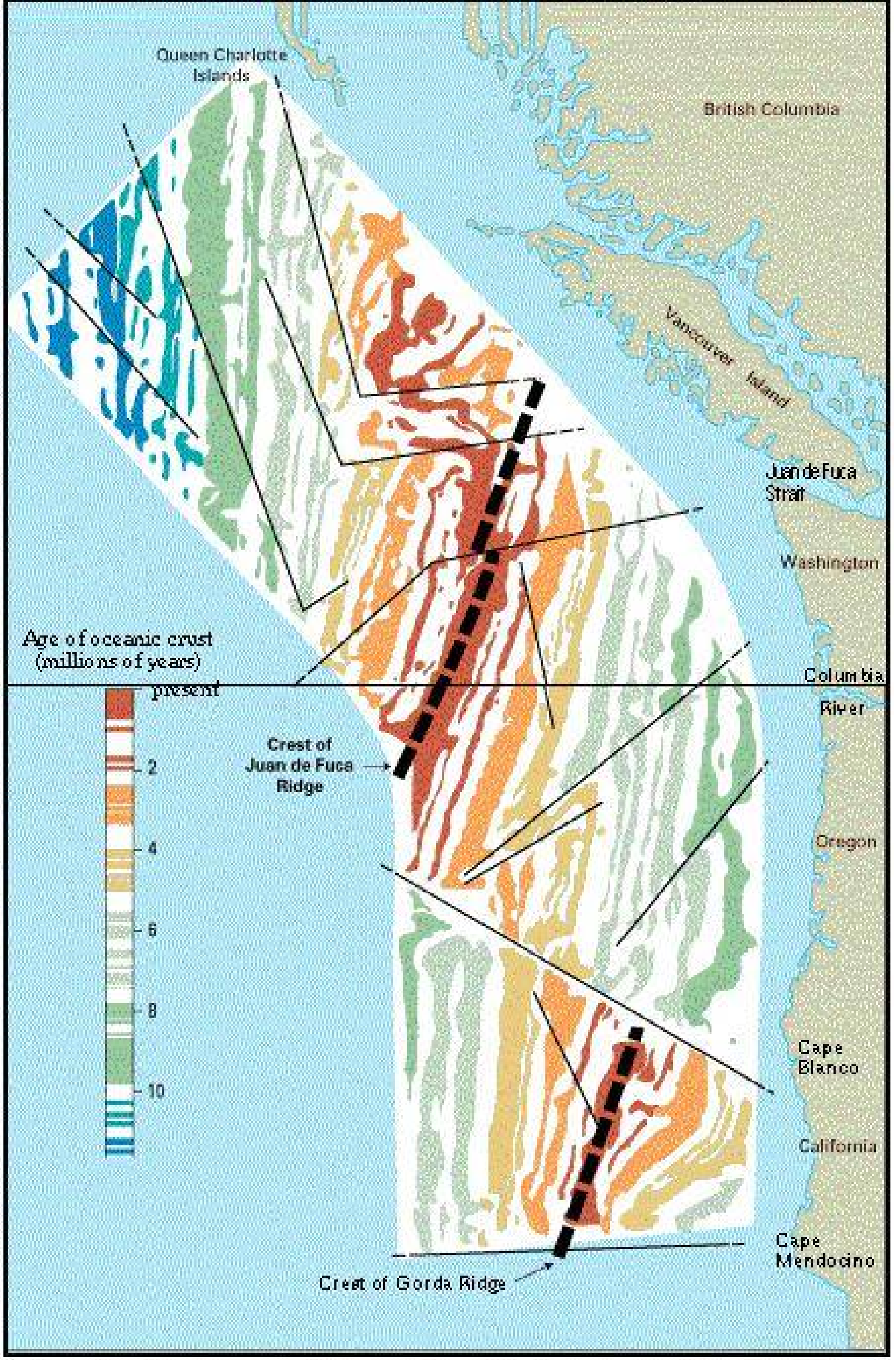
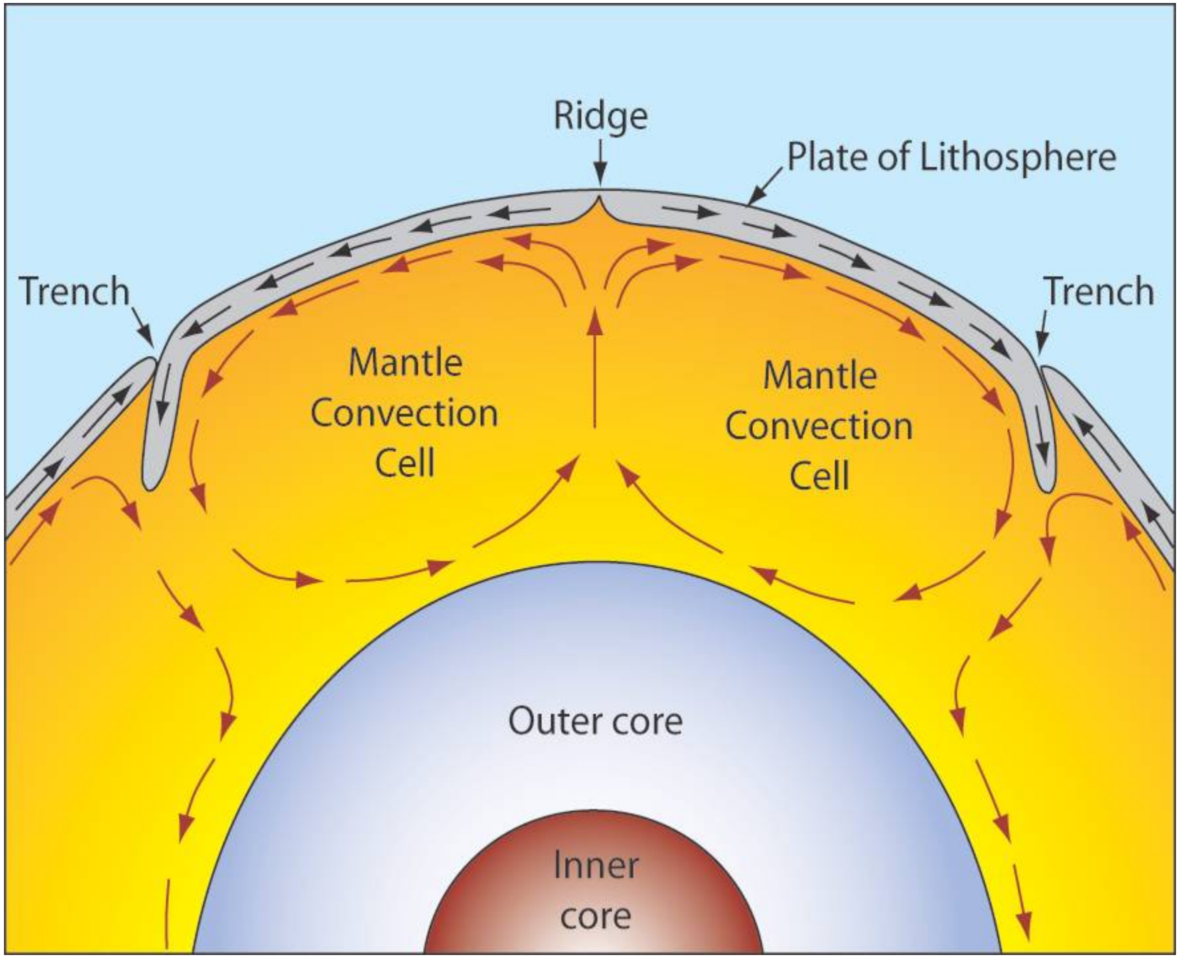


Plate Motion

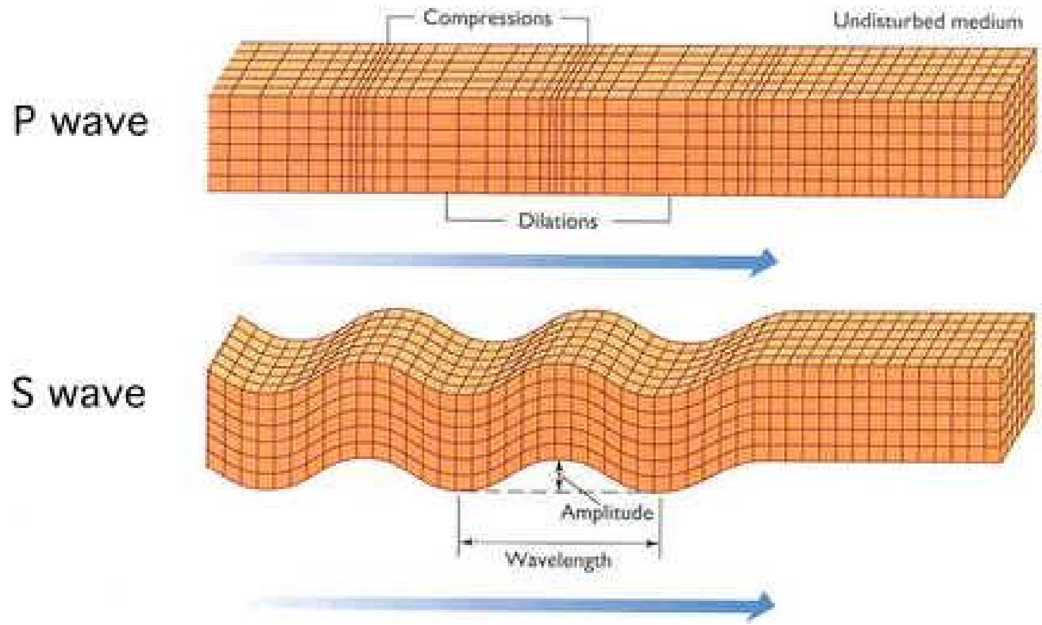
As a first approximation, mantle convection involves rising currents that bring deepest rocks to the surface **(at oceanic ridges).** These rocks are then driven by a horizontal flow and release their heat; when cooling they become denser and sink back down into the mantle **(along subduction zones).**

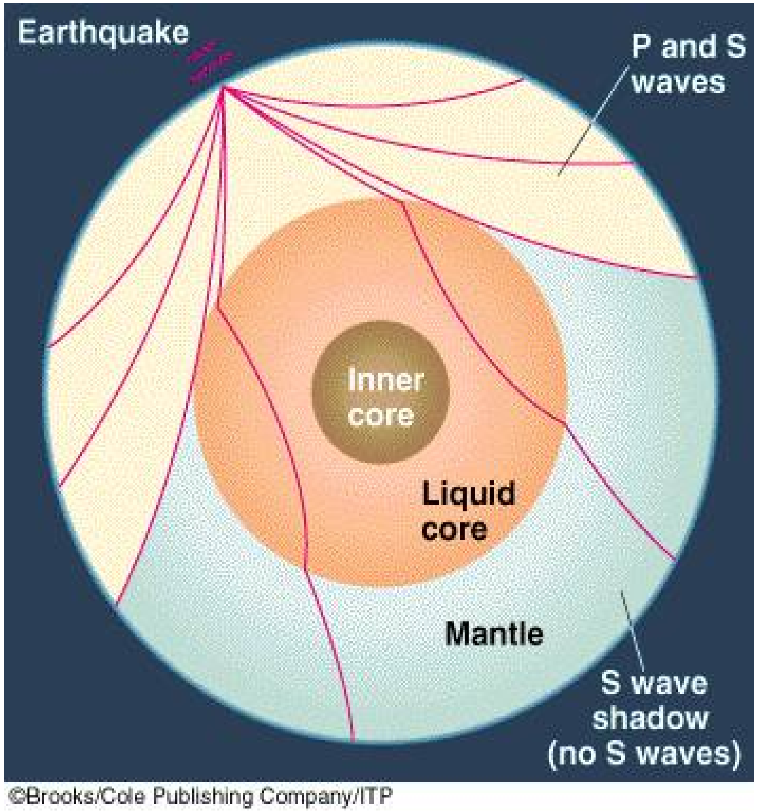


How do we know what the Earth is made of?

Geophysical surveys: seismic, gravity, magnetics, electrical, geodesy
Acquisition: land, air, sea and satellite
Geological surveys: fieldwork, boreholes, mines

TWO TYPES OF SEISMIC WAVES
P: *COMPRESSIONAL* WAVES - VOLUME CHANGES
S: *SHEAR* WAVES - DISTORTION NO VOLUME CHANGE



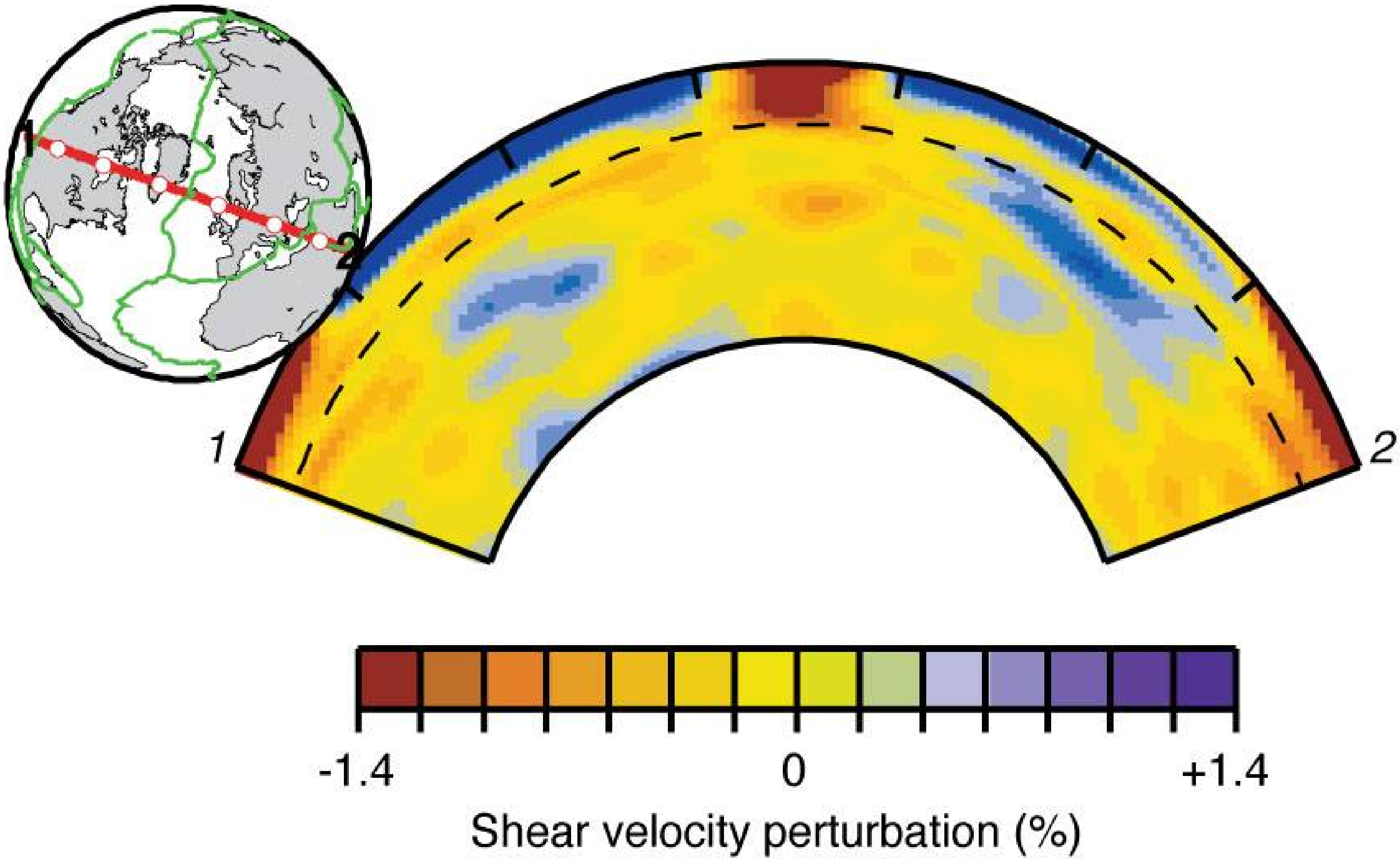


$$V_p = \sqrt{\frac{K + \frac{4}{3}G}{\rho}}$$

$$V_s = \sqrt{\frac{G}{\rho}}$$

Seismic velocities tell us about interior properties

Mantle tomography : colors represent differences in velocity of seismic waves, usually attributed **to contrasts in temperature in the mantle.**
Domains are heterogeneous, blue zones are assimilated to subducting plates.



Mantle: Peridotite (ultramafic)

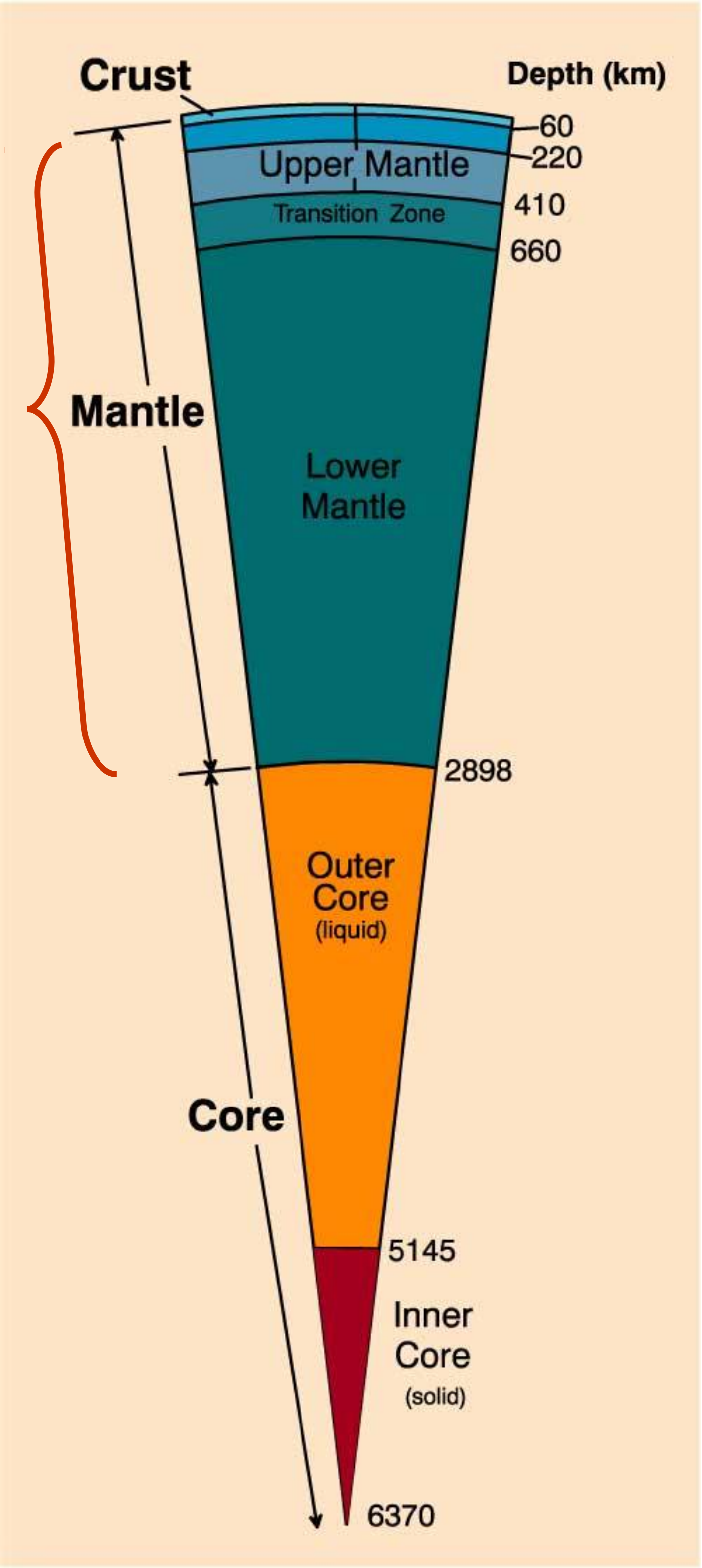
- Upper mantle to 410 km (olivine →spinel)
  - * Low Velocity Layer 60-220 km
  - * Transition Zone velocity increases at 660 km

    Spinel →perovskite-type $Si^{IV} \rightarrow Si^{VI}$

- Lower Mantle has more gradual velocity increase

Core: Fe-Ni metallic alloy

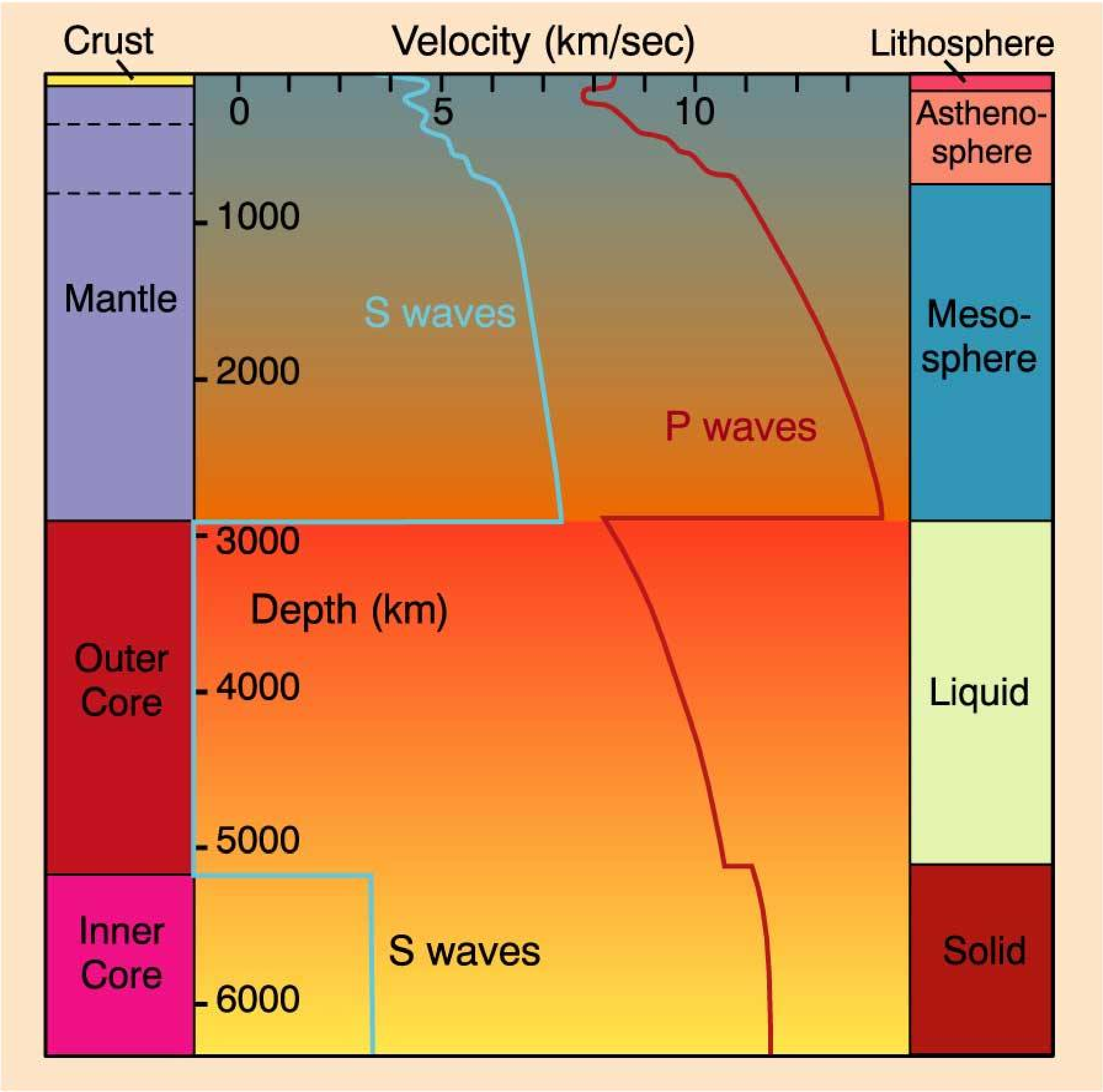
- Outer Core is liquid
- Inner Core is solid



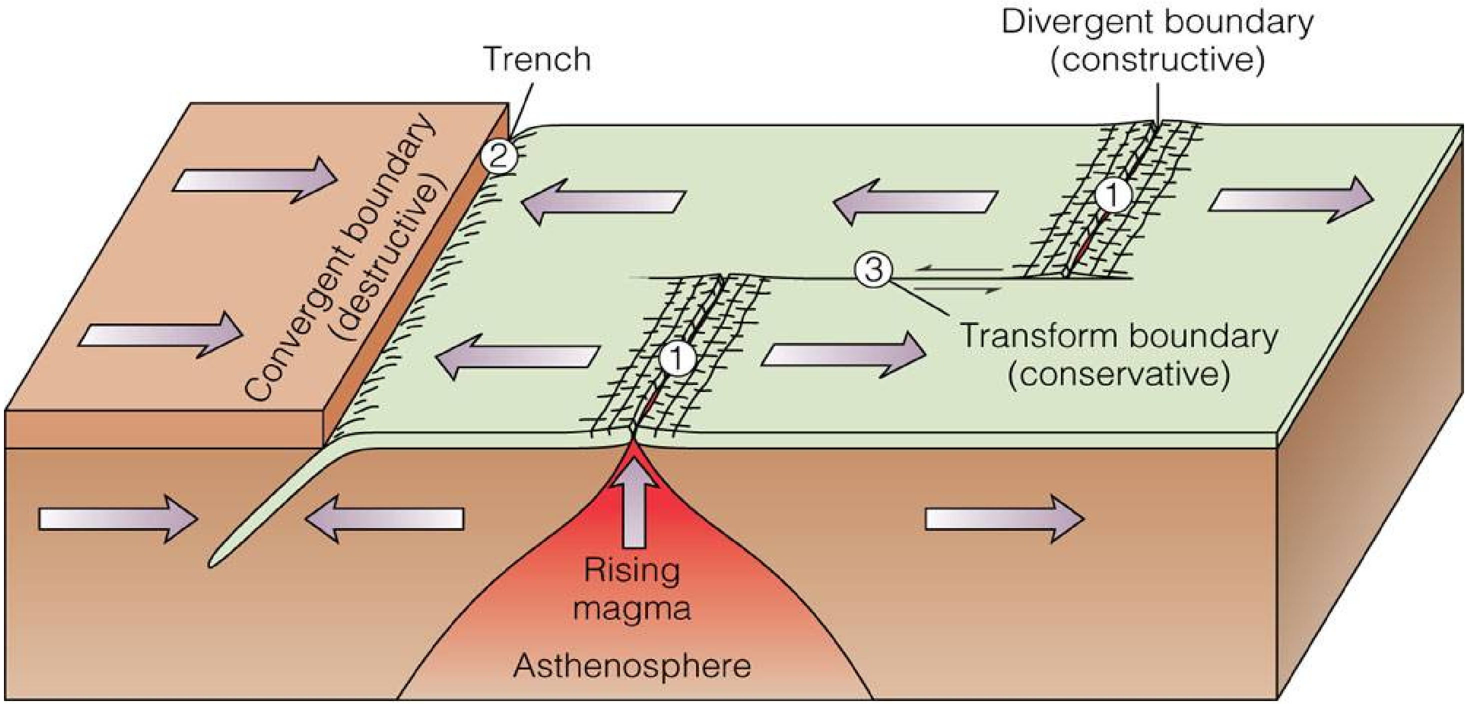
Variation in P and S wave velocities with depth (Kearey and Vine, 1990)

Compositional subdivisions of the Earth are on left,

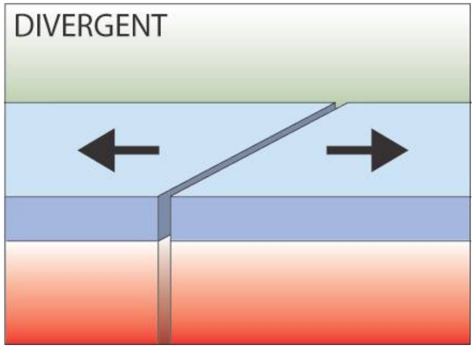
Rheological subdivisions on the right.

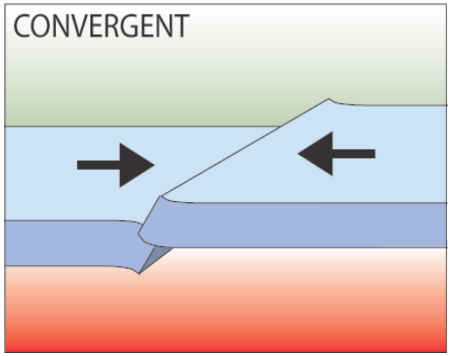


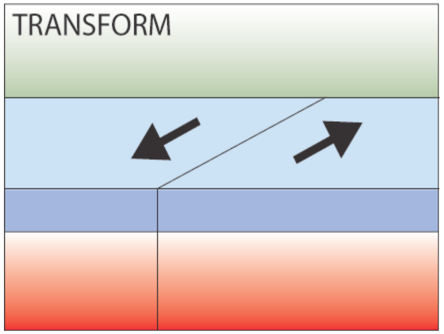
What happens at tectonic plate boundaries?



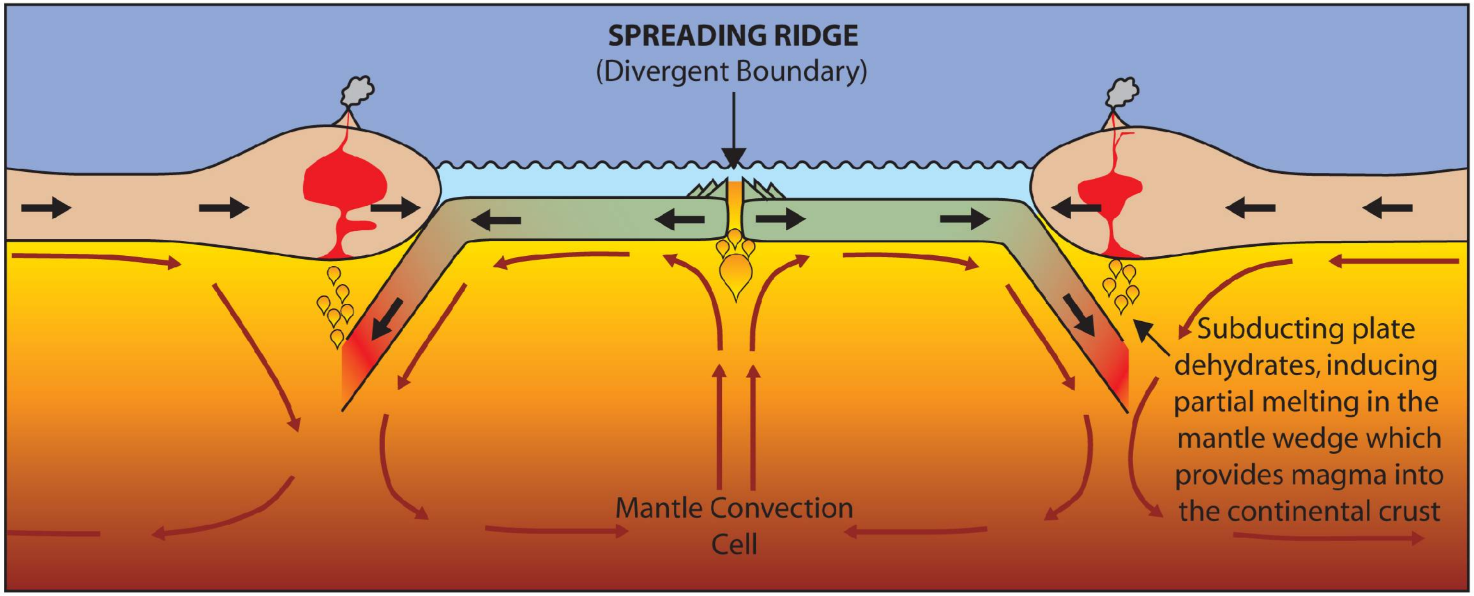
- Divergent
- Convergent
- Transform



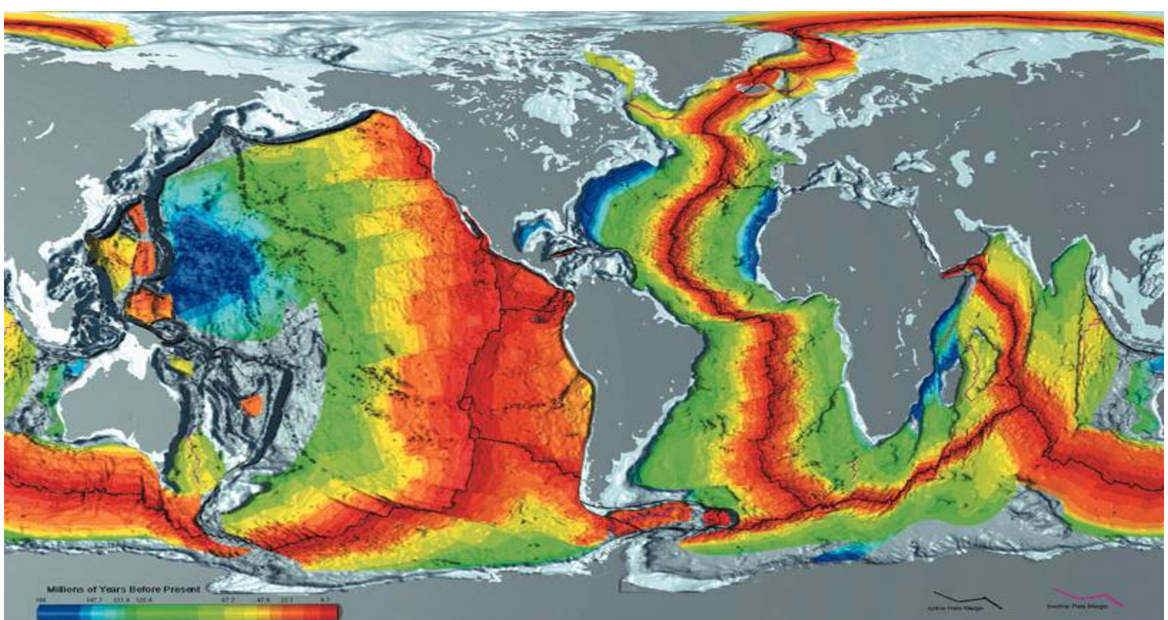


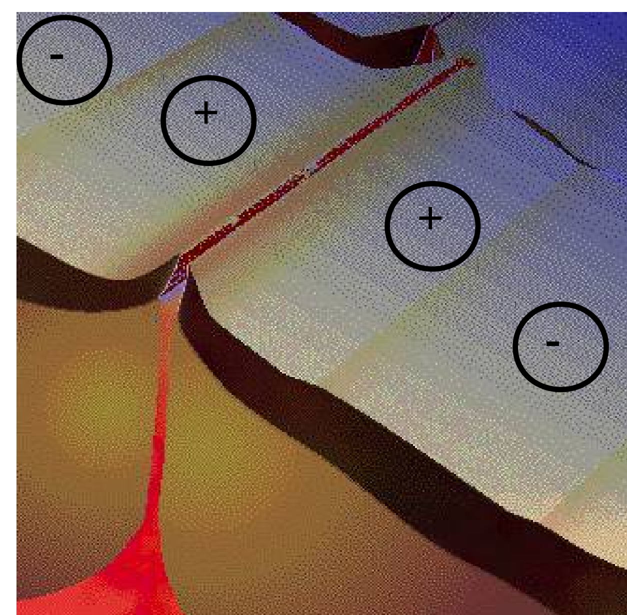


Digervent boundaries

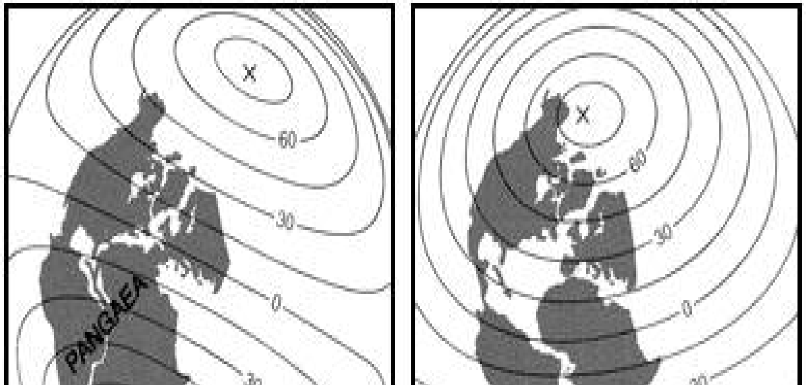


Spreading ridges : As plates move apart new material is erupted to fill the gap

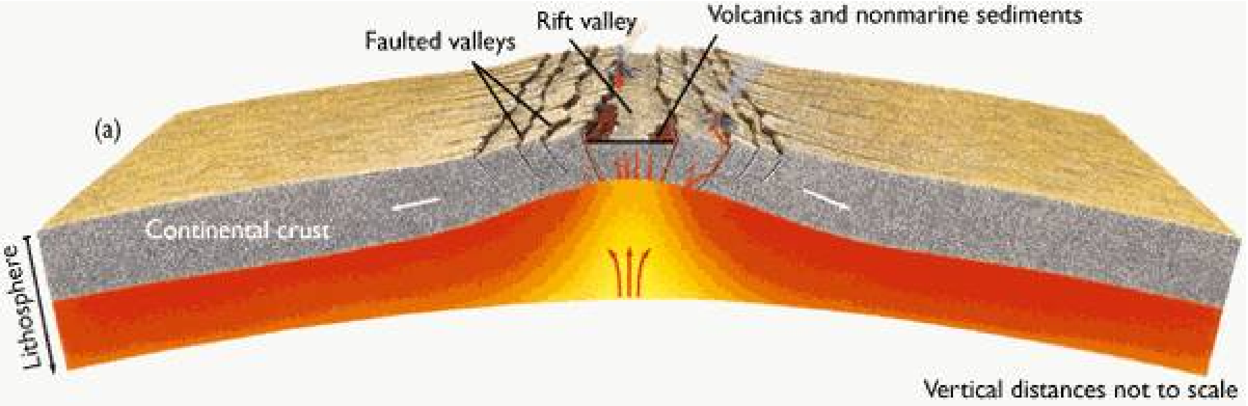




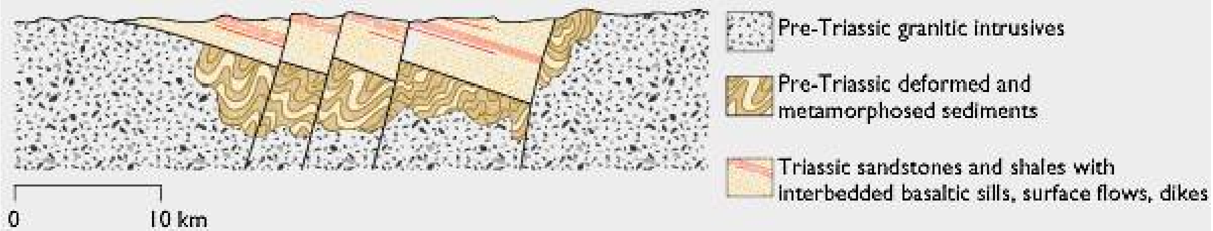
EXAMPLE:
ATLANTIC RIFTING



OPENING OF PRESENT ATLANTIC OCEAN PART OF PANGAEA BREAKUP ABOUT 200 MYR AGO



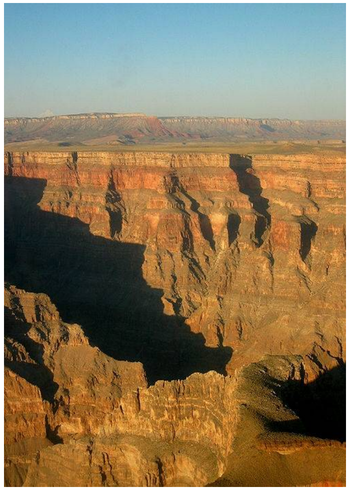
VALLEYS FORMED BASINS THAT TRAPPED SEDIMENTS & INTRUDED BY BASALTIC LAVA FLOWS (PALISADES, HUDSON RIVER)

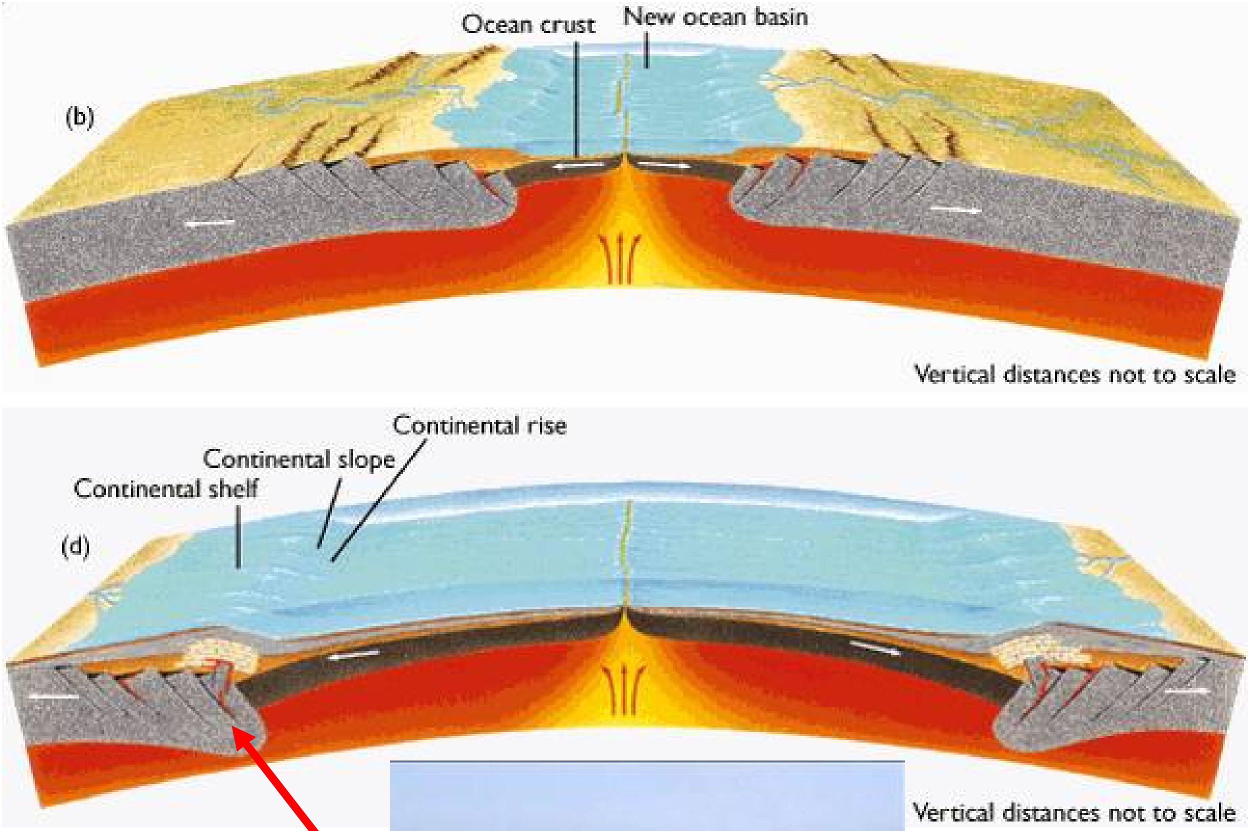


Press & Siever

PASSIVE CONTINENTAL MARGIN SEDIMENTS
Example: NORTH ATLANTIC OCEAN WIDENED, CONTINENTAL MARGIN COOLED & SUBSIDED

<u>NONE</u> ACTIVE PLATE BOUNDARY = "PASSIVE" CONTINENTAL MARGIN





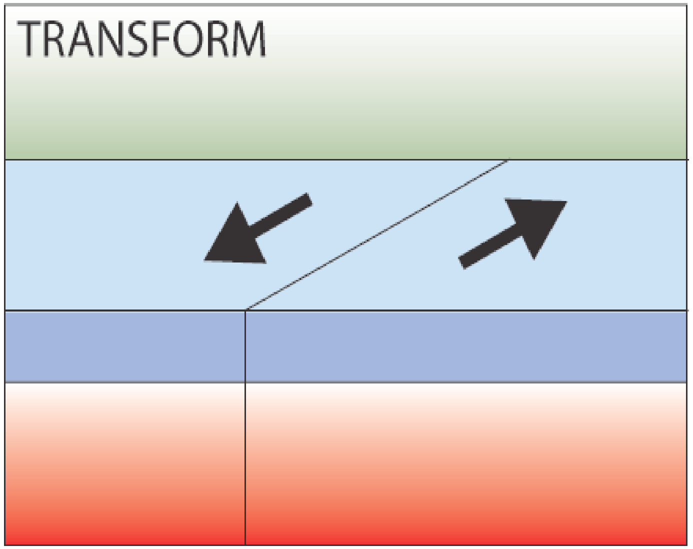
THICK (> 5 KM) SEDIMENTS ON CONTINENTAL SHELF

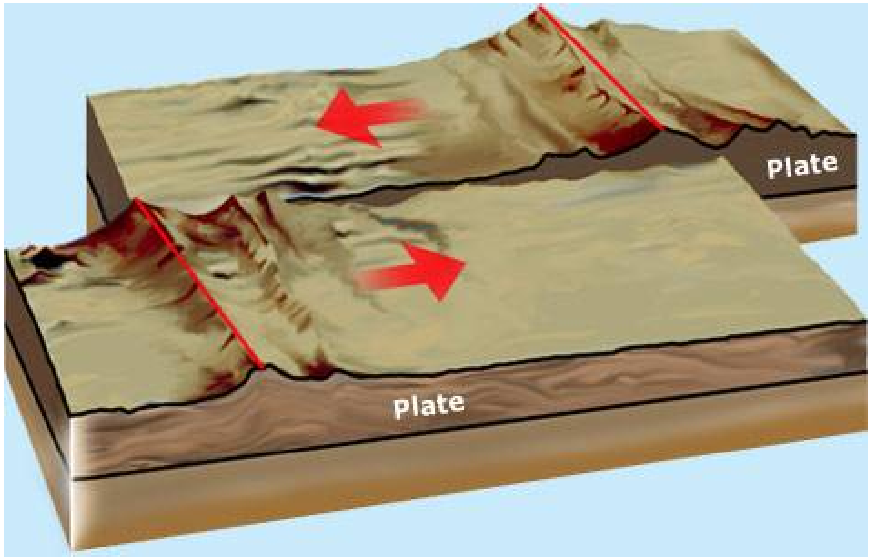
SOME SEDIMENTARY BASINS BECOME MAJOR SOURCES OF OIL & NATURAL GAS.

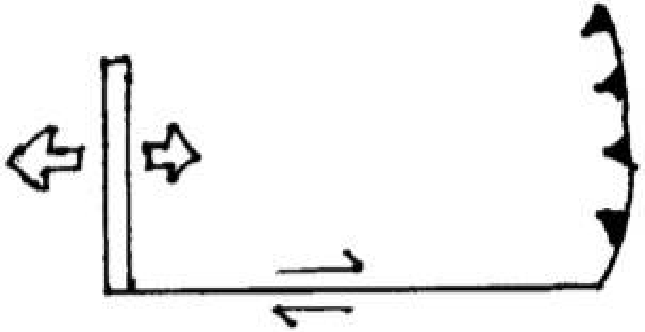
Press & Siever

Transform boundaries

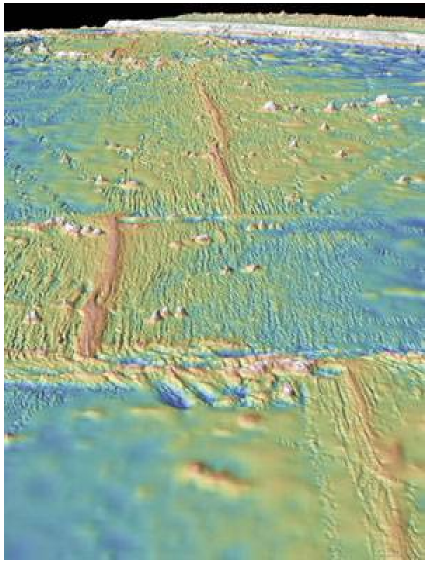
Where plates slide past each other



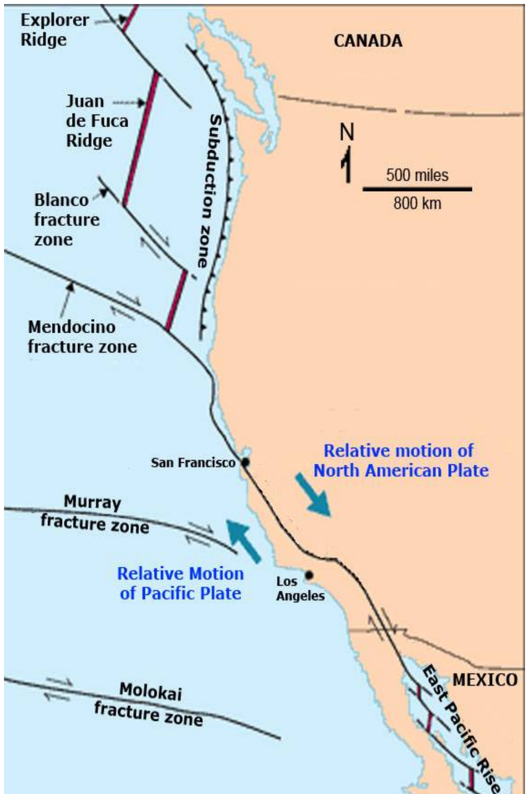


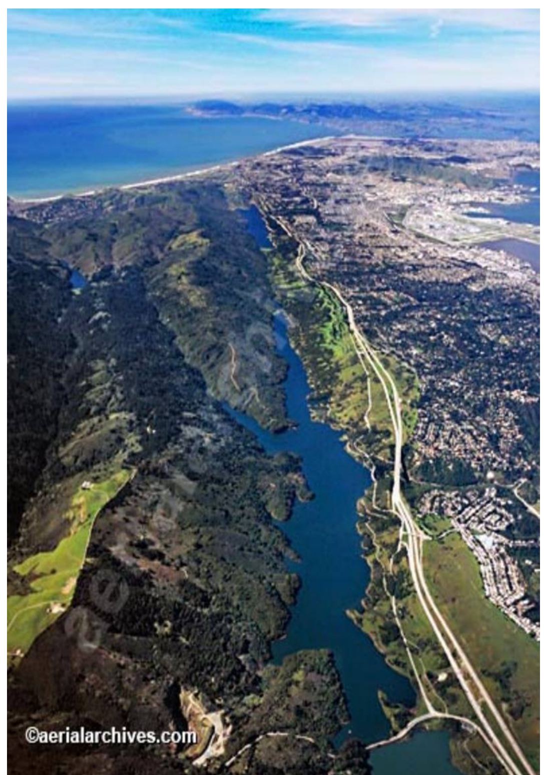


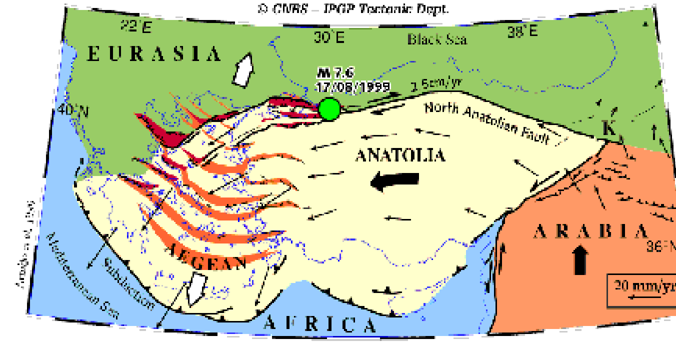
A spreading center (left) connected by a transform fault to the upper slab of a subduction zone

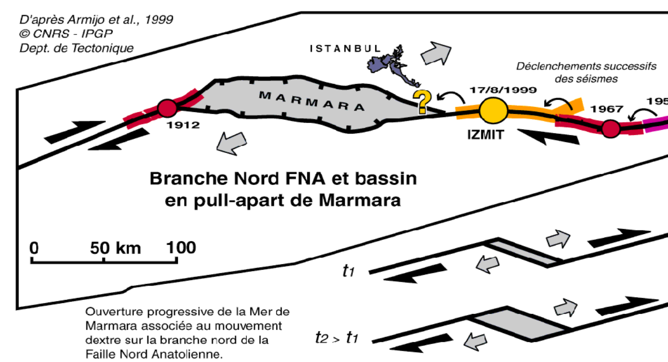


San Andreas fault,
Anatolian fault (Izmit EQ),
New Zealand Alpine Fault
Levant Fault, Etc...



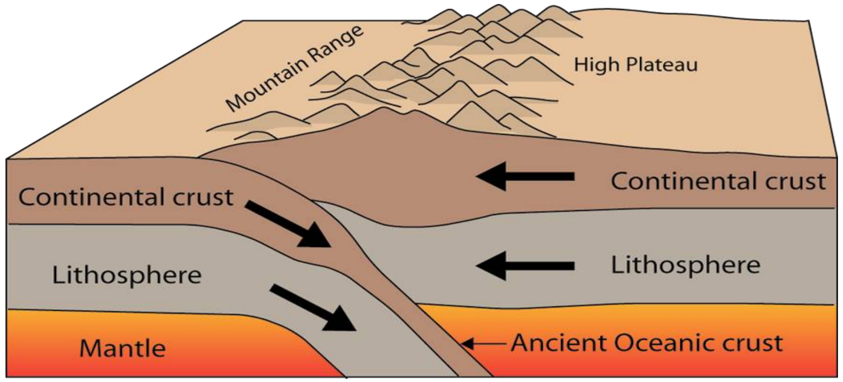




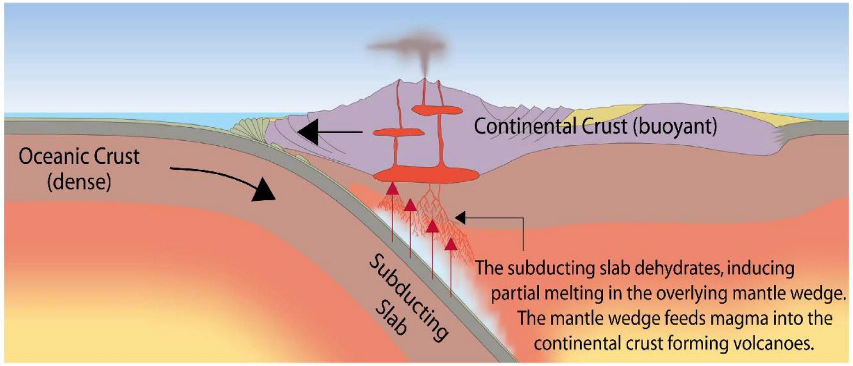


Convergent boundaries

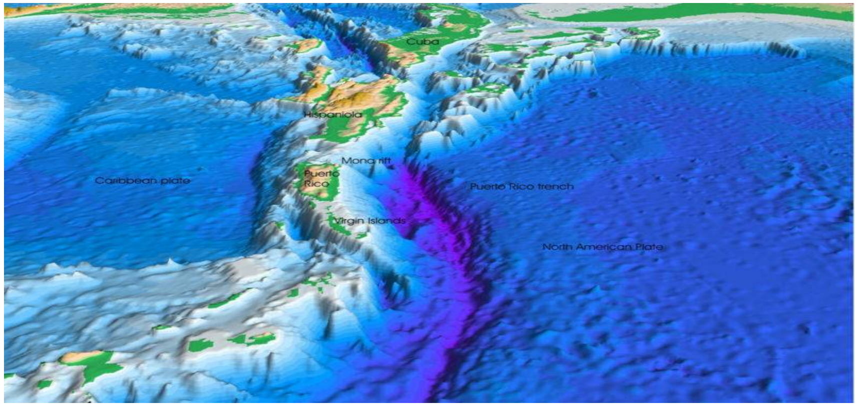
- Continent-continent collision
  e.g. European Alps, Himalayas



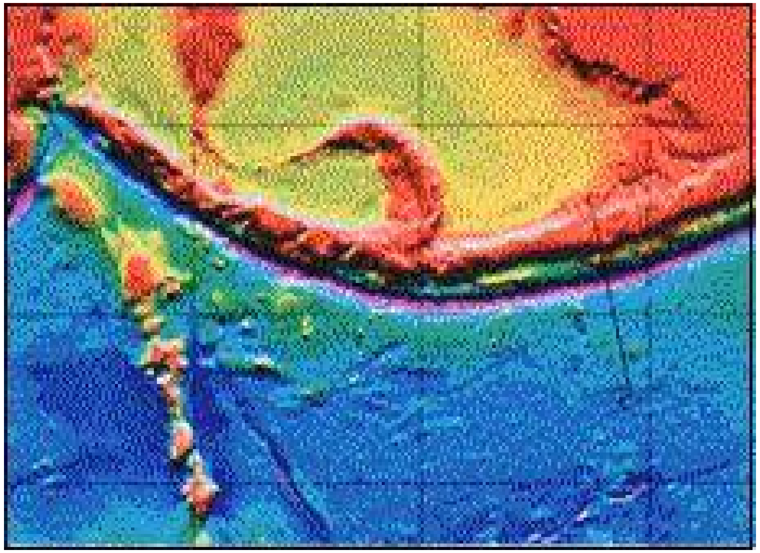
- Continent-oceanic collision
  e.g. The Andes

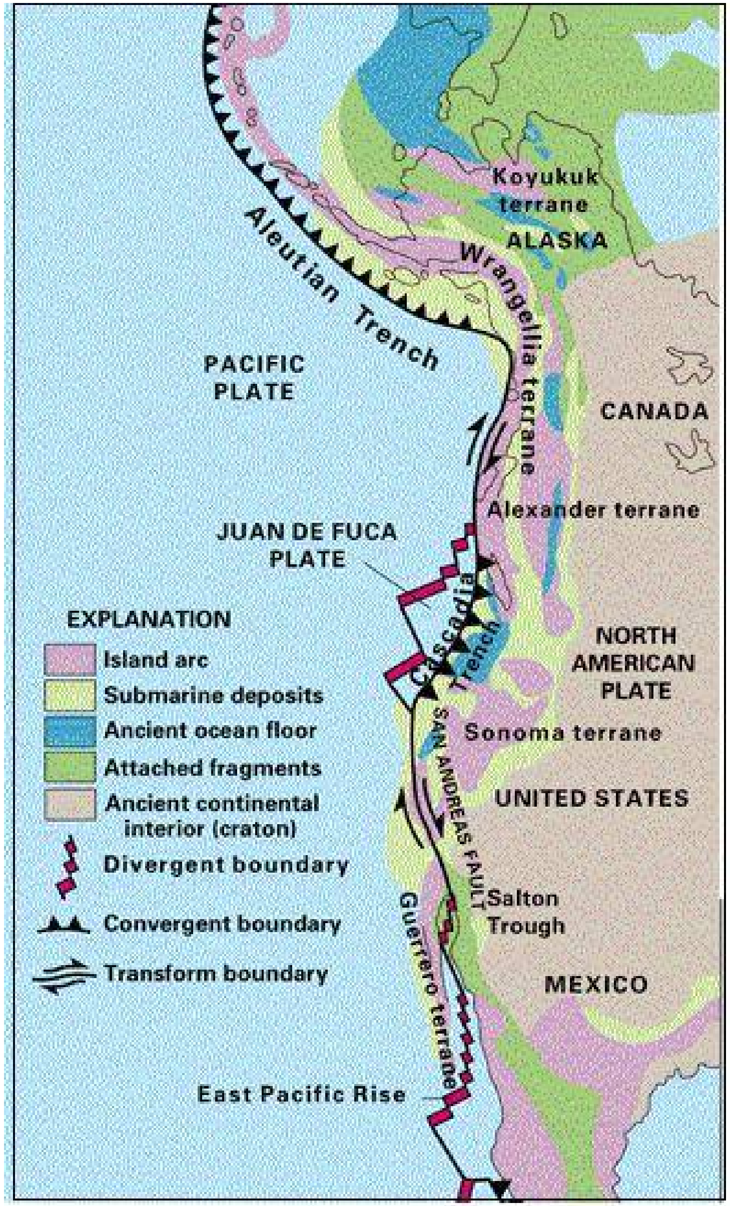


- Ocean-ocean collision

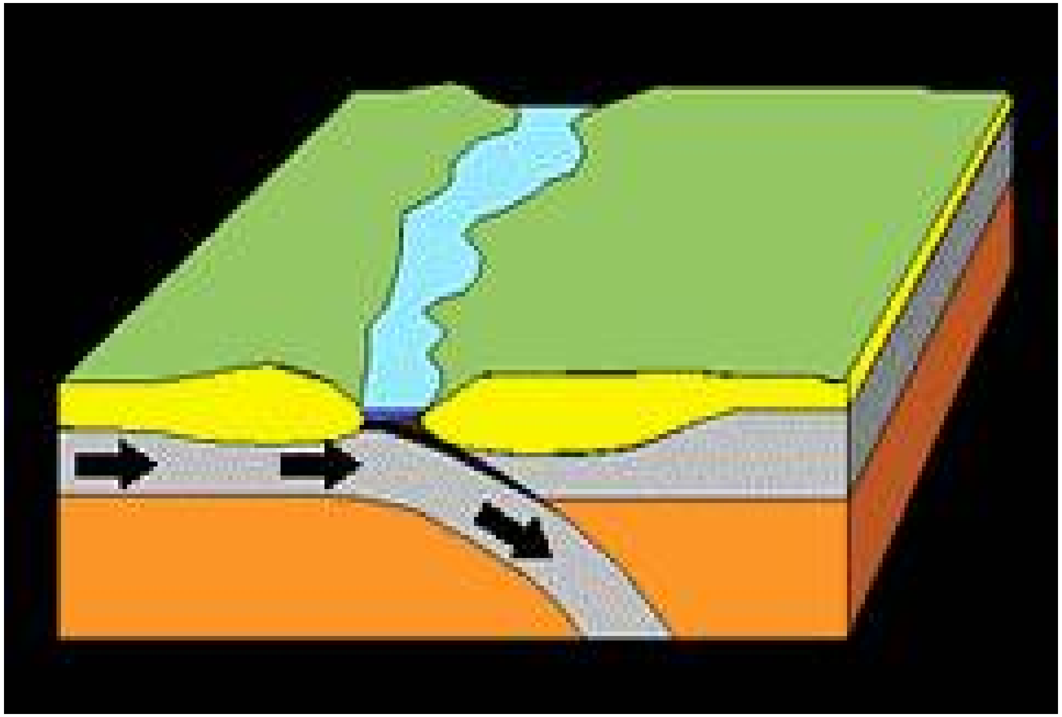


Exemple d'arc volcanique insulaire: les Aléoutiennes

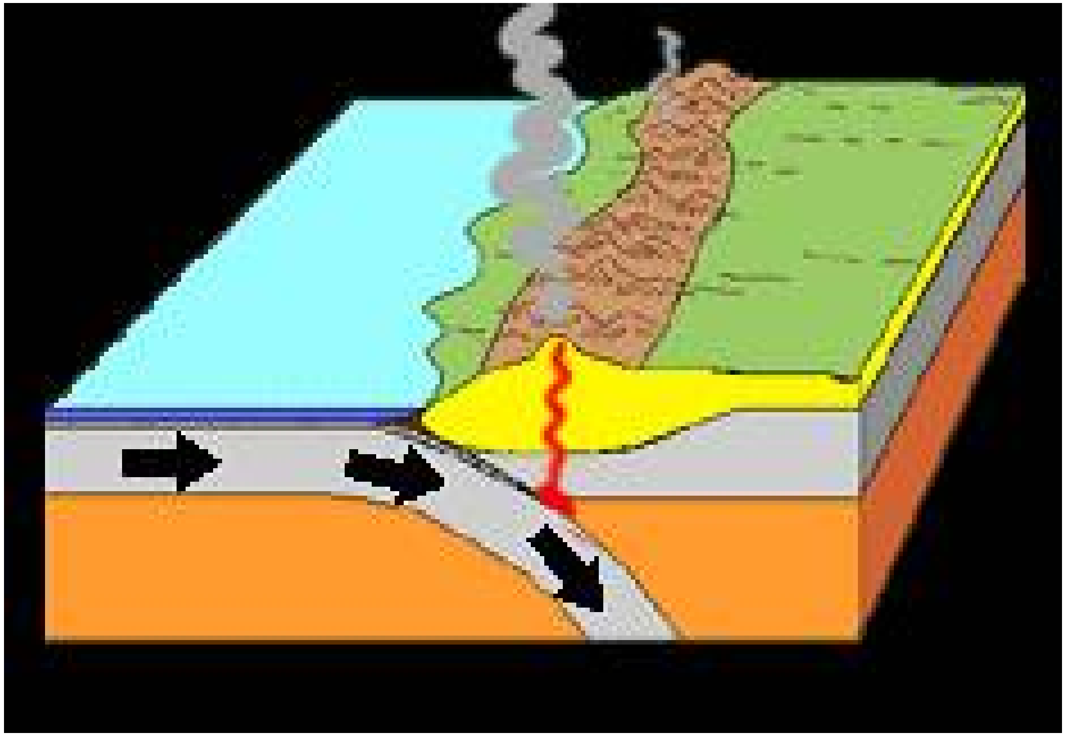




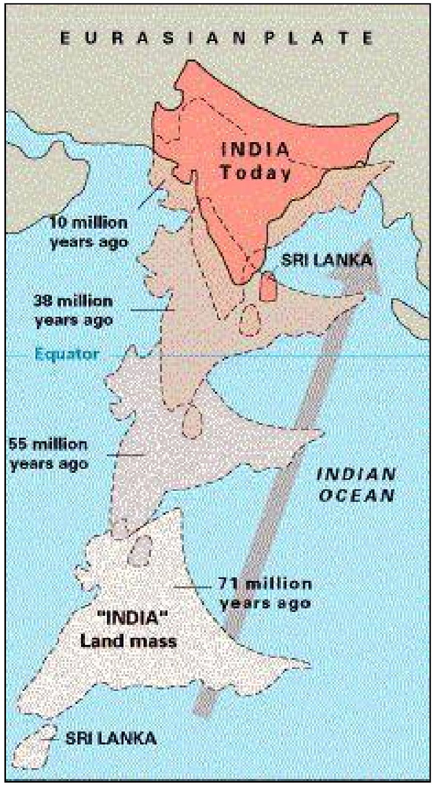
Ex: Himalaya

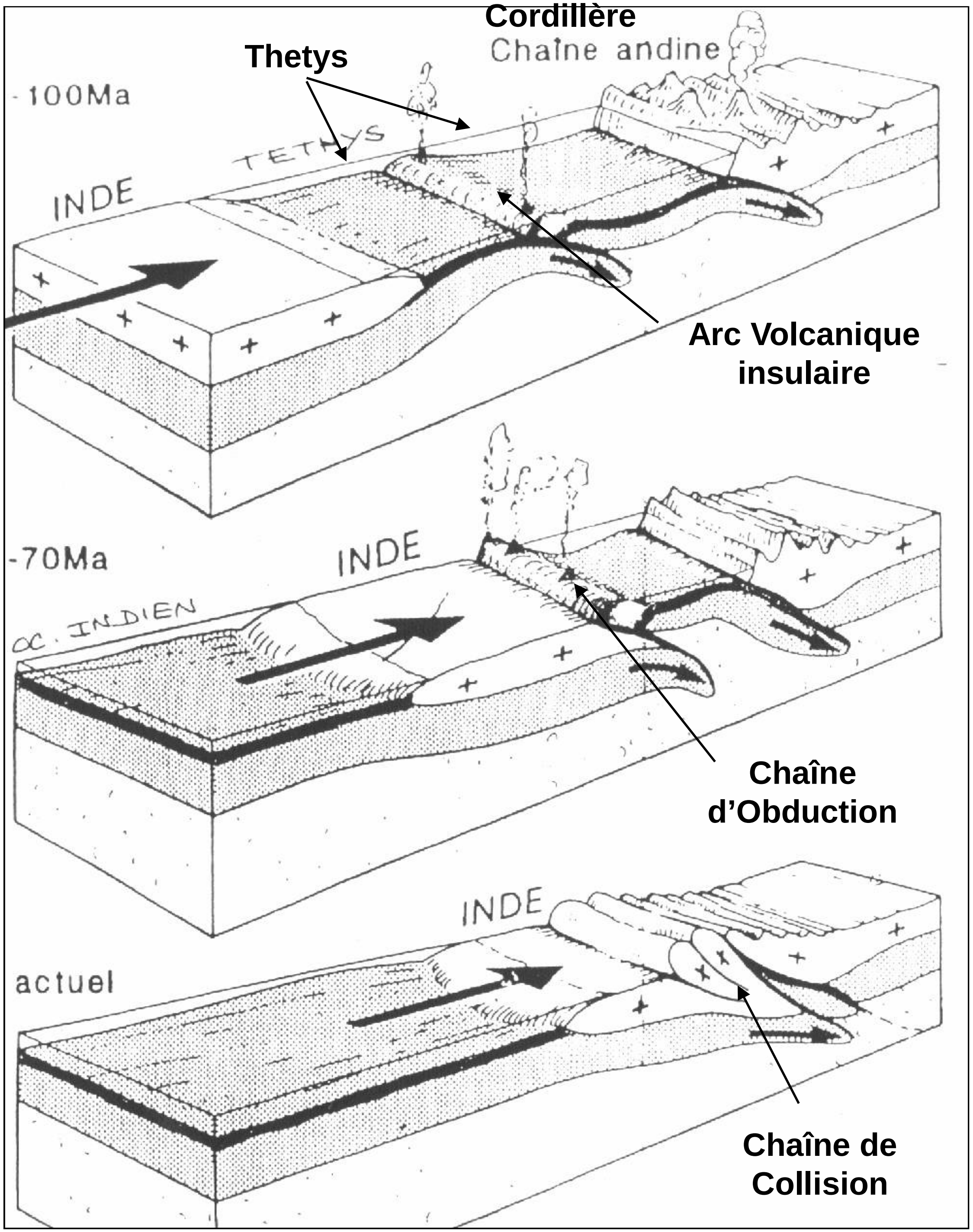


Ex: Andes

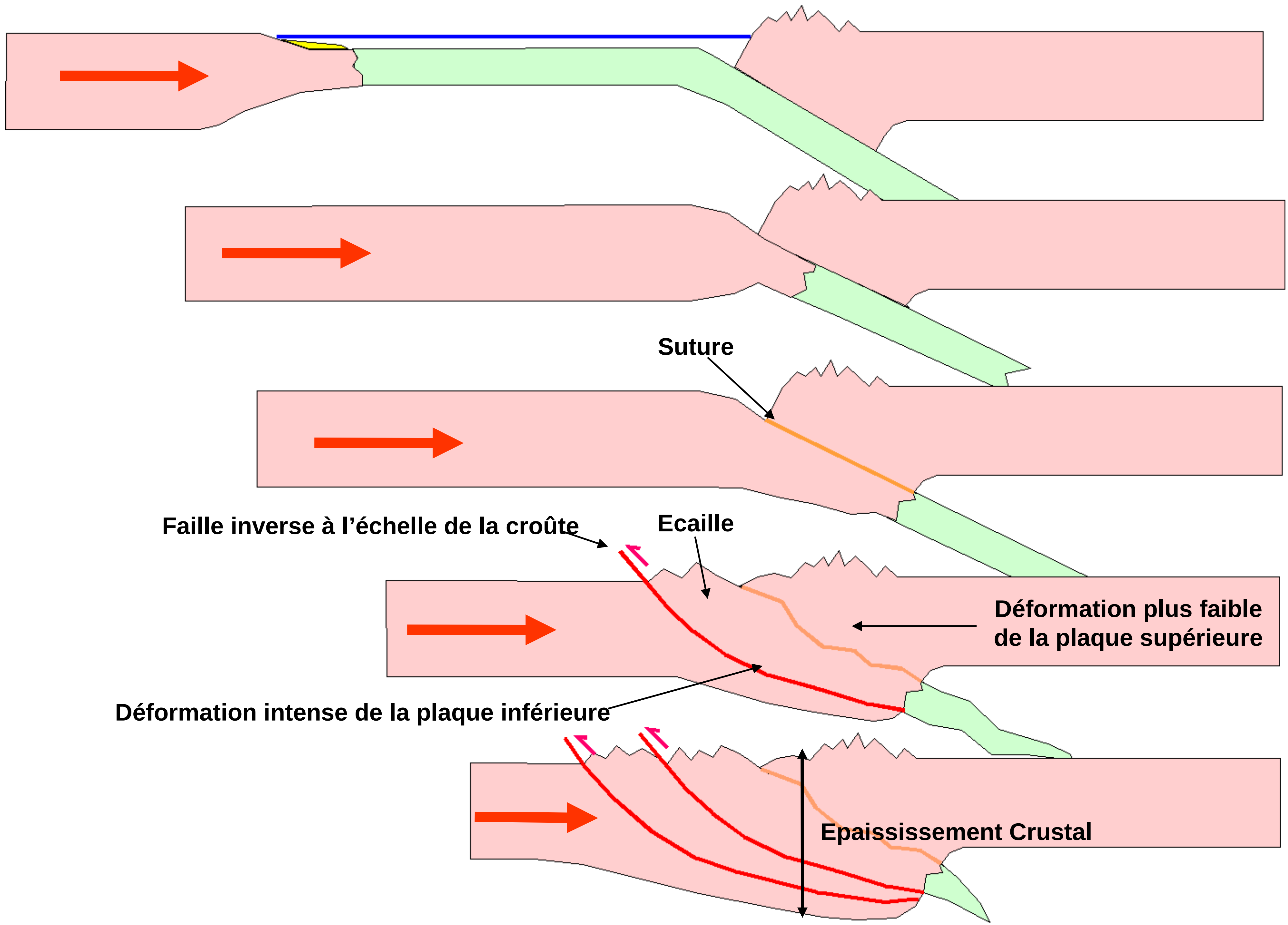


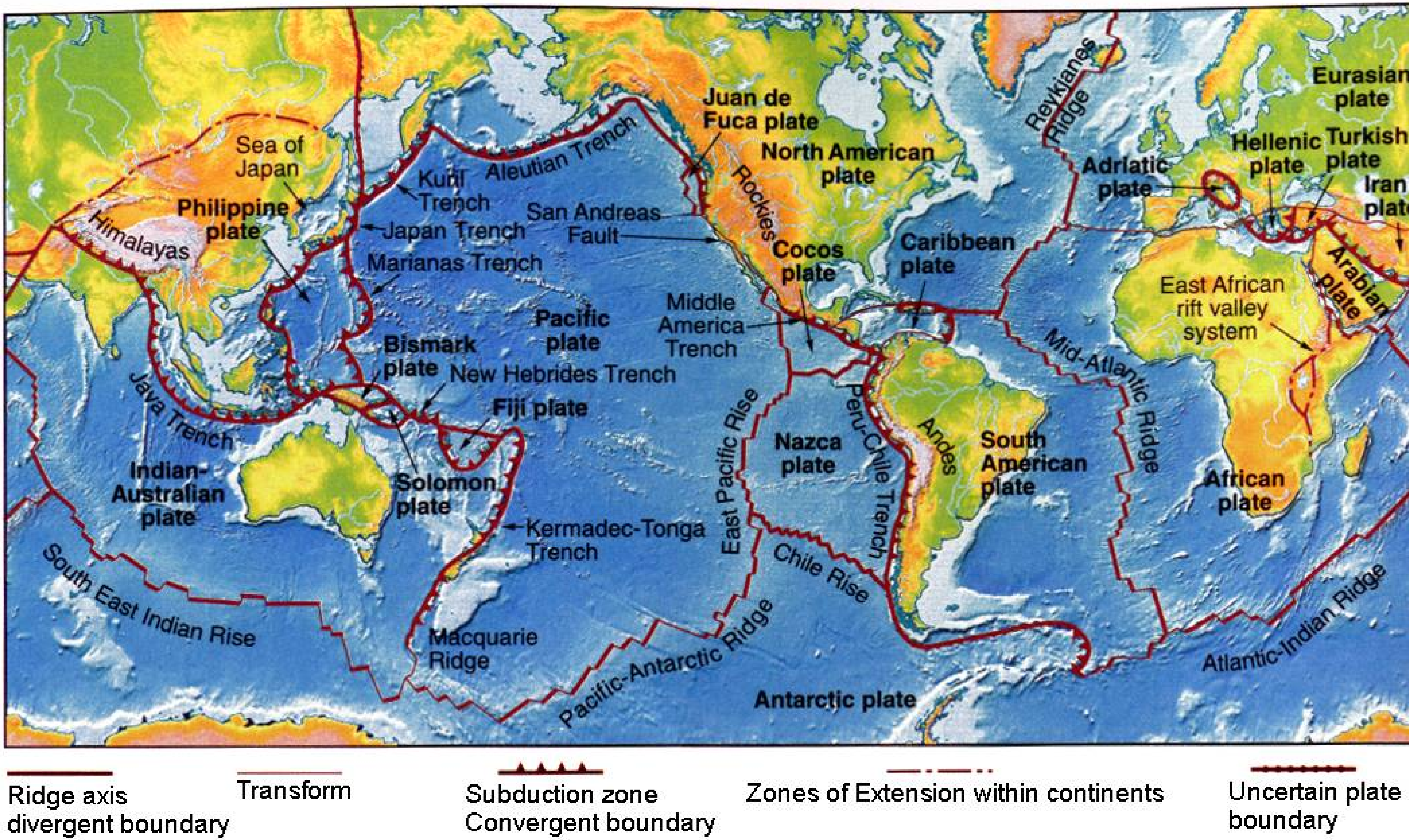
Exemple:
l'Himalaya





<u>Zone en convergence, plaques à croûtes continentales</u>
Obduction Continentale (Collision, Epaississement Crustal)



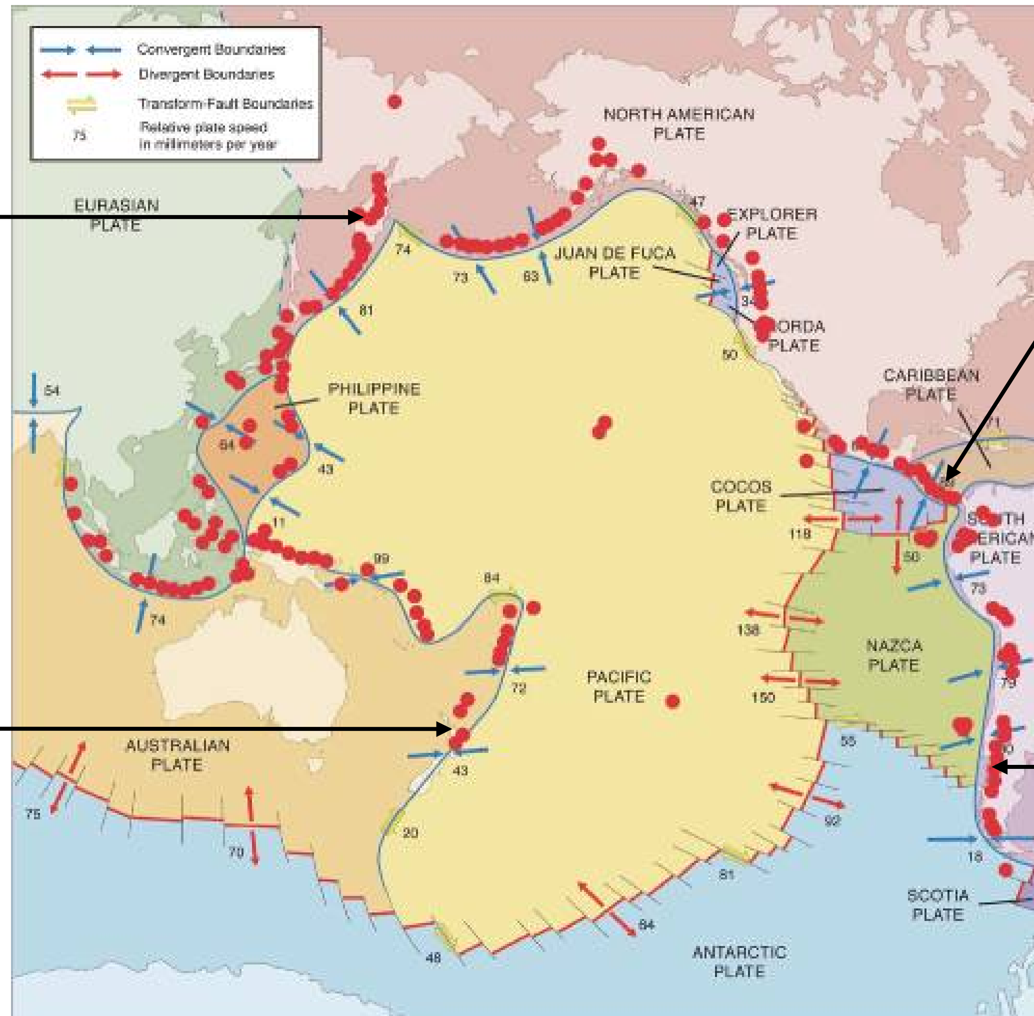


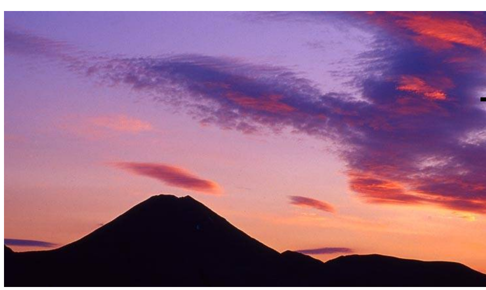
Eurasian plate
Juan de Fuca plate
Reykjanes Ridge
Sea of Japan
North American plate
Hellenic plate
Turkish plate
Aleutian Trench
Adriatic plate
Iran plate
Kuril Trench
Rockies
Philippine plate
San Andreas Fault
Himalayas
Japan Trench
Cocos plate
Caribbean plate
Arabian plate
Marianas Trench
East African rift valley system
Middle America Trench
Pacific plate
Bismark plate
Mid-Atlantic Ridge
New Hebrides Trench
Fiji plate
Java Trench
East Pacific Rise
Nazca plate
Peru-Chile Trench
Andes
South American plate
Indian-Australian plate
Solomon plate
African plate
Kermadec-Tonga Trench
Chile Rise
South East Indian Rise
Atlantic-Indian Ridge
Macquarie Ridge
Pacific-Antarctic Ridge
Antarctic plate
Ridge axis divergent boundary
Transform
Subduction zone Convergent boundary
Zones of Extension within continents
Uncertain plate boundary

Earth Plate

The origin of volcanism ?

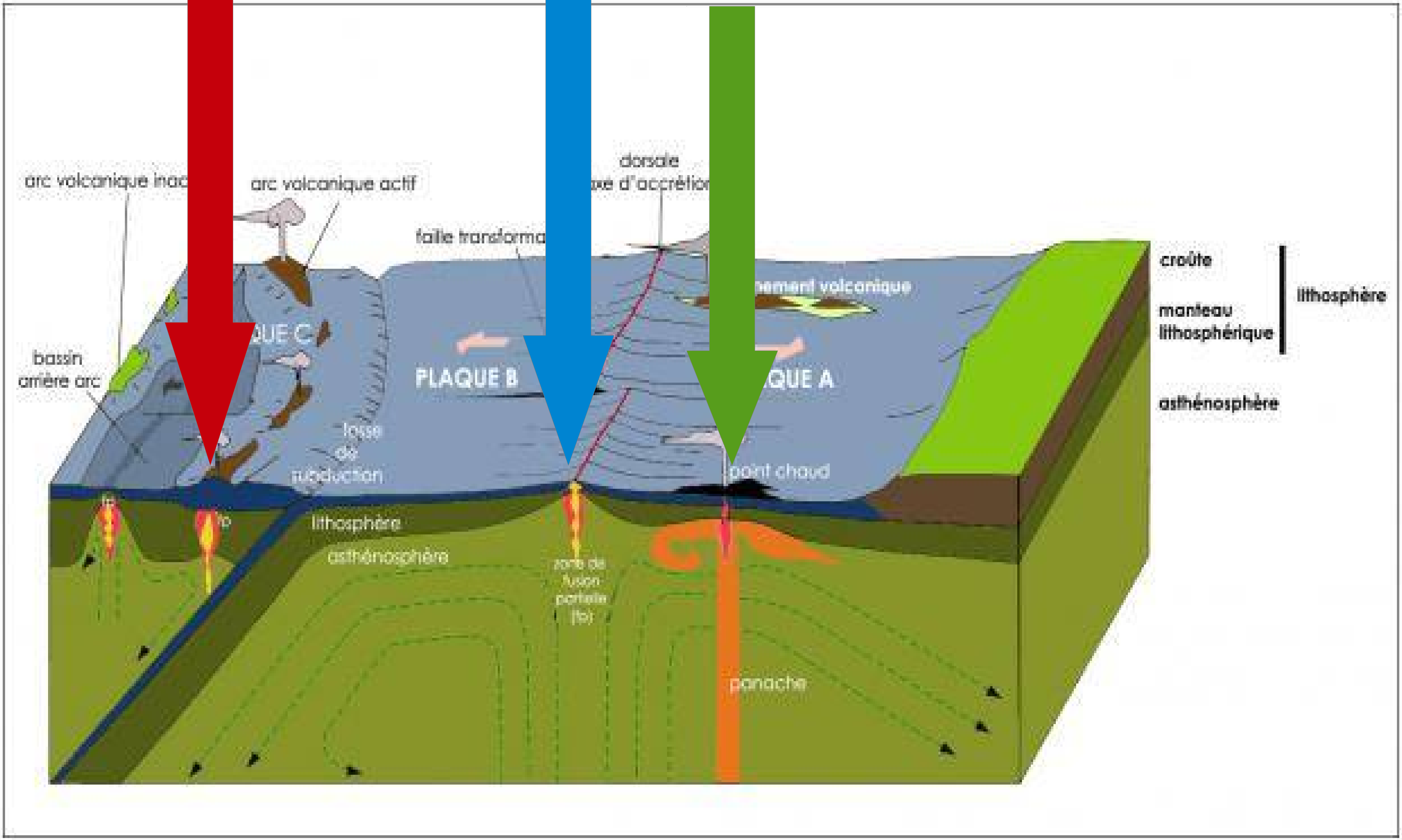
Pacific Ring of Fire





Volcanism is mostly focused at plate margins

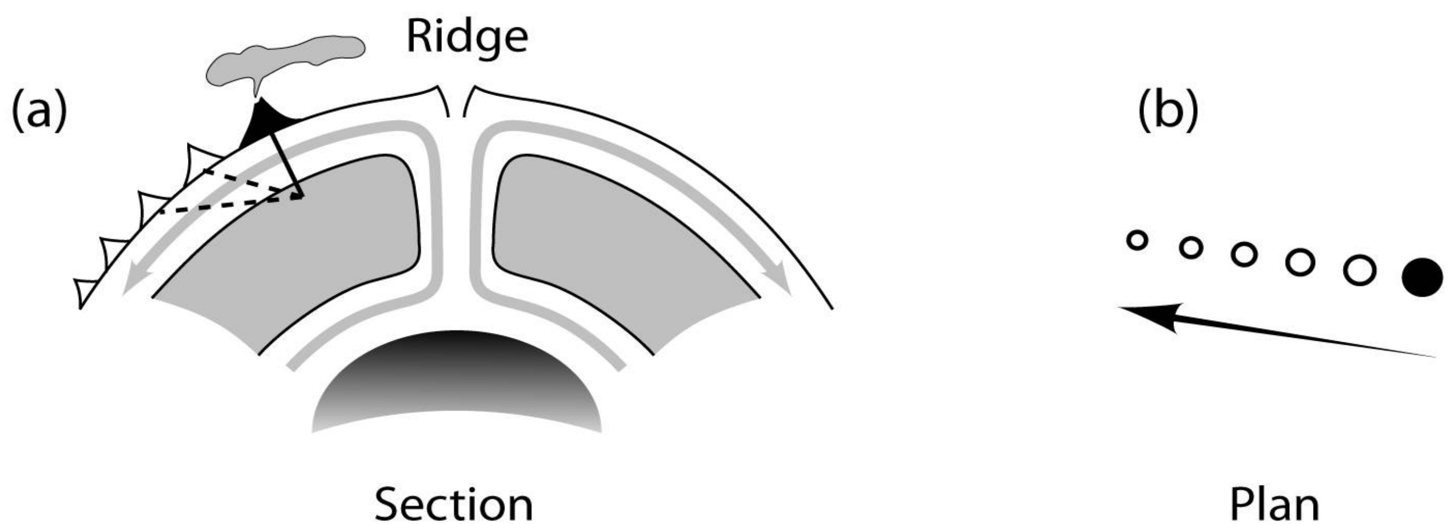
THREE different types of volcanoes:
ARC Subduction,
RIDGE volcanism (MORB),
HOTSPOT volcanism (PLUMES)

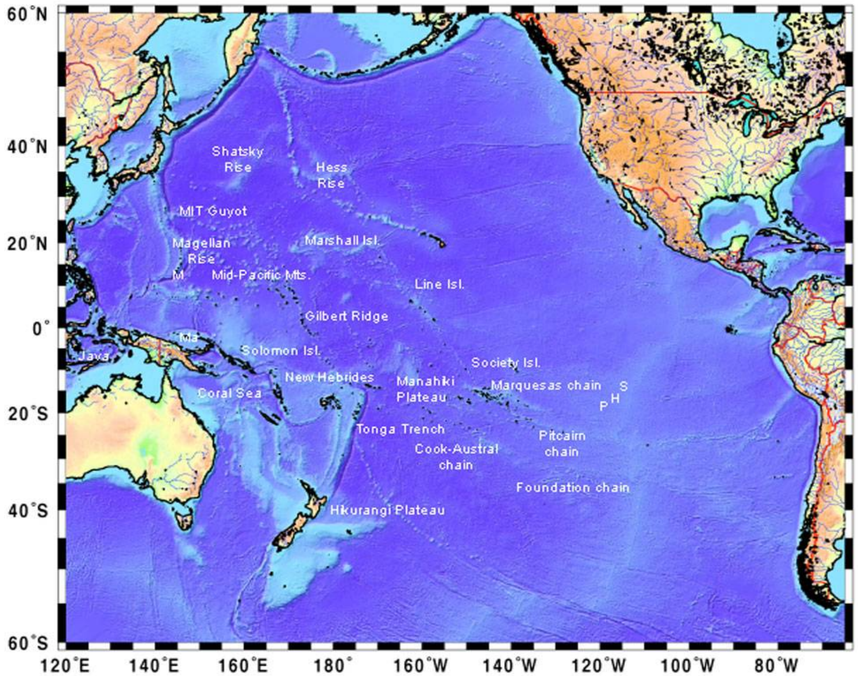


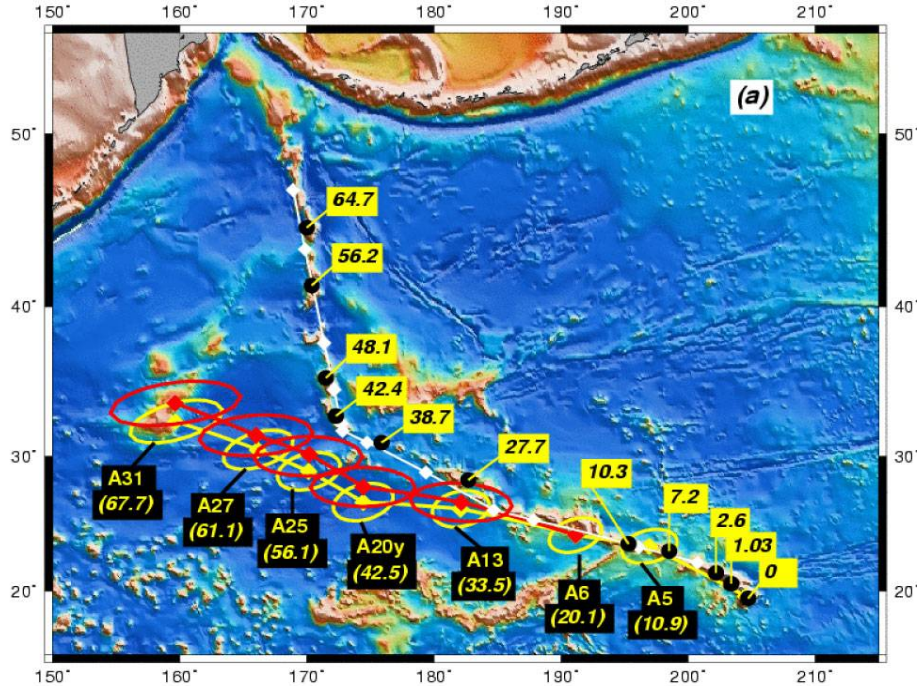
In the 1960's, Plate tectonics is recognised as the best explanation to variations in the fossile magnetic field recorded on oceanic seafloor and to worldwide seismicity.

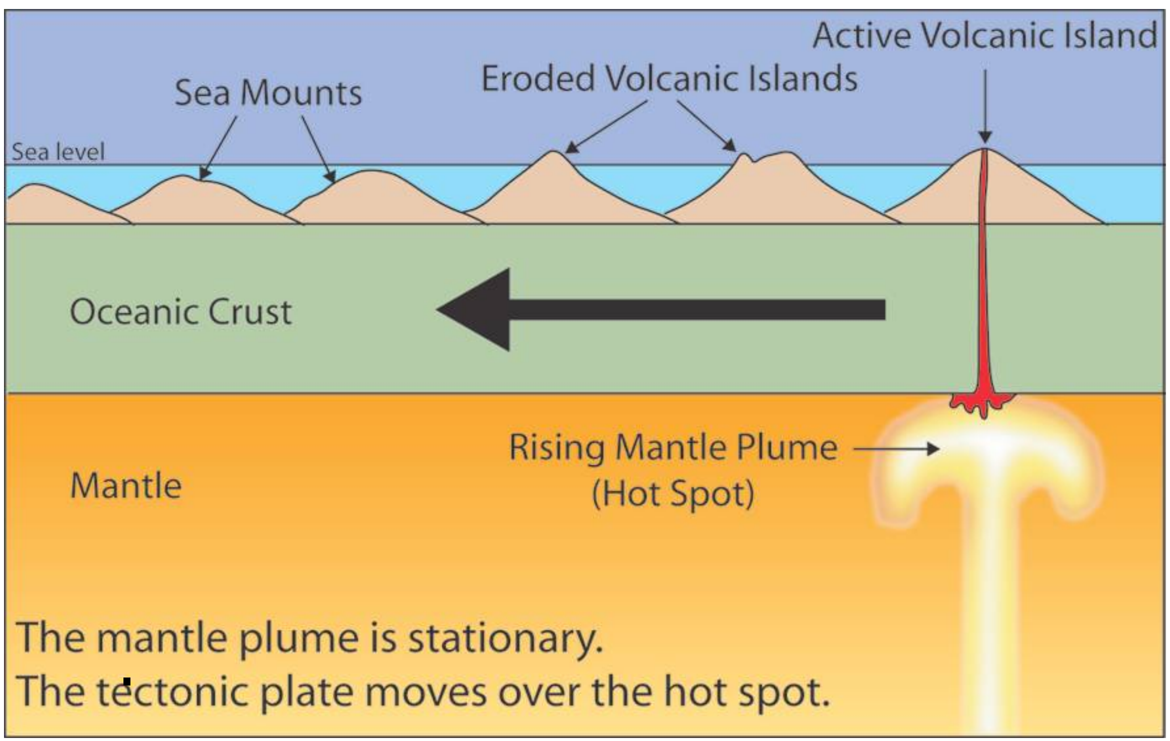
The Rayleigh-Bénard theoretical convection is used to show that the Earth's mantle should be convecting with a viscosity less than 10^{25} Pas. Haskell, in the 1930,had estimated values of the order of 10^{21} Pa.s.

T. Wilson (1963) also assumes mantle convection and plate tectonics to explain intraplate volcanism, also called hotspots, such as those of Hawai and La Reunion islands: a magmatic source in the mantle should exist that is fixed with respect to the convecting mantle and moving plates, forming a “line” or “belt” of volcanoes.



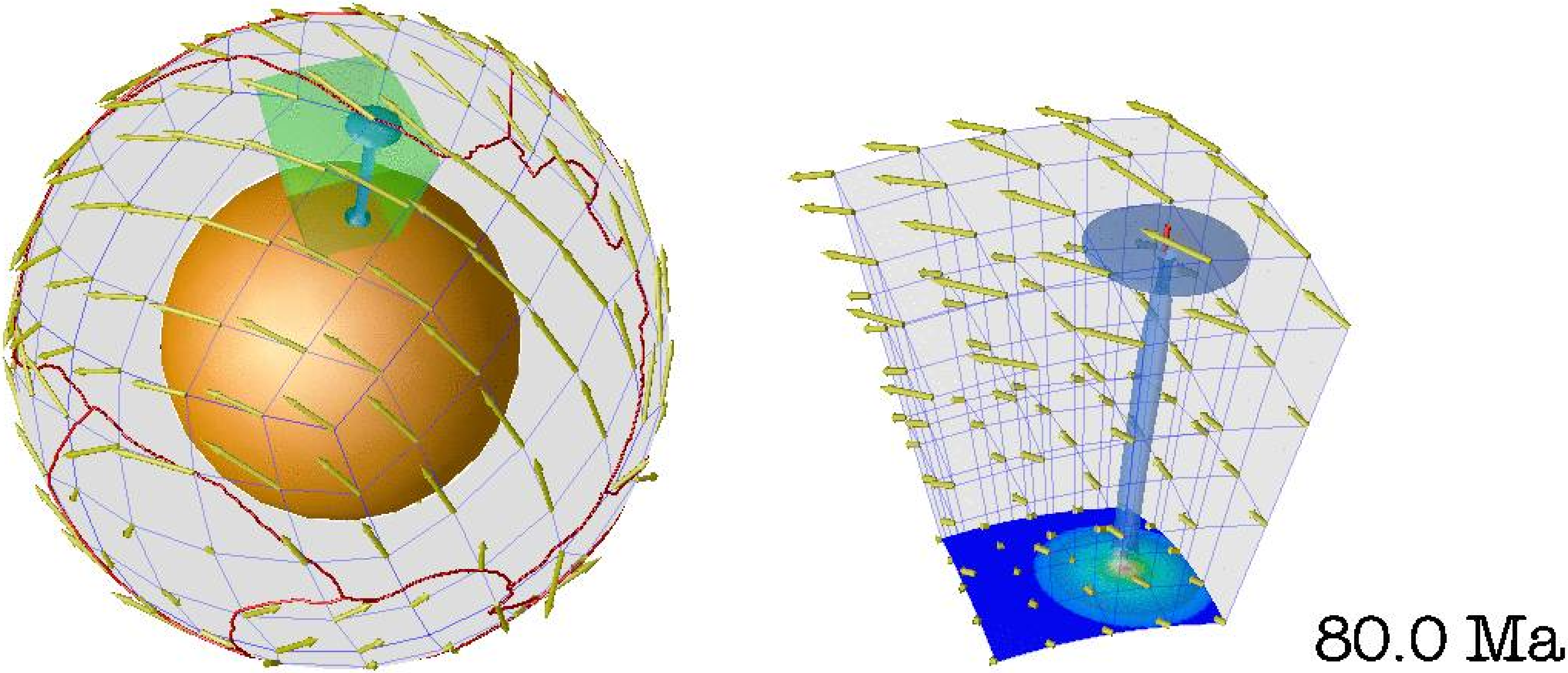






The tectonic plate moves over a fixed hotspot forming a chain of volcanoes.

The volcanoes get younger from one end to the other.

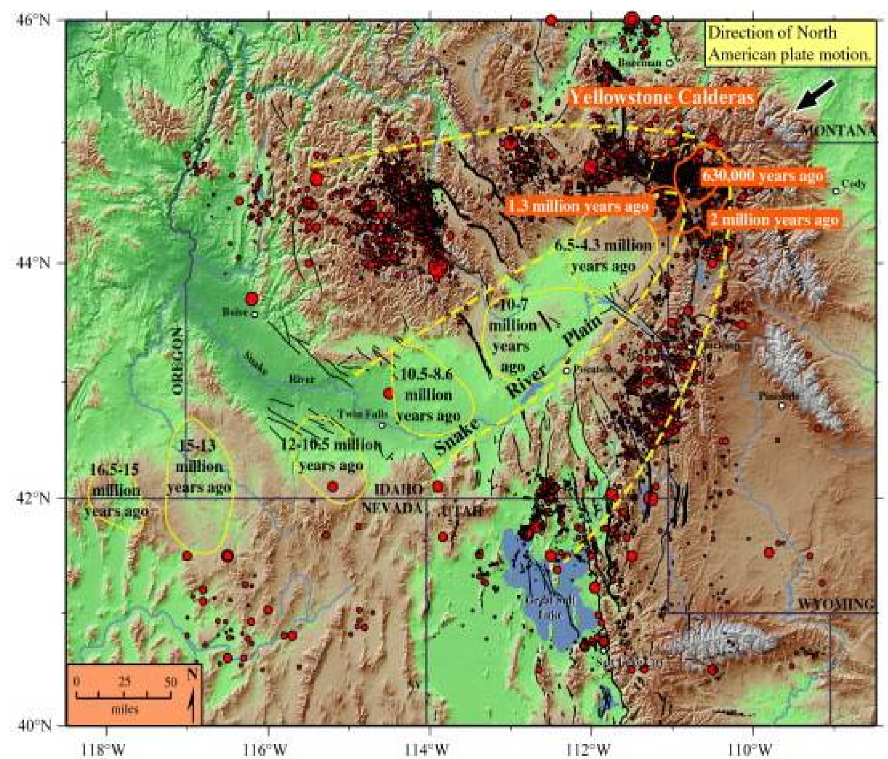


Displacement of the trace of a hot spot on the Earth's moving surface, coming from a fixed point on the D” boundary.

YELLOWSTONE HOTSPOT ?

Ansel Adams · Classic Images

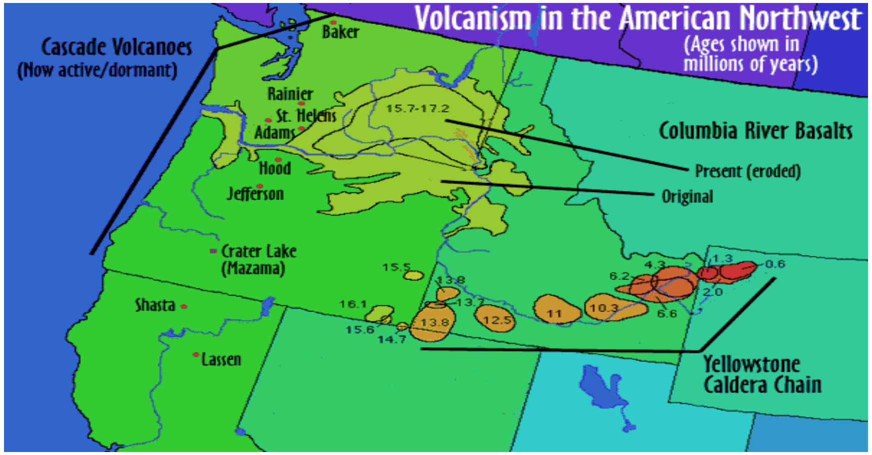
ACTIVE VOLCANIC, SEISMIC, AND GEOTHERMAL REGION

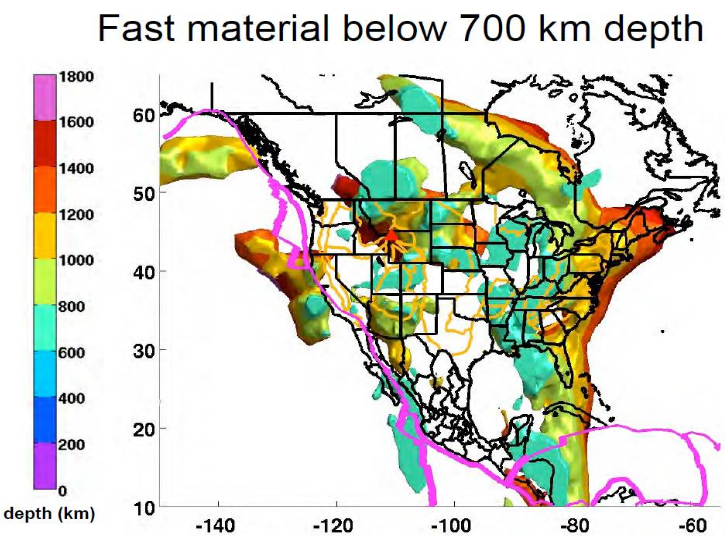


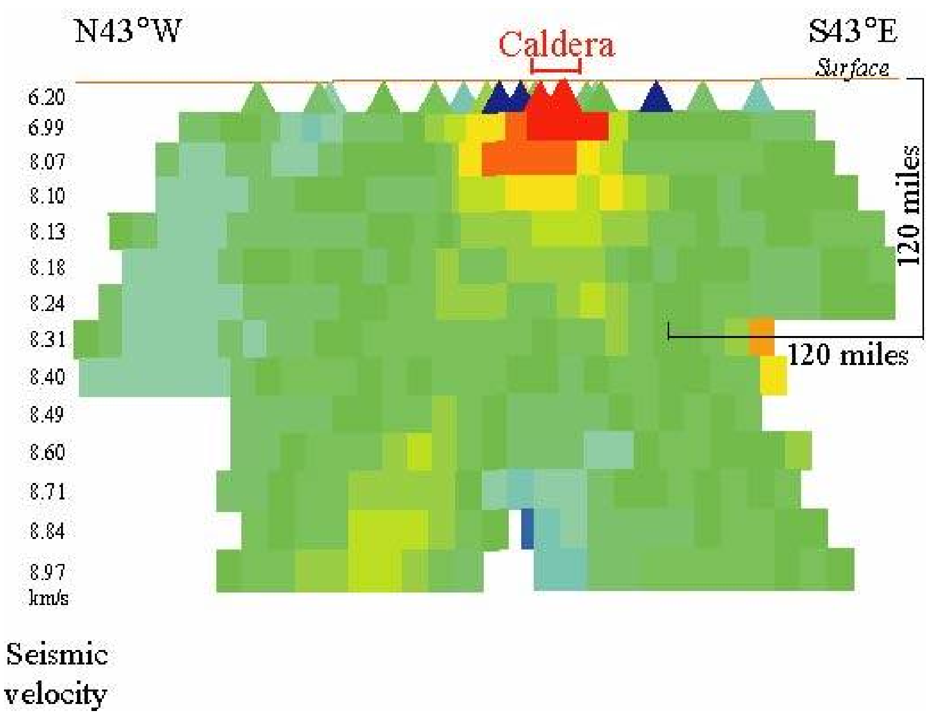
YELLOWSTONE ERUPTIONS FORM TRACES IN EXPECTED PLATE MOTION DIRECTION

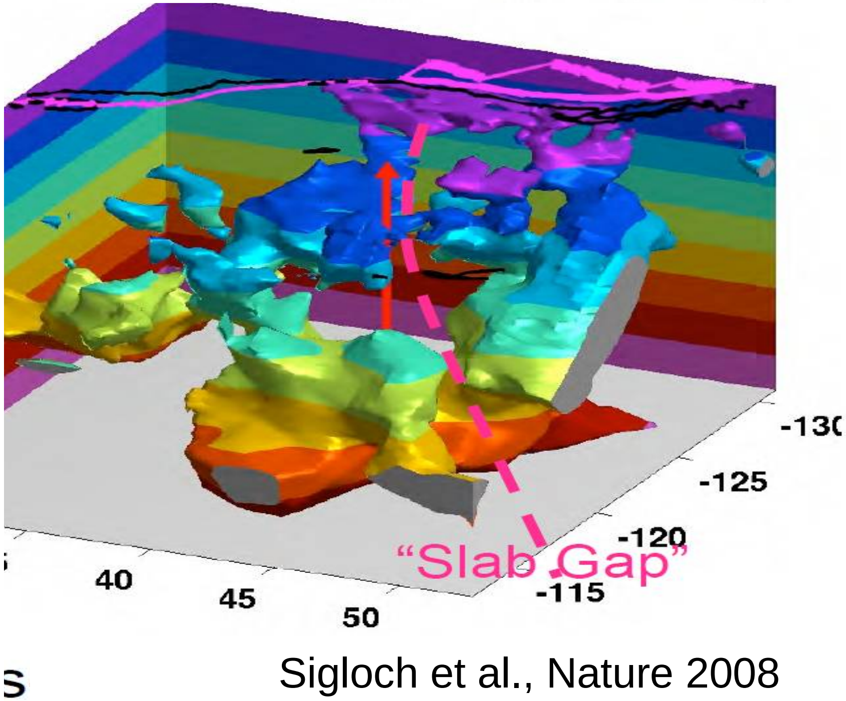
BUT, YELLOWSTONE SEISMIC TOMOGRAPHY PROBLEM

LOW VELOCITY ANOMALY (PRESUMABLY ASSOCIATED WITH HOT UPWELLING) ONLY IN UPPERMOST MANTLE



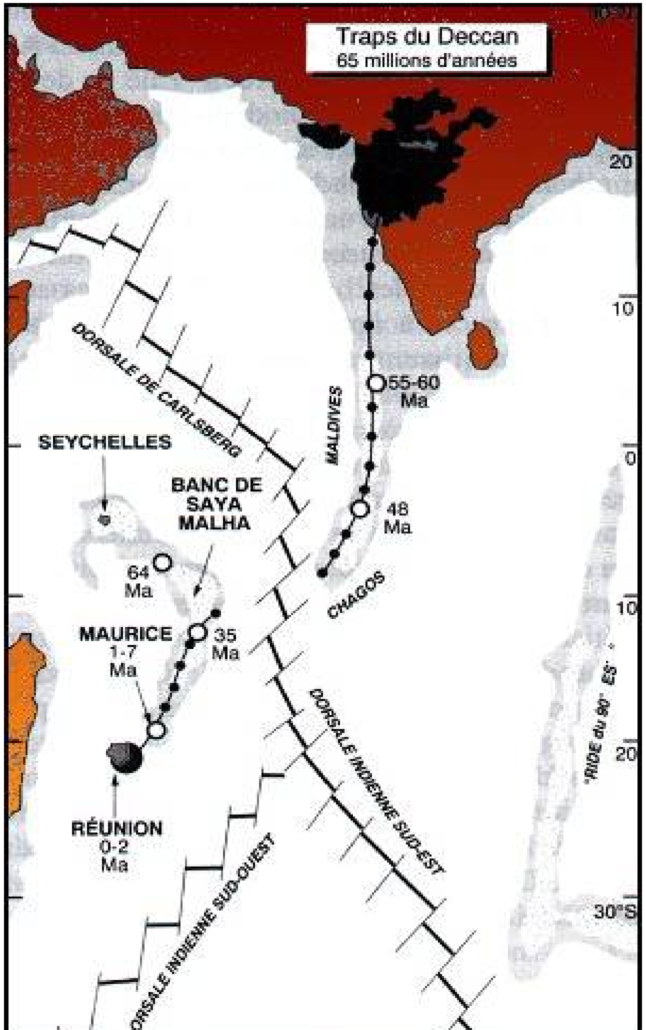


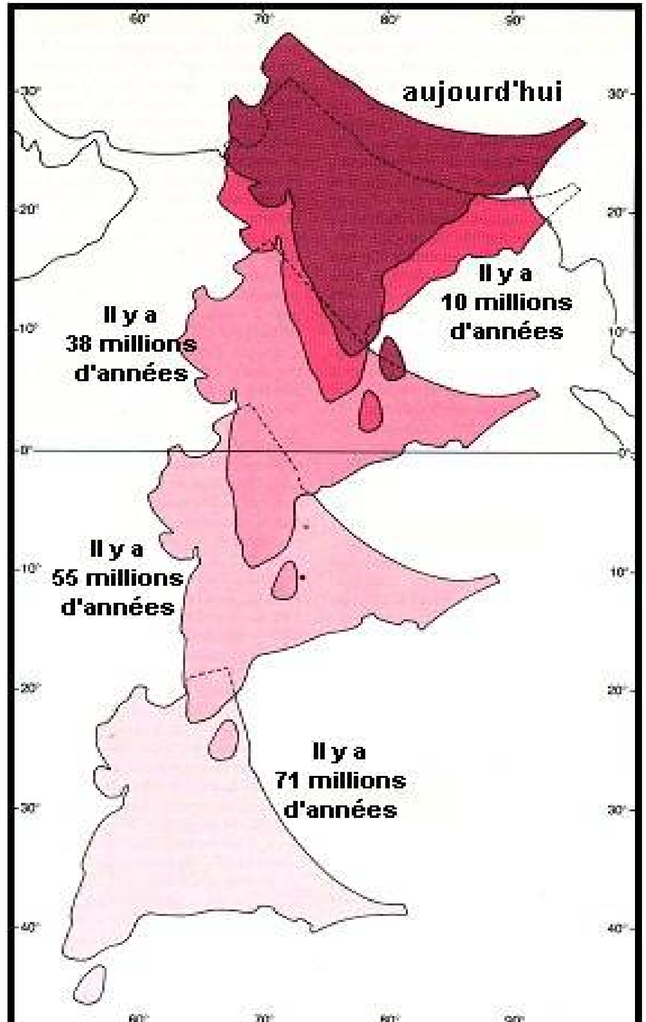




Sigloch et al., Nature 2008

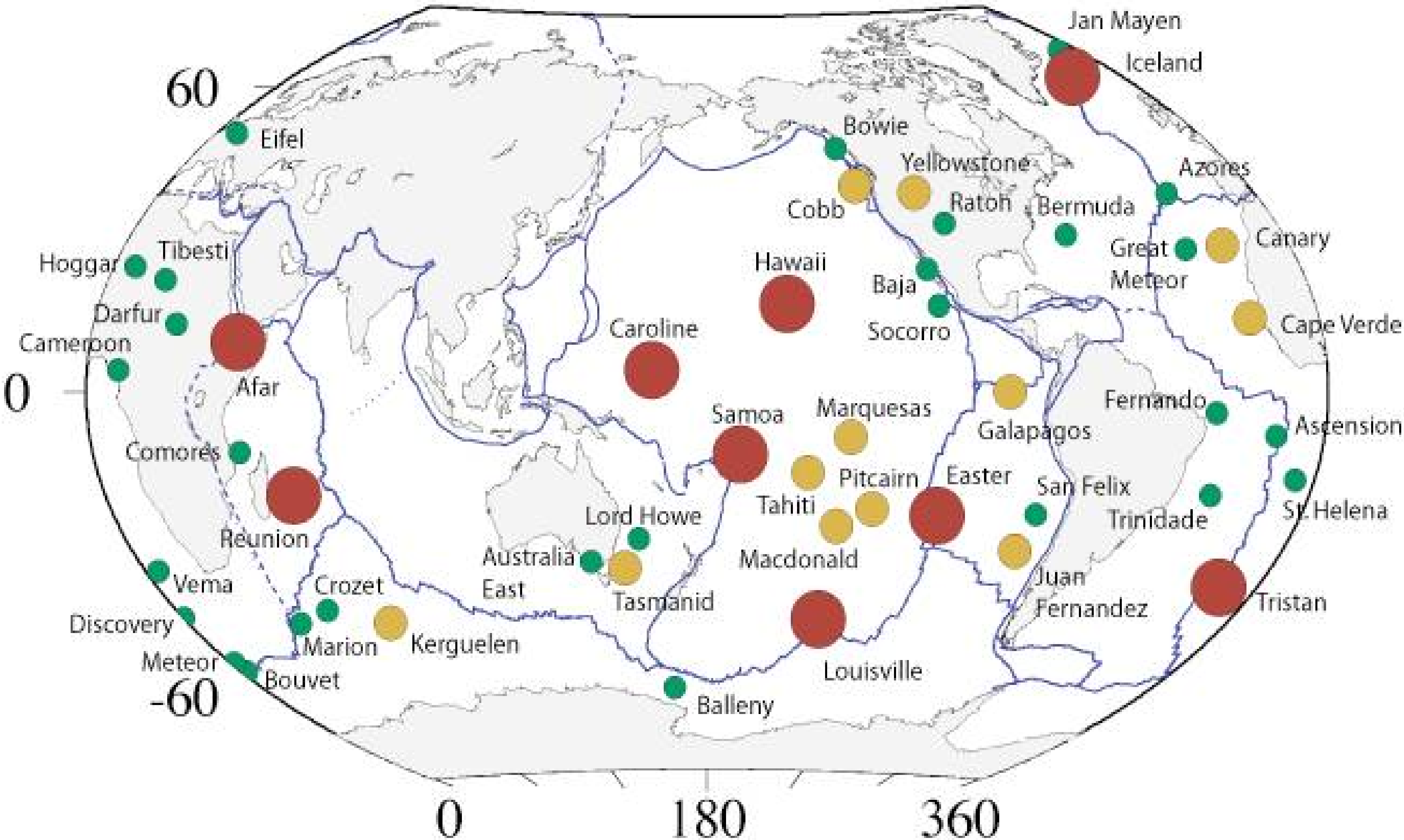
Les trapps du Deccan sont associés au point chaud de La Réunion actuel.
Les trapps se sont formés lorsque l'Inde était à 4500 km de sa position actuelle.



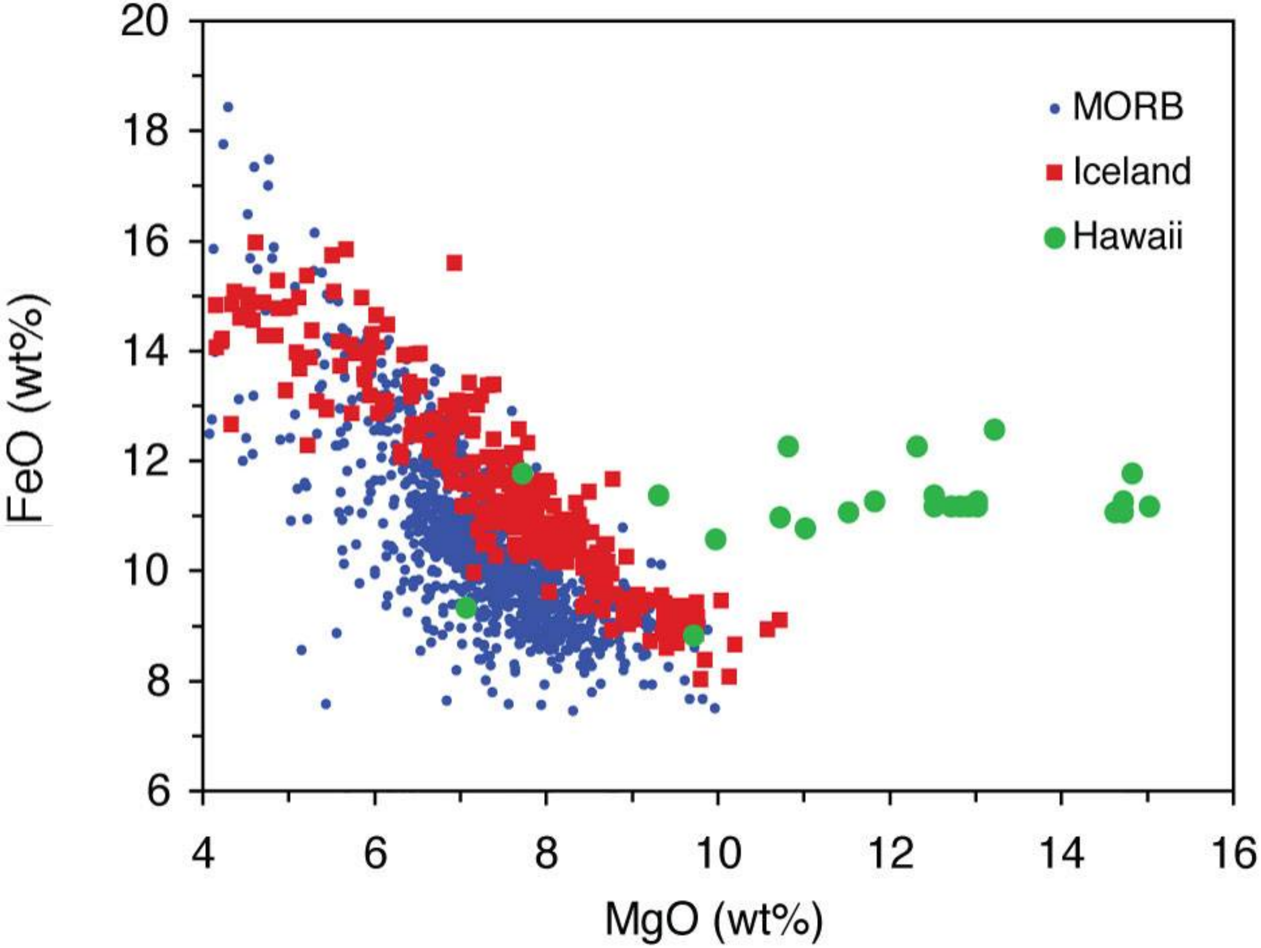


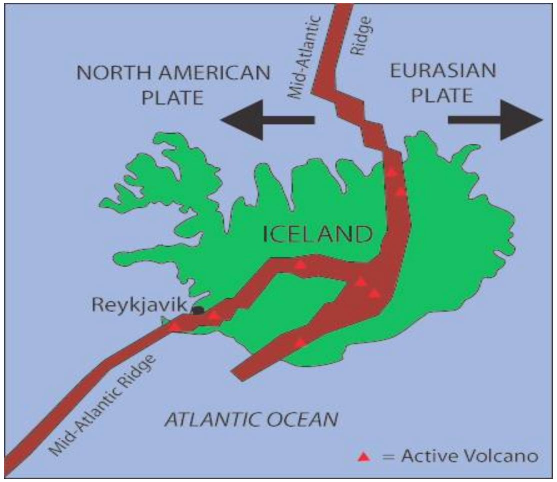
Dans la partie occidentale de l'Inde, l'épaisseur totale des trapps dépasse 2400 mètres (la moitié de la hauteur du Mont Blanc).

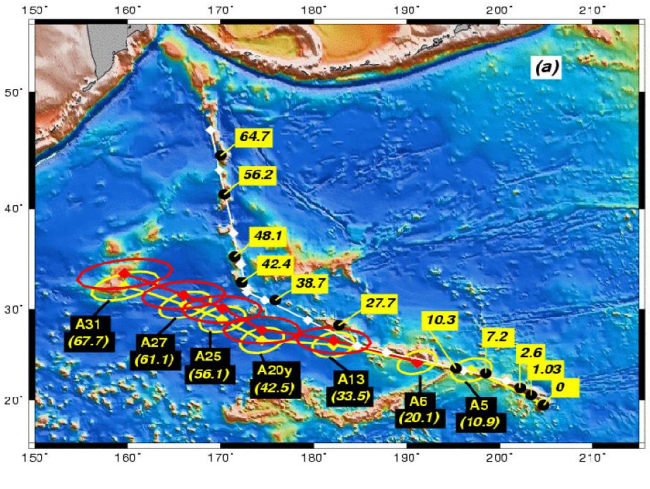
L'augmentation de CO_2 dans l'atmosphère a été importante (3 fois la teneur actuelle) et s'est accompagnée d'un rapide réchauffement de la Terre (+ 4 °C). Grâce à l'efficacité de l'altération continentale, il a fallu seulement 1,5 millions d'années pour résorber l'excès de CO_2 émis, provoquant une baisse de température de 4,55 °C, soit un refroidissement net de 0,55 °C.



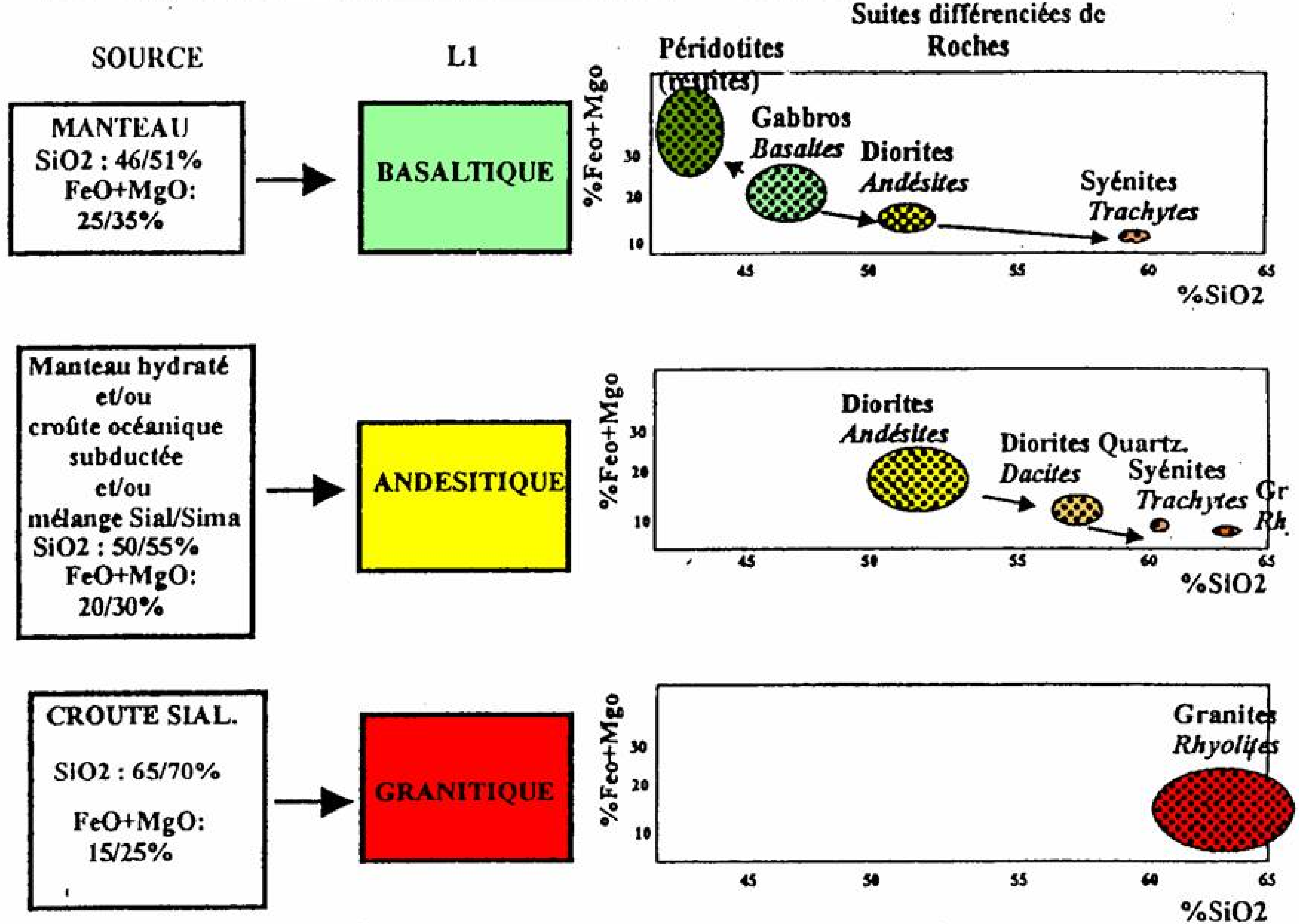
60
0
-60
0
180
360
Jan Mayen
Iceland
Eifel
Bowie
Yellowstone
Azores
Cobb
Raton
Bermuda
Hoggar
Tibesti
Canary
Hawaii
Great
Meteor
Baja
Darfur
Cape Verde
Caroline
Socorro
Cameroon
Afar
Fernando
Marquesas
Samoa
Galapagos
Ascension
Comores
Pitcairn
Easter
San Felix
Tahiti
St.Helena
Trinidade
Lord Howe
Reunion
Macdonald
Australia
East
Juan
Fernandez
Crozet
Vema
Tasmanid
Tristan
Discovery
Kerguelen
Marion
Meteor
Louisville
Bouvet
Balleny

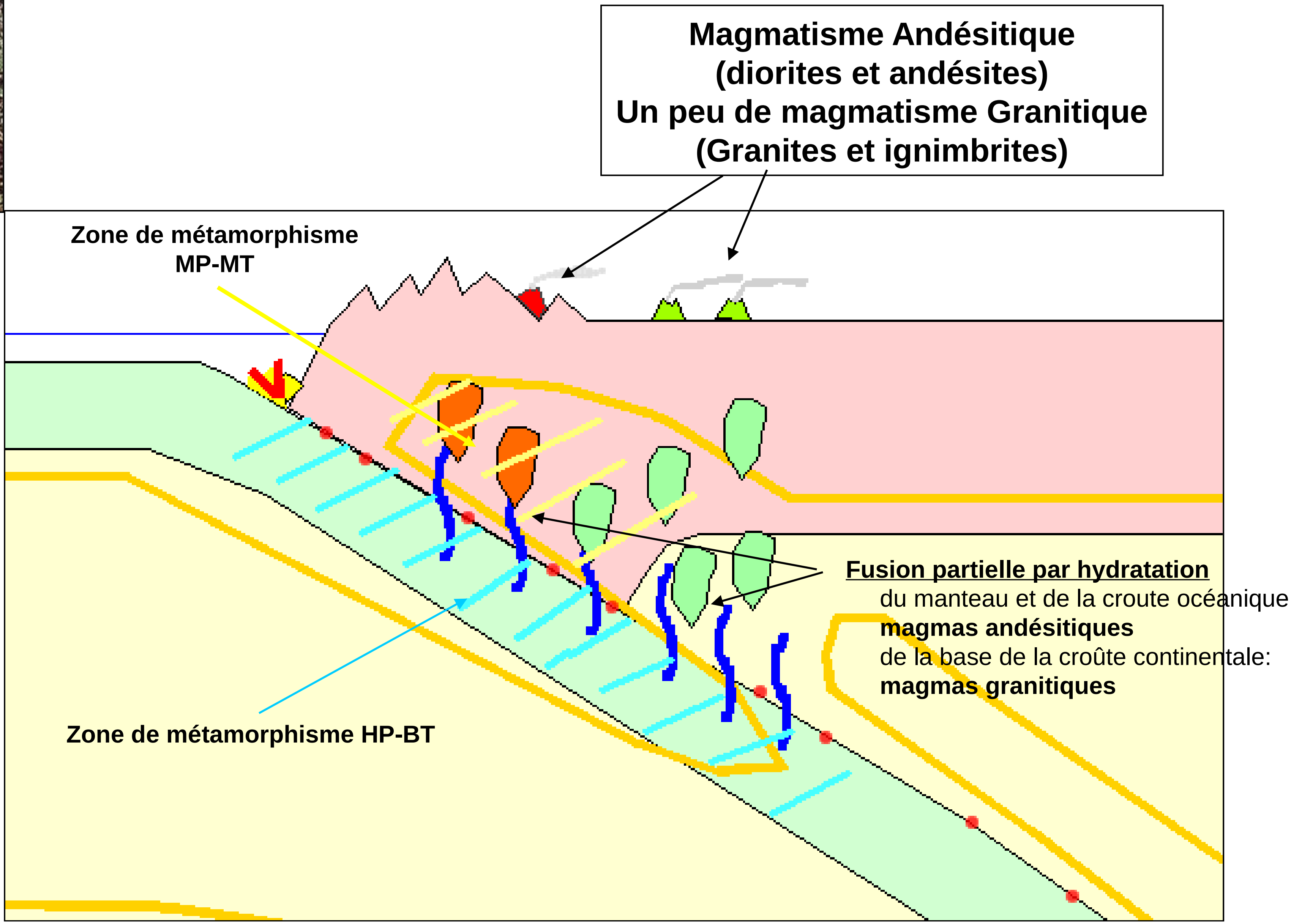

FeO (wt%)
MgO (wt%)
20
18
16
14
12
10
8
6
4
6
8
10
12
14
16
MORB
Iceland
Hawaii


NORTH AMERICAN PLATE
EURASIAN PLATE
Mid-Atlantic Ridge
ICELAND
Reykjavik
Mid-Atlantic Ridge
ATLANTIC OCEAN
= Active Volcano


(a)
64.7
56.2
48.1
42.4
38.7
27.7
10.3
7.2
2.6
1.03
0
A31 (67.7)
A27 (61.1)
A25 (56.1)
A20y (42.5)
A13 (33.5)
A6 (20.1)
A5 (10.9)

INFLUENCE DE LA SOURCE de FUSION sur la COMPOSITION des LIQUIDES PARENTAUX MAGMATIQUES

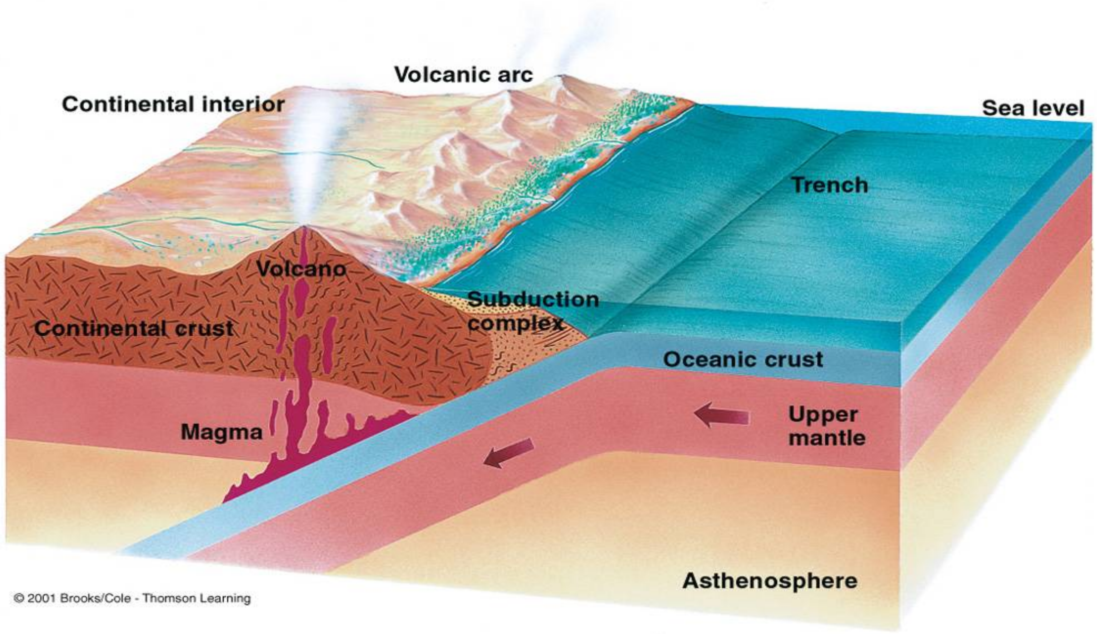




Magmatisme Andésitique
(diorites et andésites)
Un peu de magmatisme Granitique
(Granites et ignimbrites)
Zone de métamorphisme MP-MT
Fusion partielle par hydratation
du manteau et de la croute océanique:
magmas andésitiques
de la base de la croûte continentale:
magmas granitiques
Zone de métamorphisme HP-BT

Earthquakes and Plate Tectonics…

Strongest earthquakes (Chili 1960, Mw = 9.5 ; Alaska 1964, Mw = 9.2 ; Sumatra 2005, Mw = 9.1) are associated to subduction zones (a **slab** is subducting). The power of the eartthquake depends on the energy released by a huge slip **(failure) along the interface plane** , which can be considered as a huge **fault zone,** of the order of up to 1000 km long.



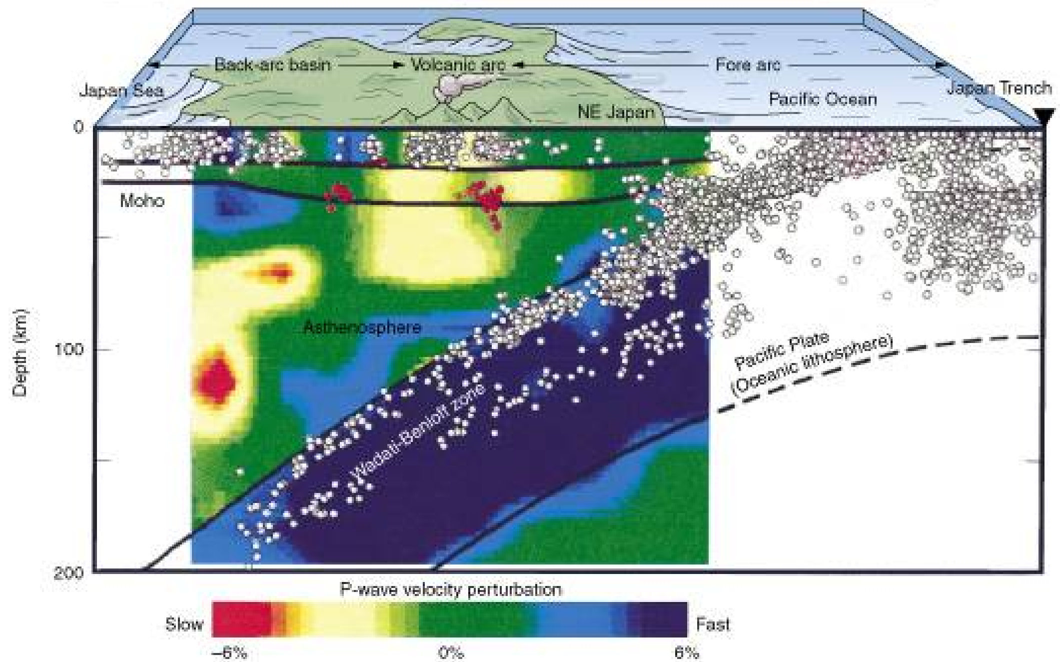
Lithospheric subduction is part of the convecting system, which is usually resolved with the Navier-Stokes equation. But taking it's solid behaviour into account , with slightly different equations, allows to study the development of fault zones, mountains, or detachment of slabs, etc...

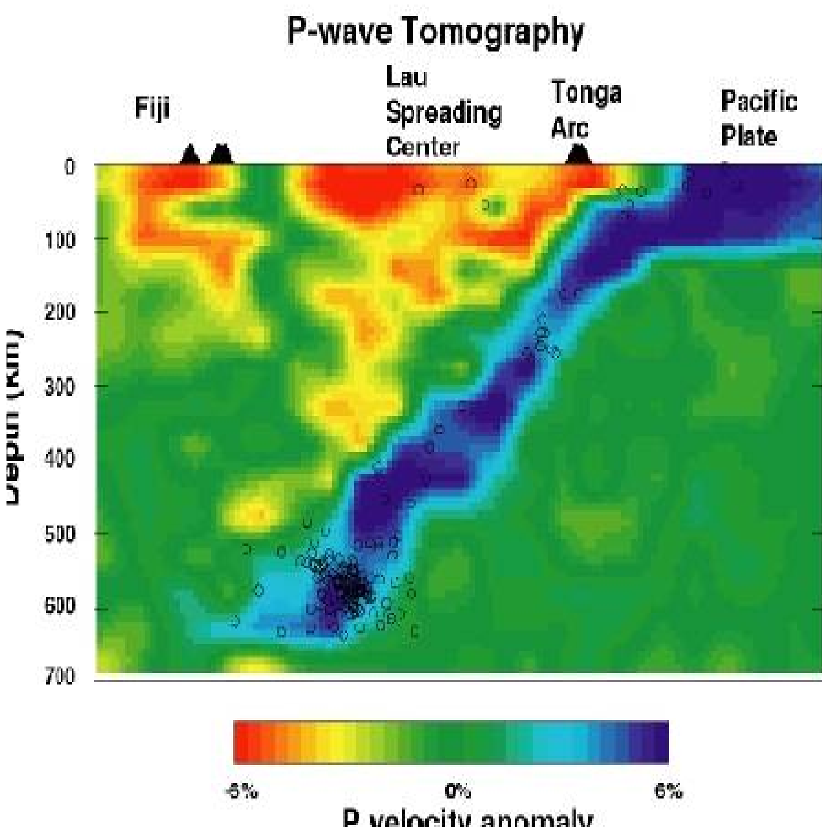
http://www.gps.caltech.edu/~gurnis/Movies/movies-more.html
http://www2.ggl.ulaval.ca/personnel/bourque/s1/volcans.html

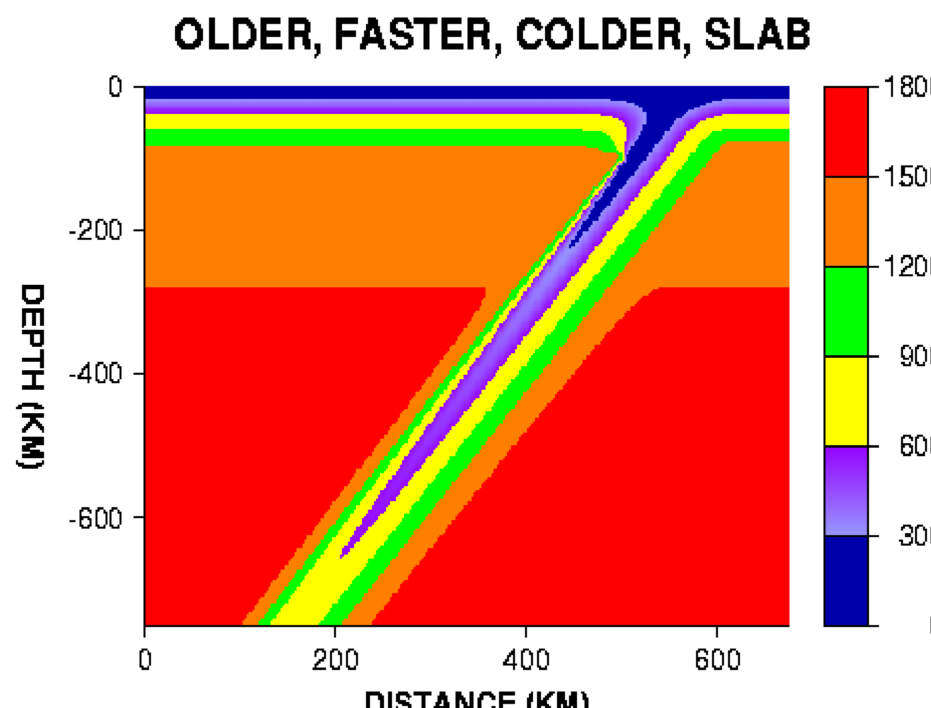
SEISMIC TOMOGRAPHY SHOWS THERMAL STRUCTURE OF DOWNGOING SLAB

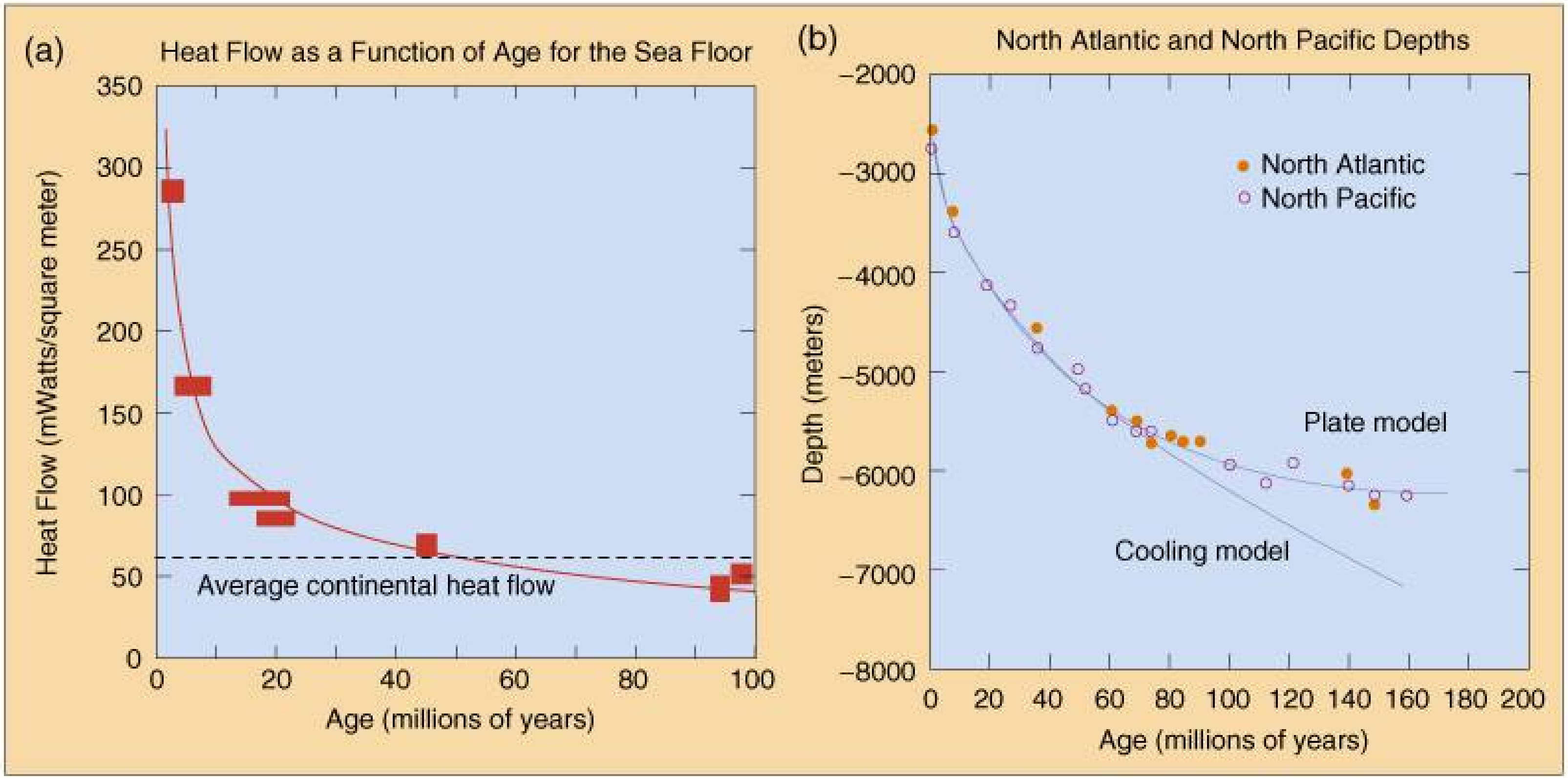
COLD (HIGH SEISMIC VELOCITY) OCEANIC PLATE SUBDUCTS INTO WARMER (LOWER SEISMIC VELOCITY) MANTLE

HEATS UP SLOWLY (MILLIONS OF YEARS)
COLD SLAB DENSER THAN MANTLE
PROVIDES *"SLAB PULL"* PLATE DRIVING FORCE









HEAT FLOW THROUGH SEA FLOOR DECREASES WITH SQUARE ROOT OF AGE

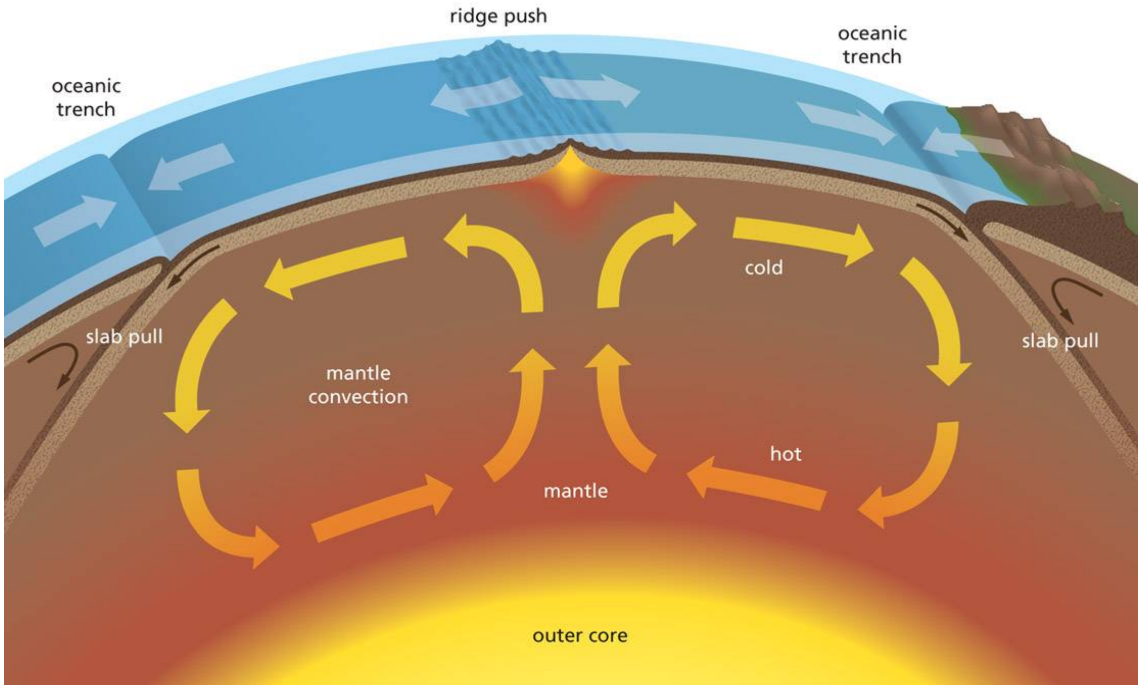
OCEAN DEPTH INCREASES WITH SQUARE ROOT OF AGE

COOLING PLATE BECOMING DENSER WITH AGE CAUSES "RIDGE PUSH" FORCE - ONE OF THE TECTONIC DRIVING FORCES

Davidson, 1997.

TECTONIC DRIVING FORCES – WILSON CYCLE

- **Three factors cause the movement of Earth's tectonic plates: mantle convection, ridge push, and slab pull.**



- **Forces at plate boundaries produce landscape features such as mountains, trenches, and island arches.**

<u>WILSON CYCLE</u> DESCRIBES OPENING & CLOSING OF OCEANS

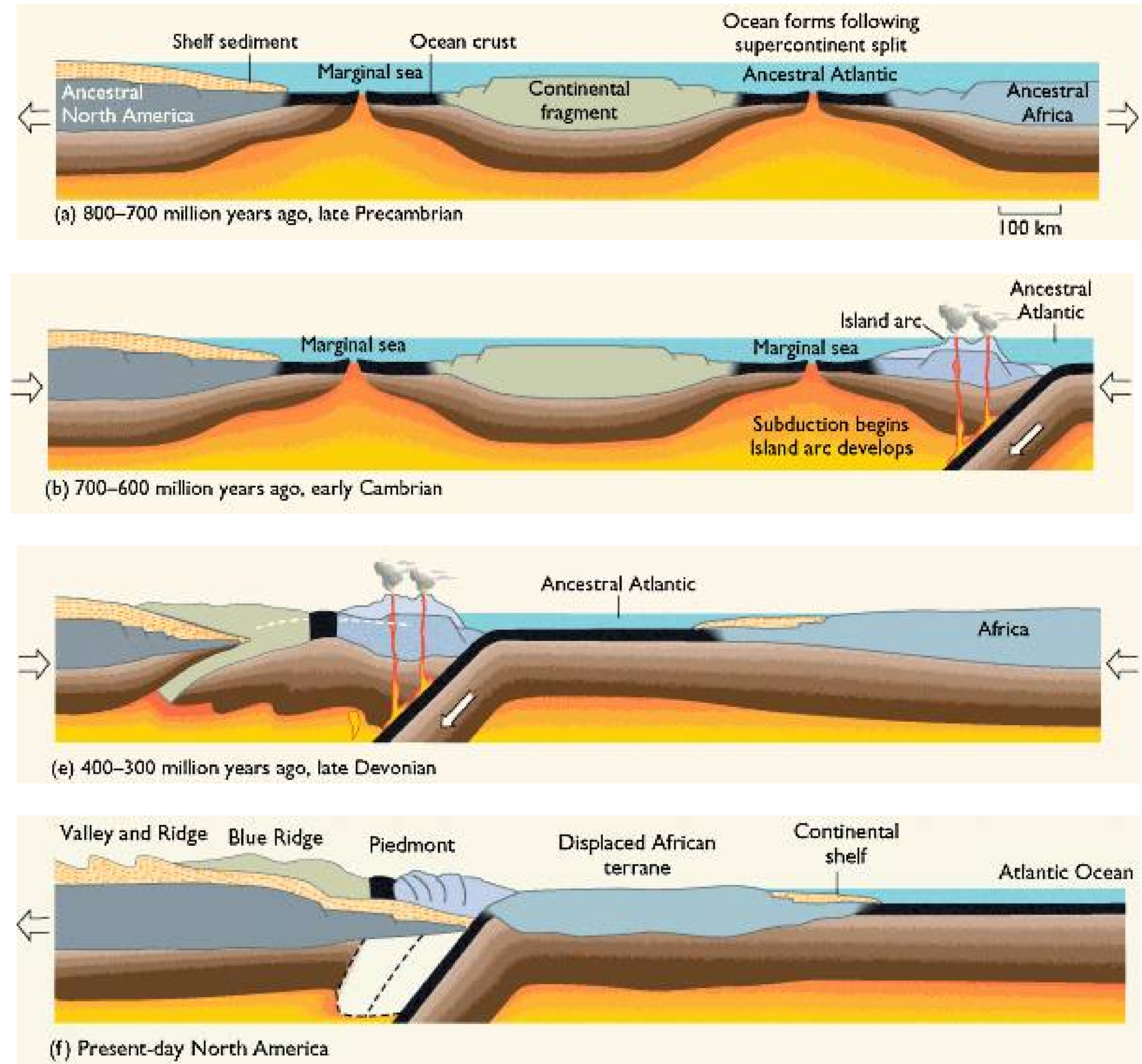
EXAMPLE

APPALACHIAN MOUNTAINS

FORMED BY CONTINENTAL COLLISION

CLOSED PREVIOUS ATLANTIC OCEAN

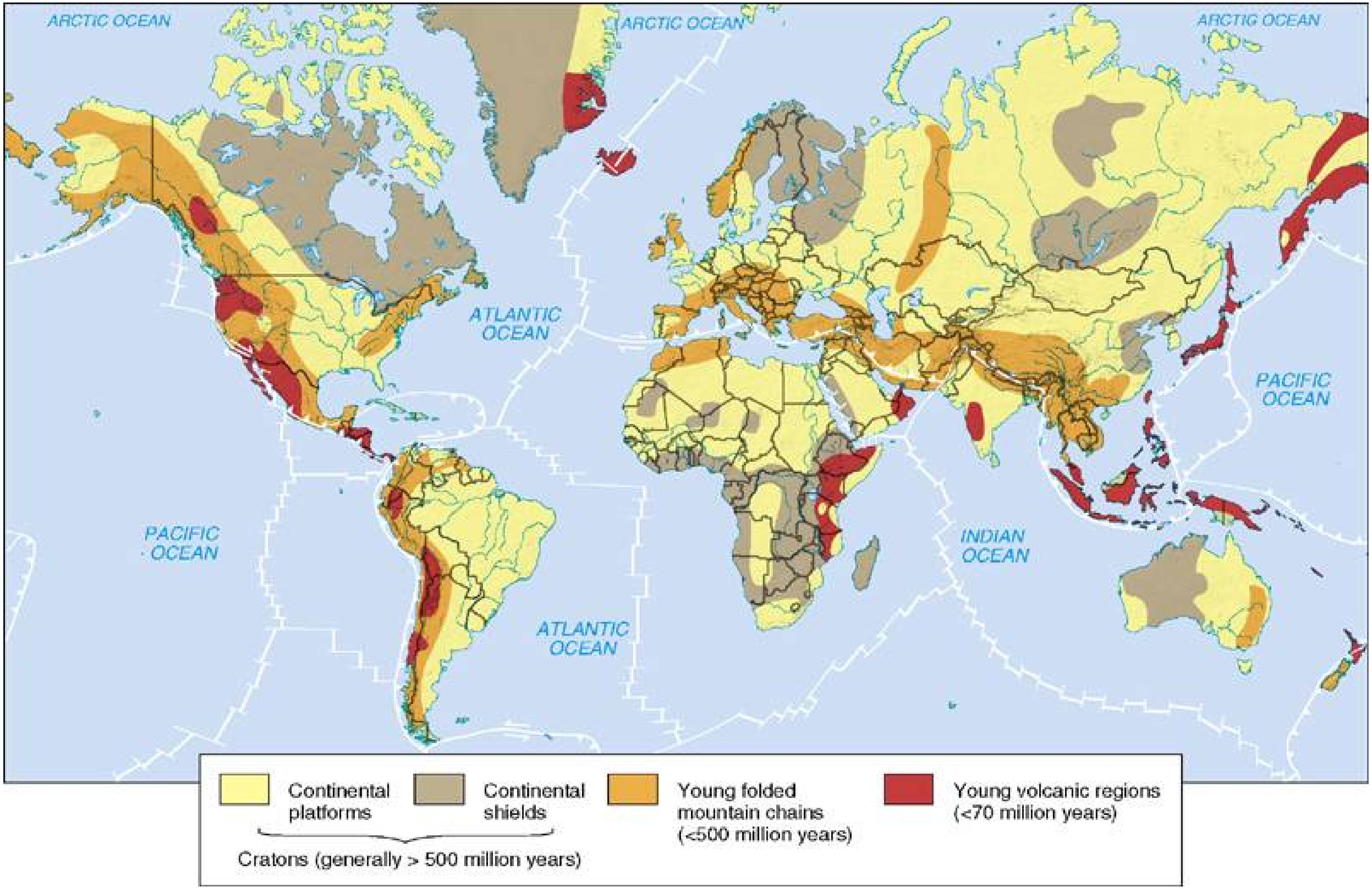
INCLUDE OLD VOLCANIC ISLAND ARCS & CONTINENTAL FRAGMENTS FROM AFRICA



Press & Siever

CONTINENTS ARE MUCH OLDER THAN SEA FLOOR

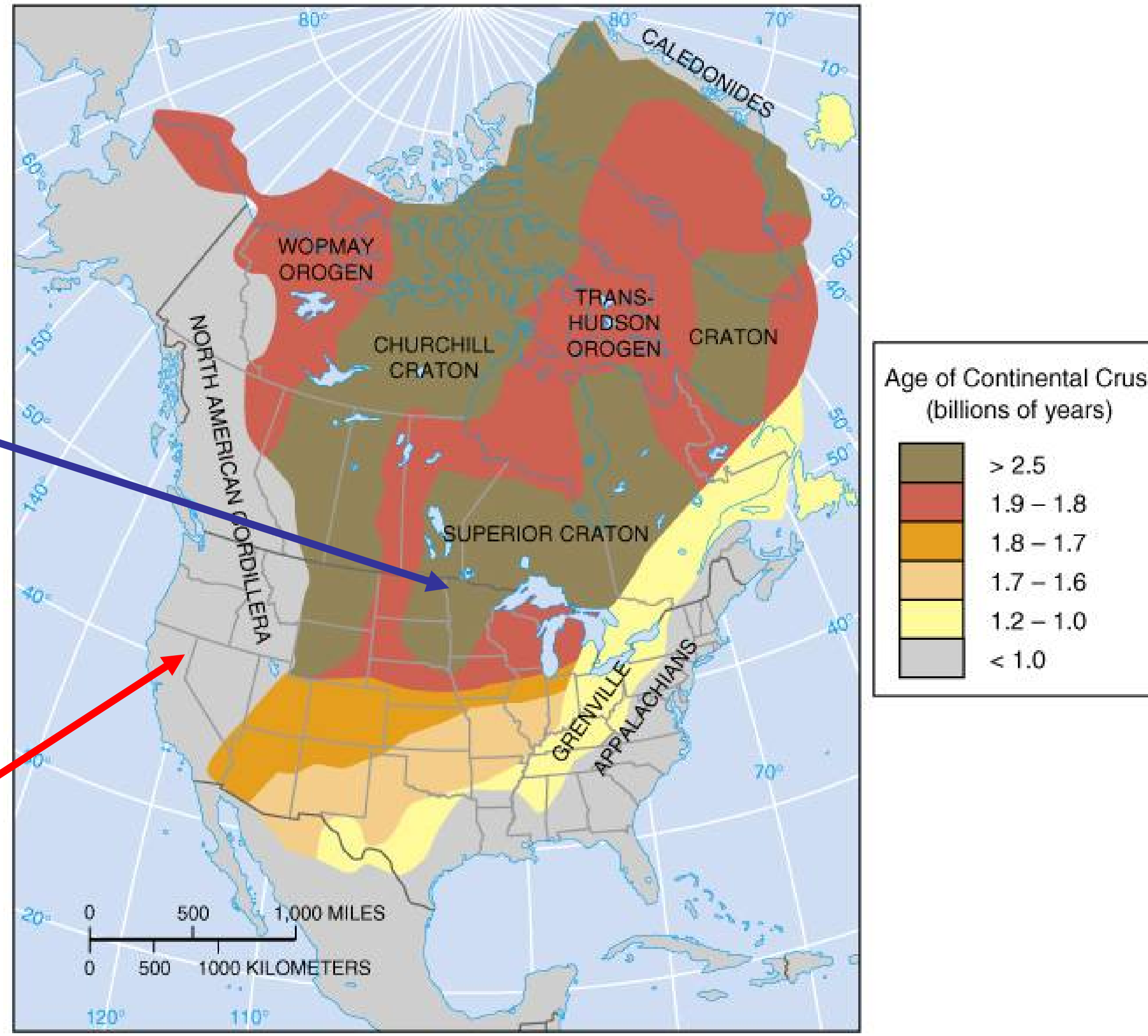
BECAUSE CONTINENTS AREN'T SUBDUCTED, THEY CAN BE BILLIONS OF YEARS OLD.



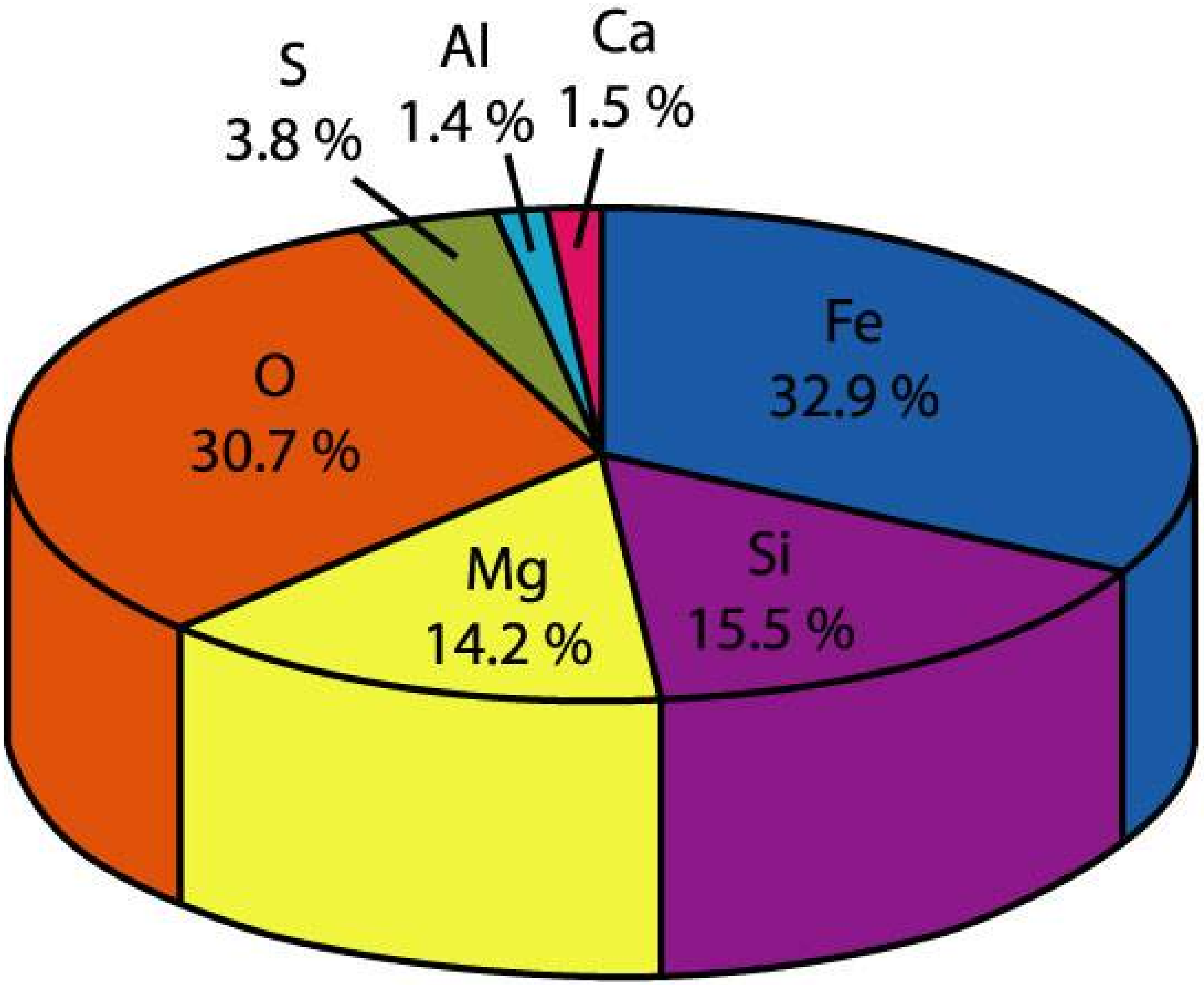
CONTINENTS GROW WITH TIME AS MATERIAL ACCRETES TO THEIR EDGES

CONTINENTAL INTERIORS CONTAIN CRATONS, LARGE FLAT AREAS >500 MY OLD

BORDERED BY PROGRESSIVELY YOUNGER BELTS OF ROCKS



What is the composition of the Earth?



Relative atomic abundances of the seven most common elements that comprise 97% of the Earth's mass.
An Introduction to Igneous and Metamorphic Petrology, by John Winter , Prentice Hall.

TERRESTRIAL RADIOACTIVITY

La Terre libère de la chaleur par 2 moyens principaux:

1) La décroissance d'elements radioactifs (80%) 30-100mW/m^2)

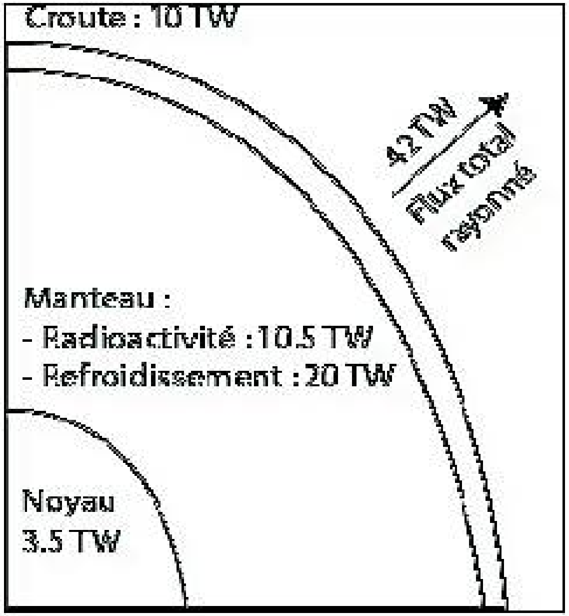
2) le refroidissement interne (20% -30mW/m^2, flux sortant du manteau)

Heat flow at the surface of the Earth ~ 70 mW/m^2

Concentration of radiogenic elements in the crust

élément	Demi-vie *Milliard d'année*	Taux de production de chaleur $\mu W.kg^{-1}$	concentration dans le manteau *ppb & ppm*	concentration dans la croûte *ppm & %*
^{238}U	4.468	94.35	20.15 ppb	1.41 ppm
^{235}U	0.7038	4.05	0.15 ppb	0.01 ppm
^{232}Th	14.01	26.6	79.5 ppb	5.6 ppm
^{40}K	1.250	0.0035	240 ppm	1.88 %

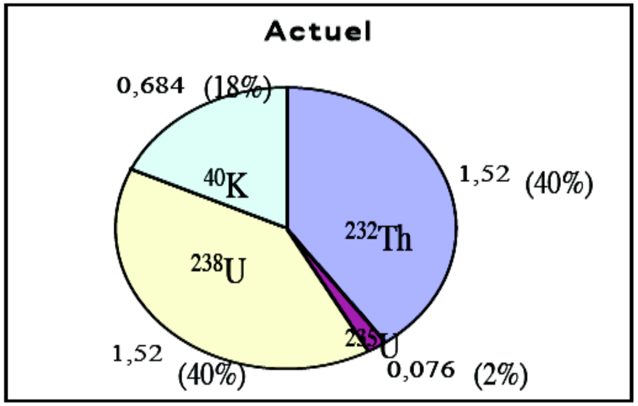
TAB. 1.1: *Principaux éléments radioactifs contribuant à l'apport d'énergie radiogénique et leurs caractéristiques, d'après Hamza & Beck (1972), McDonough & Sun (1995), Rudnick & Fountain (1995)*



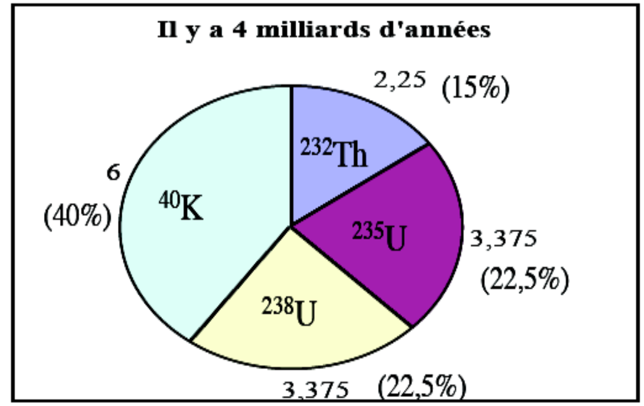
Zone	Concentration en U	Puissance (pW/kg)
Croûte continentale	5μ g/g	1000
Croûte océanique	71 ng/g	14
Manteau supérieur	7 ng/g	1.4
Météorites chondritiques	20 ng/g	5

Lemery, 2001

Taux de production de chaleur en 10^{13} W.



Total = $3{,}8.10^{13}$ W



Total = 15.10^{13} W

Quelles sont les roches crustales les plus riches en éléments radiogéniques ?

Tipo roca	Concentración [ppm/peso]			Producción de Calor [$10^{-11} W/kg$]			
	U	Th	K	U	Th	K	Total
Granito	4.6	18	33,000	43.8	46.1	11.5	101
Basalto alkalino	0.75	2.5	12,000	7.1	6.4	4.2	18
Basalto toleítico	0.11	0.4	1,500	1.05	1.02	0.52	2.6
Peridotita	0.006	0.02	100	0.057	0.051	0.035	0.14
Chondrita	0.015	0.045	900	0.143	0.115	0.313	0.57
Corteza continental	1.2	4.5	15,500	11.4	11.5	5.4	28
manto	0.025	0.087	70	0.238	0.223	0.024	0.49

La redistribution des éléments par désintégration+ le refroidissement de notre planète conduisent

À sa différentiation en densité

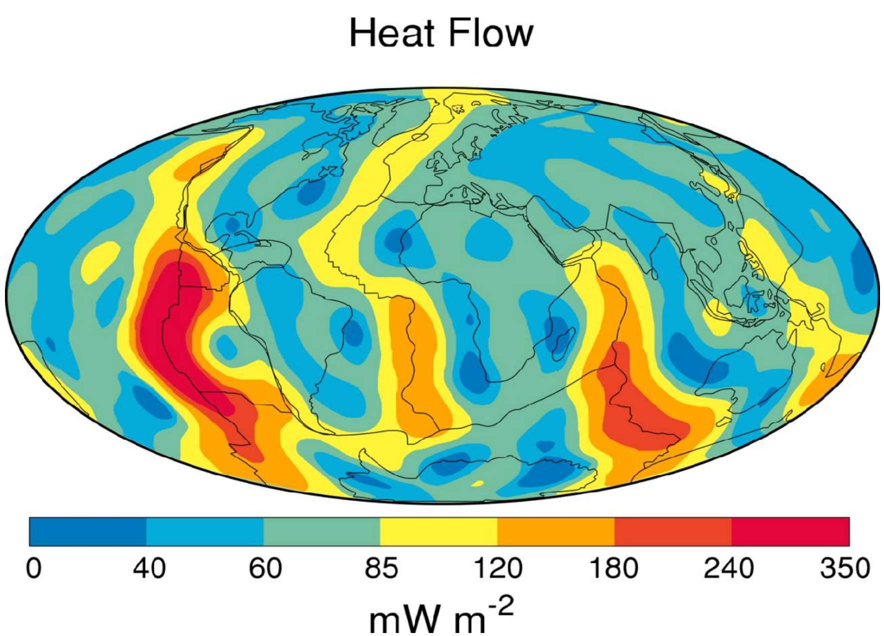
La Terre perd de la chaleur au profit de l'extérieur : comment est-elle transportée ?

THE EARTH IS A THERMAL MACHINE

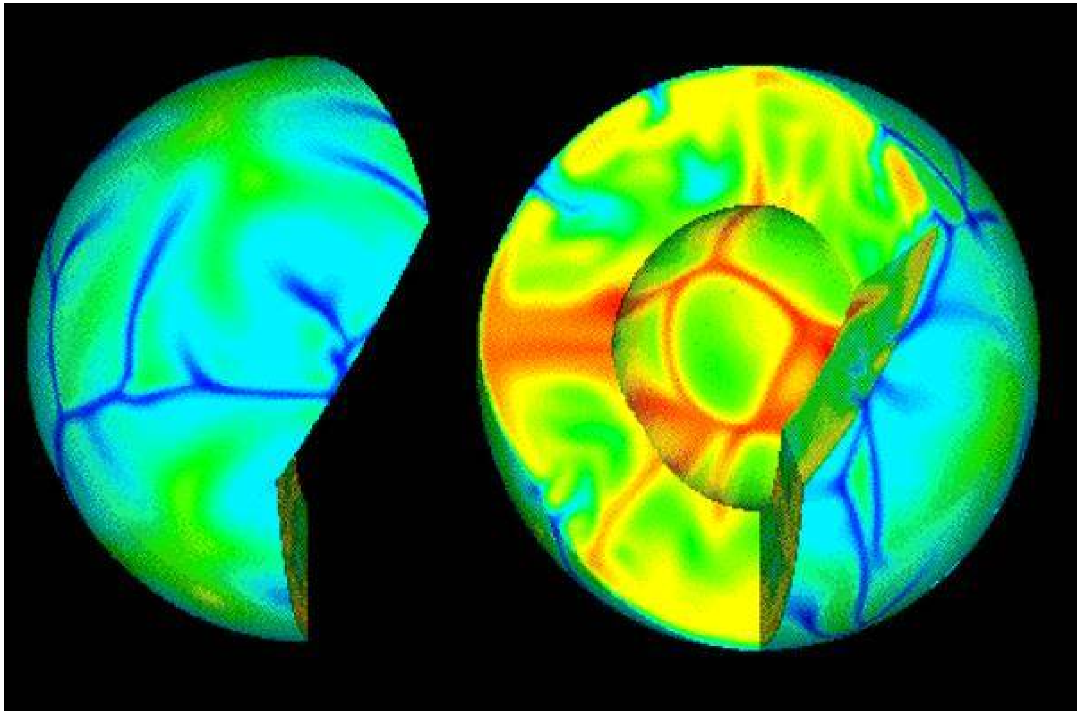
Total heat coming form the Sun : 4000.10^{12} W or 340 W/m²

Internal (Terrestrial) heat production : 40.10^{12} W or 0.07 W/m²

Heat produced by a human being in winter: 2000 W/m²

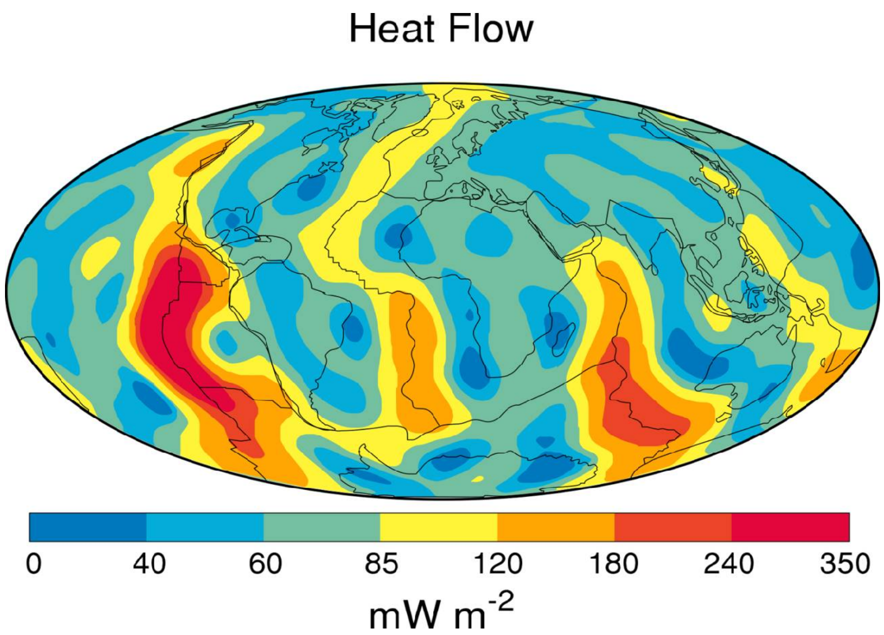


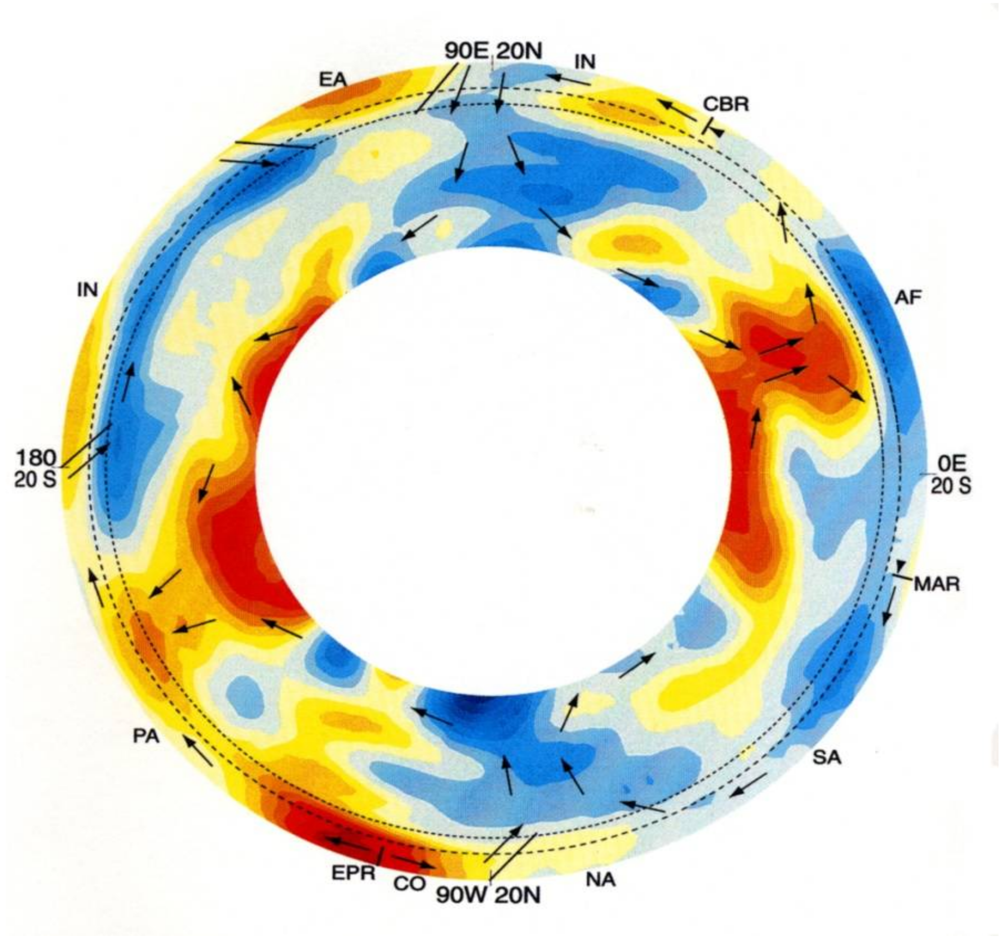
Pattern of global heat flux compiled from >20000 observations and modeled on a spherical harmonic expansion to degree 12. Pollack et al. (1993).



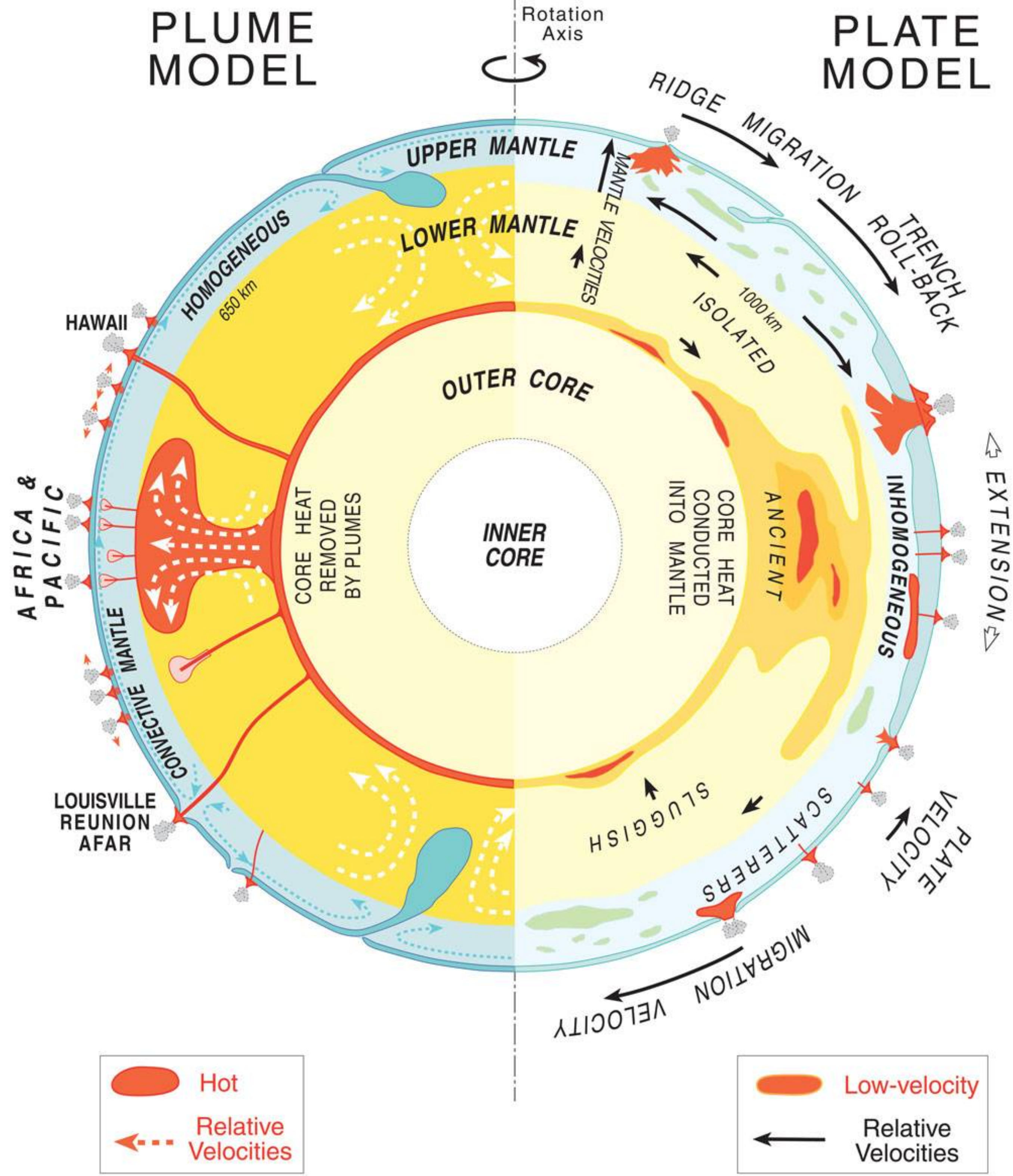
Thermal structure in a 3D spherical mantle convection model (red is hot, blue is cold). Davies & Bunge
www.ocean.cf.ac.uk/people/huw/AGU99/mantlecirc.html

The Geothermal Gradient





Cross-section of the mantle based on a seismic tomography model. Arrows represent plate motions and large-scale mantle flow and subduction zones represented by dipping line segments. *EPR=East pacific Rise, MAR= Mid-Atlantic Ridge, EA= Eurasian, IN= Indian, PA= Pacific, NA= North American, SA= South America. From Li and Romanowicz (1996).*

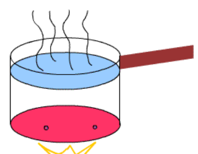

PLUME MODEL
Rotation Axis
PLATE MODEL
RIDGE MIGRATION
TRENCH ROLL-BACK
UPPER MANTLE
LOWER MANTLE
MANTLE VELOCITIES
HOMOGENEOUS
650 km
1000 km
ISOLATED
HAWAII
OUTER CORE
AFRICA & PACIFIC
CORE HEAT REMOVED BY PLUMES
INNER CORE
CORE HEAT CONDUCTED INTO MANTLE
ANCIENT
INHOMOGENEOUS
EXTENSION
CONVECTIVE MANTLE
LOUISVILLE
REUNION
AFAR
SLUGGISH
SCATTERERS
PLATE VELOCITY
MIGRATION VELOCITY
Hot
Relative Velocities
Low-velocity
Relative Velocities

Heat transfer equation

- (1D, Cartesian)

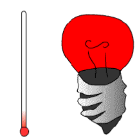
$$\frac{\partial T}{\partial t} + v\frac{\partial T}{\partial z} = \kappa\frac{\partial^2 T}{\partial z^2} + \frac{H}{C_p}$$

Advected component | Conductive component | Heat production



Mantle and fluid core

lithosphere and solid core



Radioactivity > crust

- Thermal diffusivity $\kappa = k/(\rho C_p)$ ($m^2 s^{-1}$), k conductivity
- Diffusion timescale:

$$t \sim \frac{d^2}{\kappa}$$

Convection equations

A full study of mantle convection requires 3 equations of conservation:

*** Mass conservation (…)**

*** Conservation of momentum** (fundamental law of dynamics applied to the continuum), and which allows to estimate the velocities: also called **the Navier-Stokes equation:**

$$\rho\left[\frac{\partial v}{\partial t}+v\cdot\nabla v\right]=\eta\nabla^2 v-\nabla P+\Delta\rho g\, y$$

Zero for steady-state flows

Yuk! *Inertial* term. Source of turbulence.

Diffusion.Warning, $\nabla^2 u$ is complicated.

Pressure gradient

Buoyancy force

*** Conservation of energy** (calculates the temperature field),
For a particle to move upwards, it should not exchange too much heat with its environment by conduction. The characteristic time for heat diffusion must be greater than the diffusion of momentum. The ratio of these two times is the **Prandtl number.**

$$Pr=\frac{\sigma}{\kappa}$$

The Prandtl number (Pr) is the ratio between the kinematic viscosity (σ = μ/ρ) and the thermal diffusivity of a medium. The higher Pr, the more efficient is convection in transferring heat. The Earth's mantle has ***Pr*~10^{25}.**

Convection equations

The Heat equation and Navier-Stokes equations are co*upled* because temperature affects flow (via buoyancy) and flow affects temperature (via advection). This coupling makes solving convection problems hard.

Navier-Stokes

$$\rho \frac{\partial v}{\partial t} = \eta \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial z^2} \right) - \nabla P + \boxed{\rho g \alpha T}$$

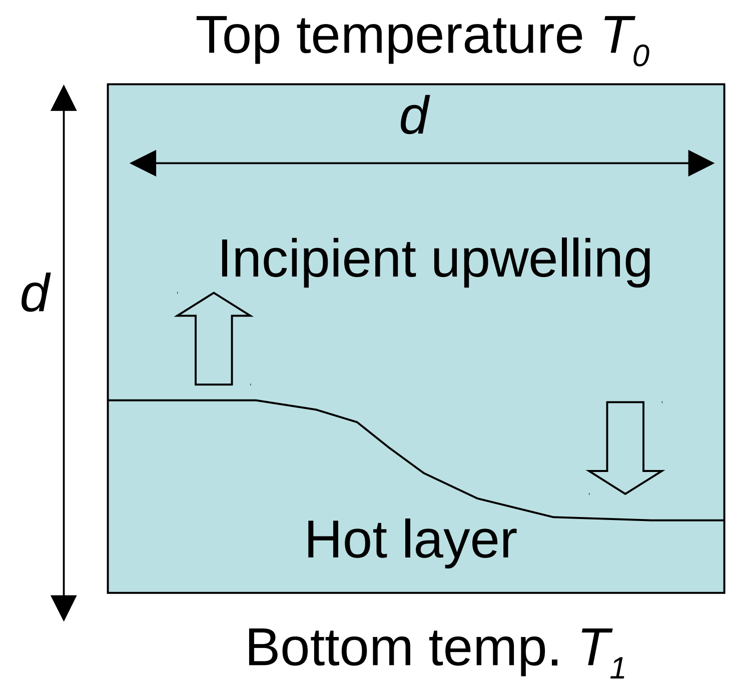
Buoyancy force

Thermal Evolution

$$\frac{\partial T}{\partial t} = \kappa \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2} \right) - \boxed{v \cdot \nabla T}$$

Advective term

Initiation of Convection



Buoyancy forces favour motion, viscous forces oppose it.

Whether or not convection occurs is governed by the **Rayleigh number**:

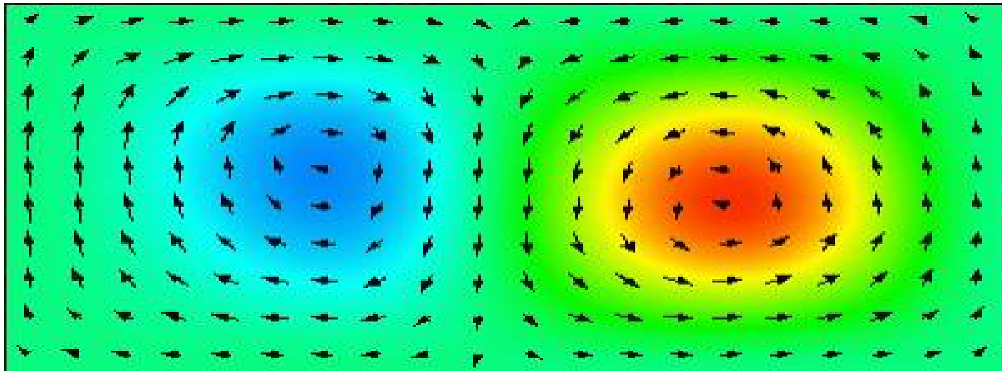
$$Ra = \frac{\rho g \alpha (T_1 - T_0) d^3}{\kappa \eta}$$

η : viscosité dynamique [Nm/s],
κ : diffusivité thermique[m²/s],
g : gravité [m/s²],
α : expansion thermique [1/K],
R: distance caracteristique [m]

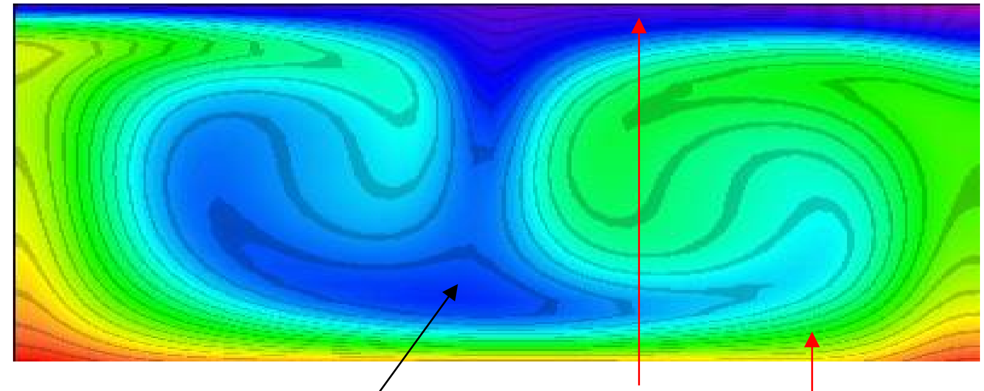
Ra *is also written without the density ρ[kg/m³] and with the kinematic viscosity ν [m²/s].*

Convection occurs if *Ra* is greater than a critical value Ra_c, ~ 1000.

Champ de vitesse (fonction de courant)



Champ de température



Panache thermique descendant

Couches limites thermiques: lithosphère et Couche D’’

* In the entire Earth's mantle

Thermal expansion $\alpha = 3.10^{-5}$ K ,

Viscosity $\nu = 3.10^{17}$ Nm/s,

Conductivity k= 3 W/m/K, $C_p = 10^3$ J/kg/K, $\kappa = k/\rho C_p = 10^{-6}$ m²/s

Gravity g= 10 m/s², **Depth d = 2900 km**

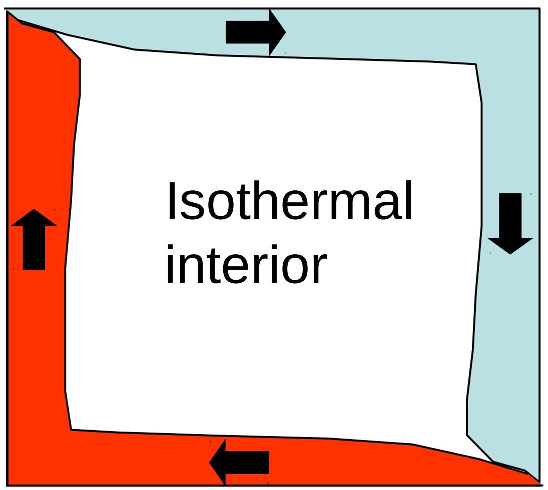
$Ra = 5.10^8$

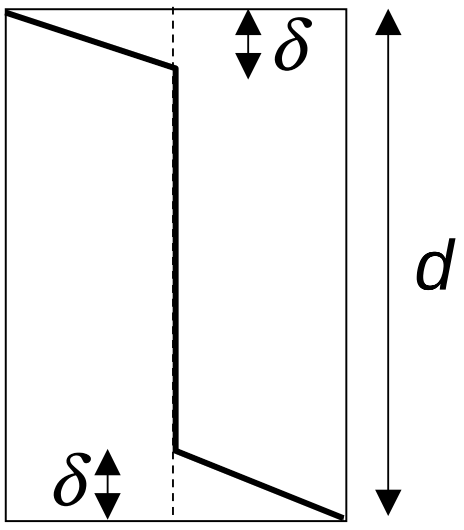
* In the upper mantle : **Depth d = 670 km**

$Ra = 5.10^5$

Constant viscosity convection

- Convection results in hot and cold boundary layers and an isothermal interior,
- In constant-viscosity convection, top and bottom b.l. have same thickness.





- Heat is *conducted* across boundary layers $F_{conv} = k\frac{(T_1 - T_0)}{2\delta}$
- In the absence of convection, heat flux is $F_{cond} = k\frac{(T_1 - T_0)}{d}$

➡ So convection gives higher heat fluxes than conduction.

- The **Nusselt number** defines the convective efficiency:

$$Nu = \frac{F_{conv}}{F_{cond}} = \frac{d}{2\delta}$$

A perfect conductive medium has Nu=1.
Nu increases with invigorating convection.

Mantle Adiabatic Gradient

In the mantle where convection becomes the dominant mode of heat transfer, temperature gradient becomes small. When the convective flow is vigorous, the thermal gradient becomes adiabatic, with no loss nor gain of heat, and depends only on variations of volume.

QUICK DEMONSTRATION:

Variation of entropy in the system can be written as: $dS = \frac{\partial S}{\partial T} dT + \frac{\partial S}{\partial P} dP$

* Maxwell relations give: $\frac{\partial S}{\partial P}|_T = -\frac{\partial V}{\partial T}|_P$

* Definition of the thermal expansion is α : $\alpha = \frac{1}{V}\frac{\partial V}{\partial T}|_P$

* Definition of heat capacity ***Cp***: $c_p = T\frac{\partial S}{\partial T}|_P$

* **If the entropy of the system is zero (adiabatic hypothesis):**

$$dS = \frac{\partial S}{\partial T} dT + \frac{\partial S}{\partial P} dP = C_p / T \, . dT - \alpha V dP = 0$$

And noting that for *1* kg *V=1/ρ*, one deduces :

$$\frac{\partial T}{\partial P}|_S = \frac{T\alpha}{\rho c_p}$$

*To know the temperature dependency on depth (***r***),
we use the relationship of Pressure with depth *dP = ρgd****r****:*

$$\frac{dP}{dr} = -\rho g$$

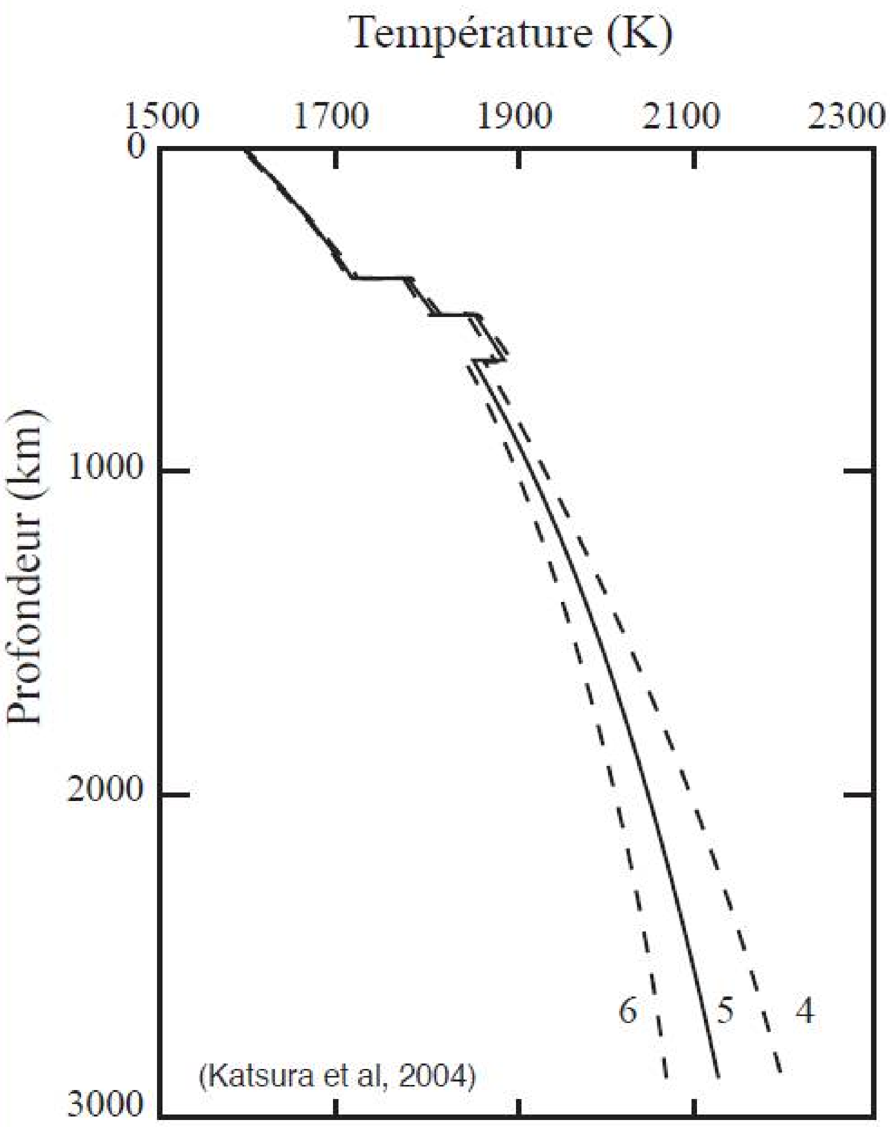
We deduce the gradient:

$$\frac{\partial T}{\partial r}|_S = \frac{\partial T}{\partial P}|_S \frac{dP}{dr} = -\frac{T\alpha}{\rho c_p}\rho g$$

The thermal gradient (with depth *r*) is thus pressure independent (adiabatic) :

$$\frac{\partial T}{\partial r}|_S = -\frac{T\alpha g}{c_p}$$

Isentropic gradient (adiabatic mantle)



$$\frac{\partial T}{\partial z} = \frac{\alpha g T}{C_p}$$

Sous la lithosphère :

$$\begin{aligned} \alpha &\simeq 3\ 10^{-5}\mathrm{K}^{-1} \\ g &\simeq 10\ \mathrm{m\ s}^{-2} \\ T &\simeq 1600\ \mathrm{K} \\ C_p &\simeq 1000\ \mathrm{J\ K}^{-1}\mathrm{kg}^{-1} \end{aligned}$$

$$\Rightarrow \frac{\partial T}{\partial z} \simeq 0.5\mathrm{K\ km}^{-1}$$

α diminue avec la pression (profondeur)
$\Rightarrow \partial T/\partial z \simeq 0.3\mathrm{K\ km}^{-1}$ dans le manteau profond.

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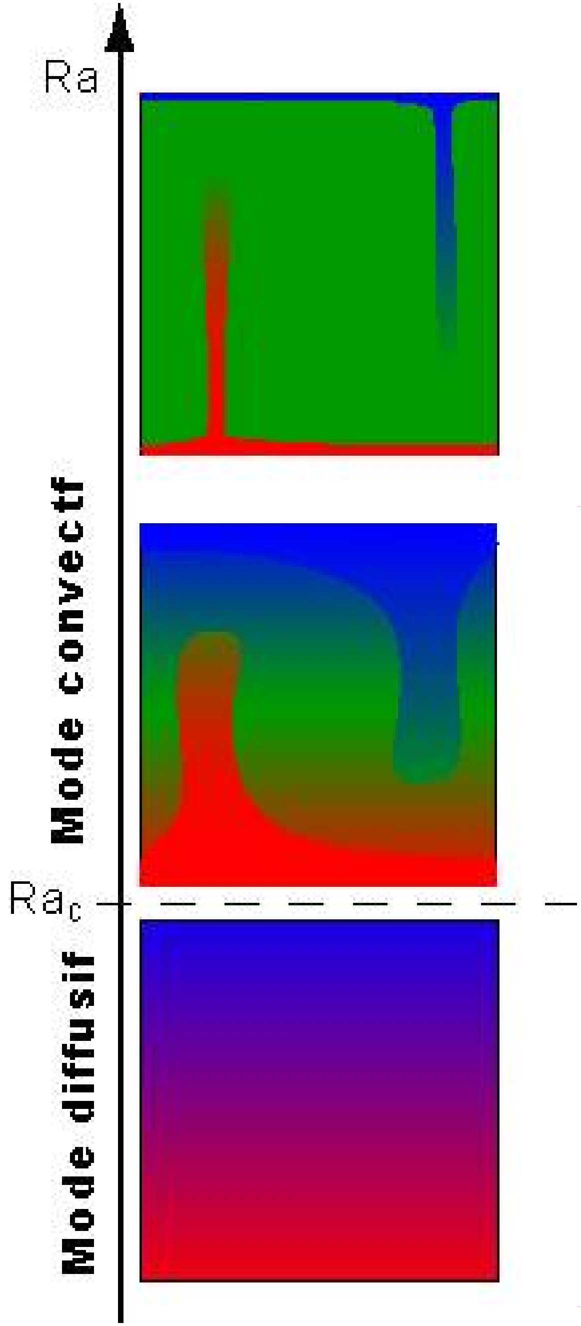
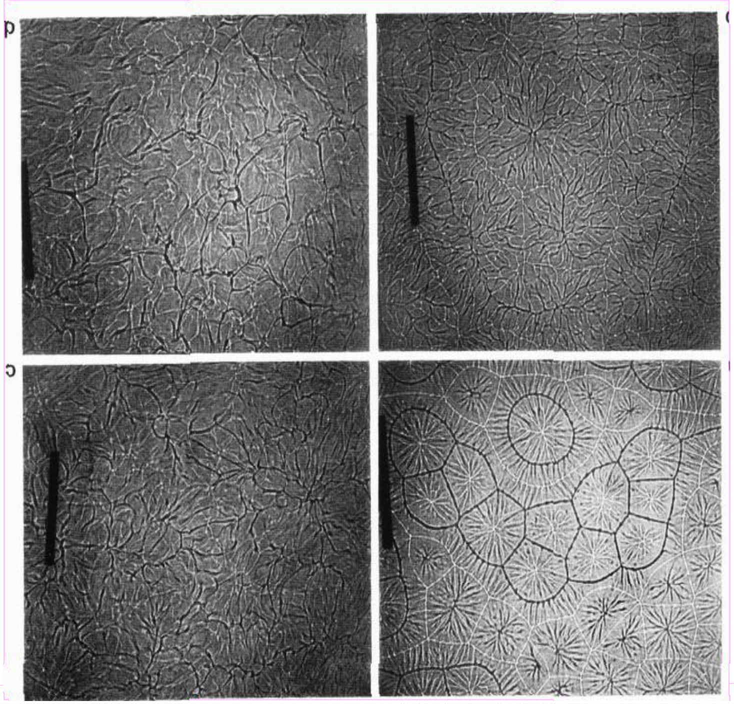
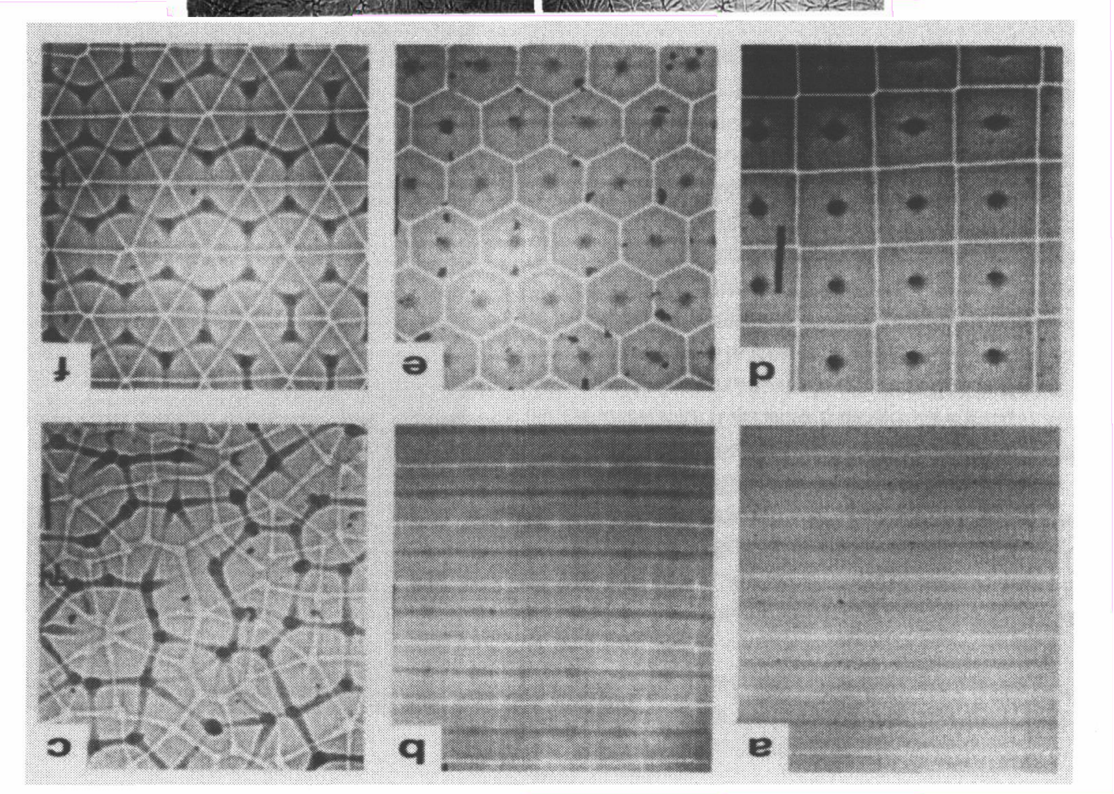
Uncertainty on the temperature at
the base of the mantle => modeling

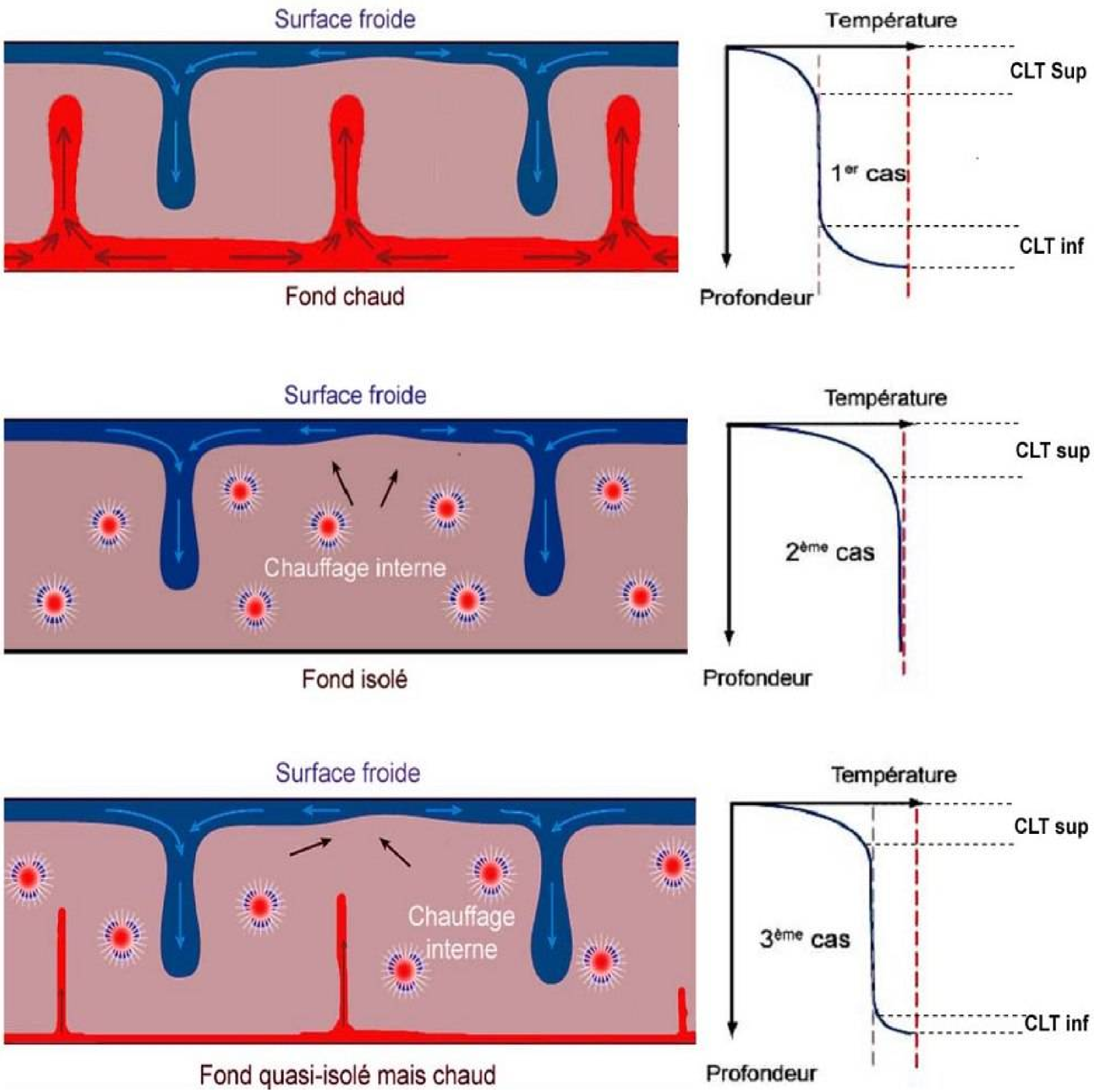
Labrosse, ENS, 2009

Analog models









CASE 1: the medium is heated from below only.

Le haut plus dense plonge activement ; le bas, moins dense monte activement. Les couches supérieure froide et inférieure chaude sont appelées **couches limites thermiques (CLT)** supérieure et inférieure. Entre ces 2 CLT, la température est quasi constante.

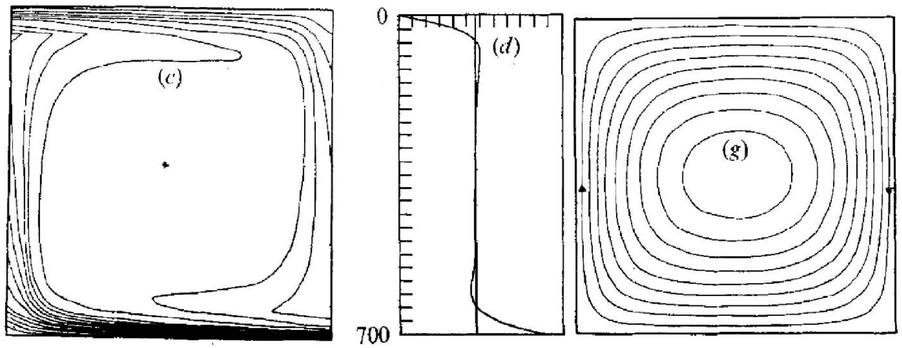
CASE 2: heat is produced internally by the medium (small suns)

Le haut plus dense plonge activement ; le bas n'a aucune raison de remonter, si ce n'est passivement, pour compenser les mouvements descendants. Il y a alors une CLT supérieure, mais pas de CLT inférieure.

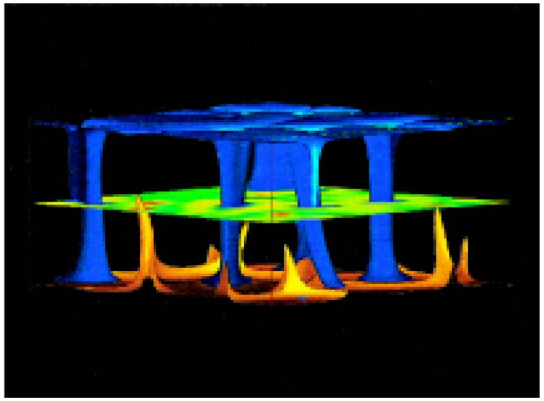
CASE 3: both heat sources exist, which best ressembles the Earth.

Numerical modeling of mantle convection

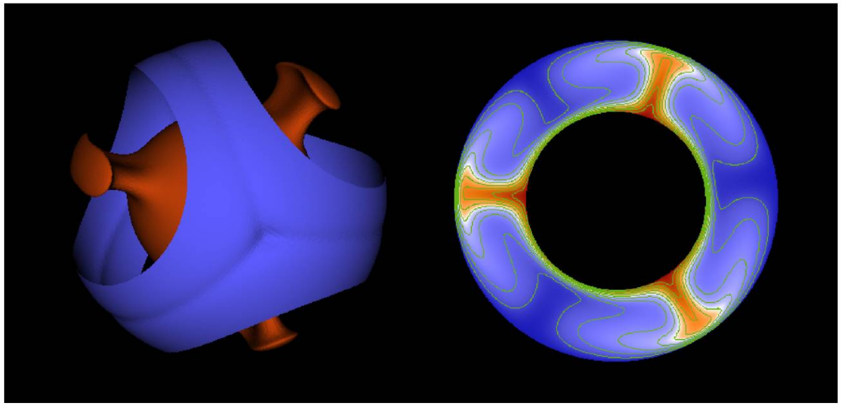
Since the 1970's geophysicists have modeled mantle convection...



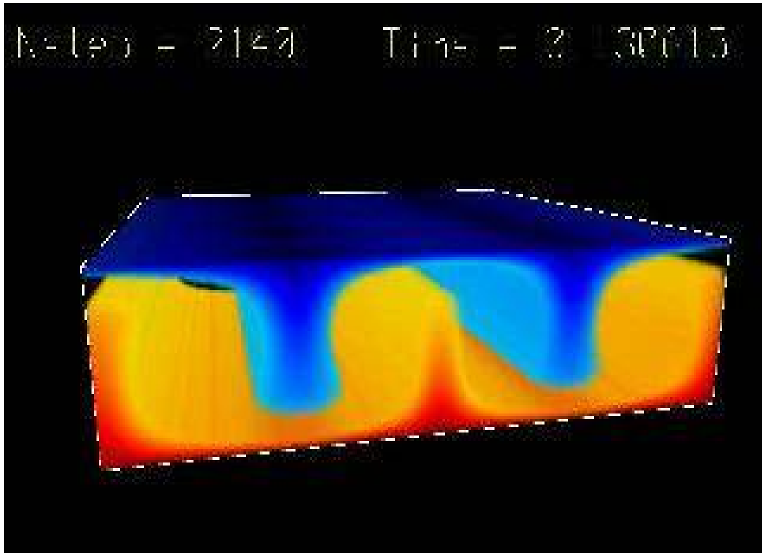
2D isoviscous (McKenzie et al., 1974).

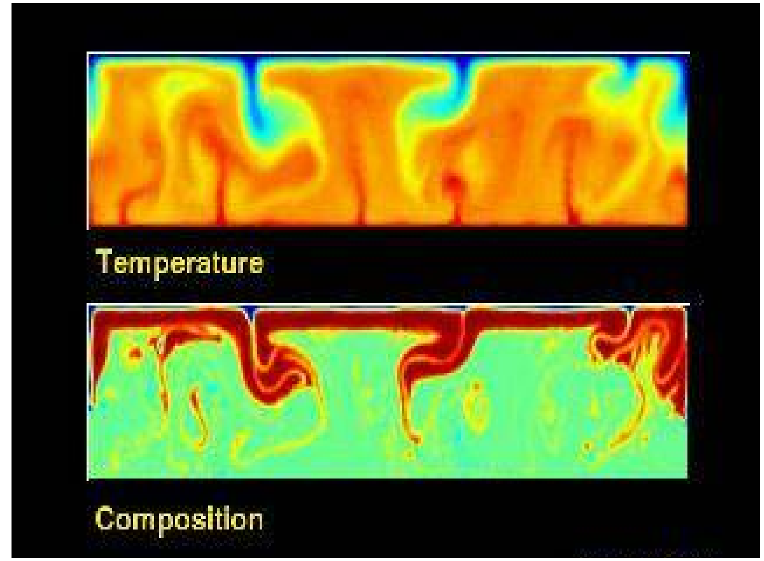


3D cartesian (Sotin et al., 96).



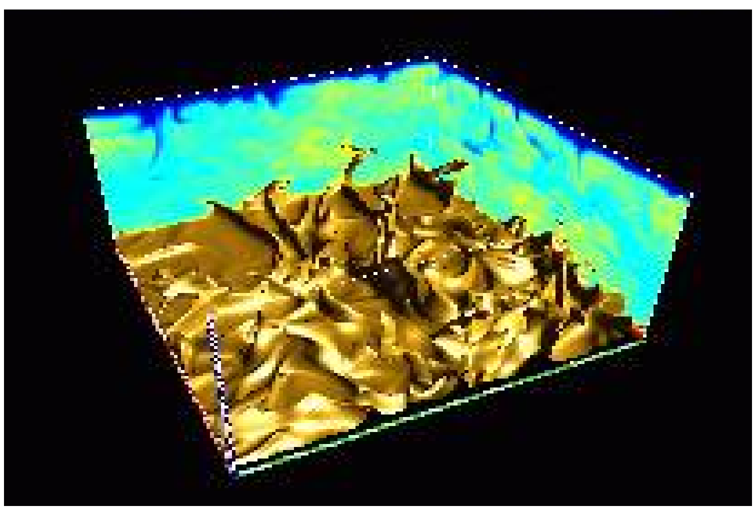
3D isoviscous spherical (Tackley et al., 2010).

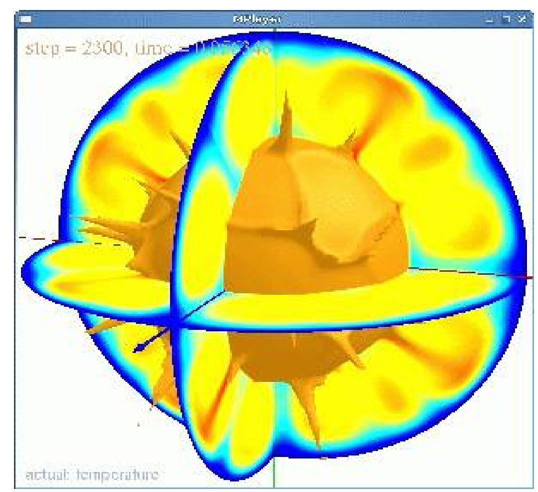




Thermal convection Ra=10*4, steady state

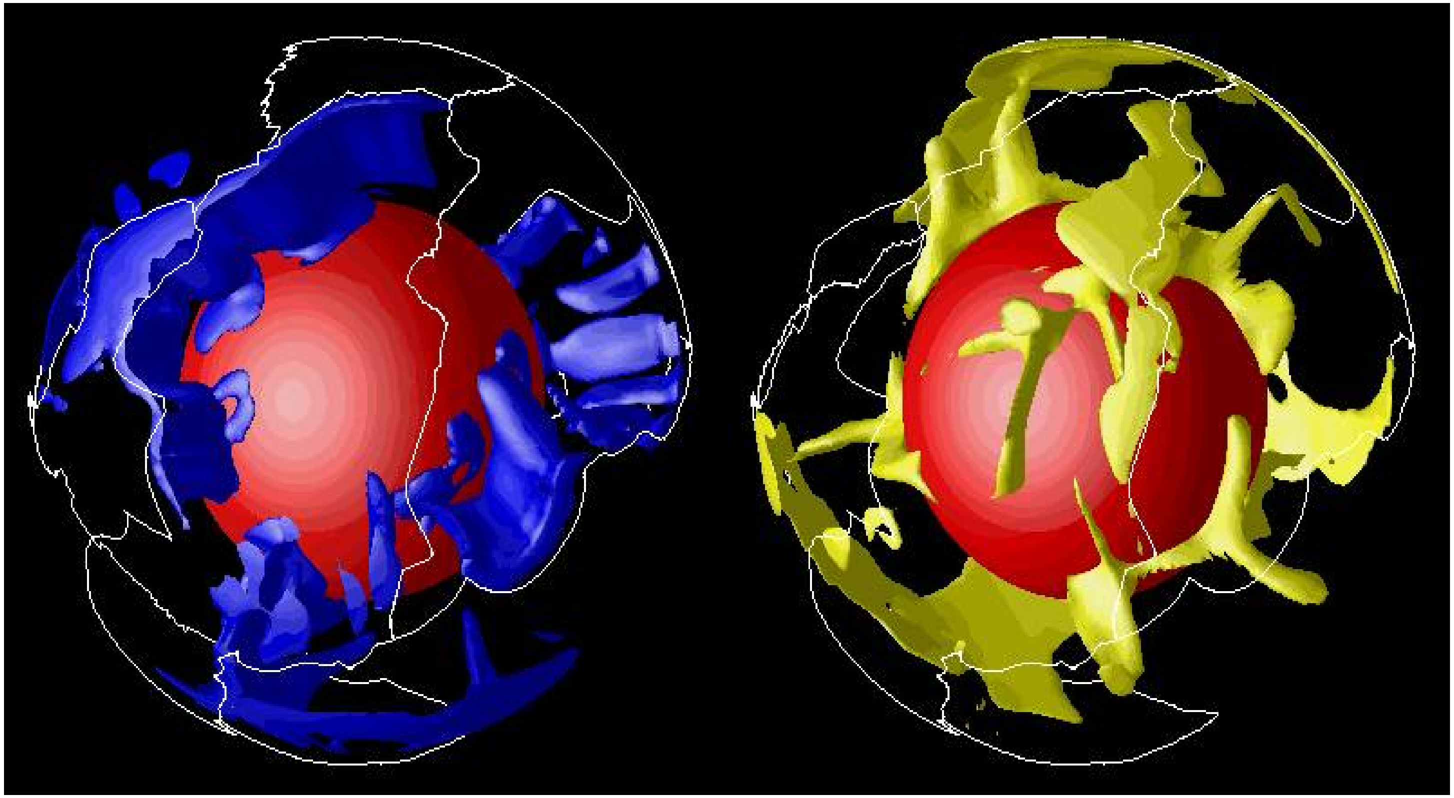
2D thermo-chemical convection, heavy material is created with T and depth





http://earth.uni-muenster.de/~joergs/movies/index.html

Joerg Schmalzl



This animation shows the evolution of thermal structure within the mantle over a period of about 4 transit times (equivalent to ~200 Ma). The scale of thermal structure is controlled by surface plates. Downwelling sheets and upwellings plumes are the predominant structures. Thermal anomalies below spreading centers only extend to a depth of about 200 km.

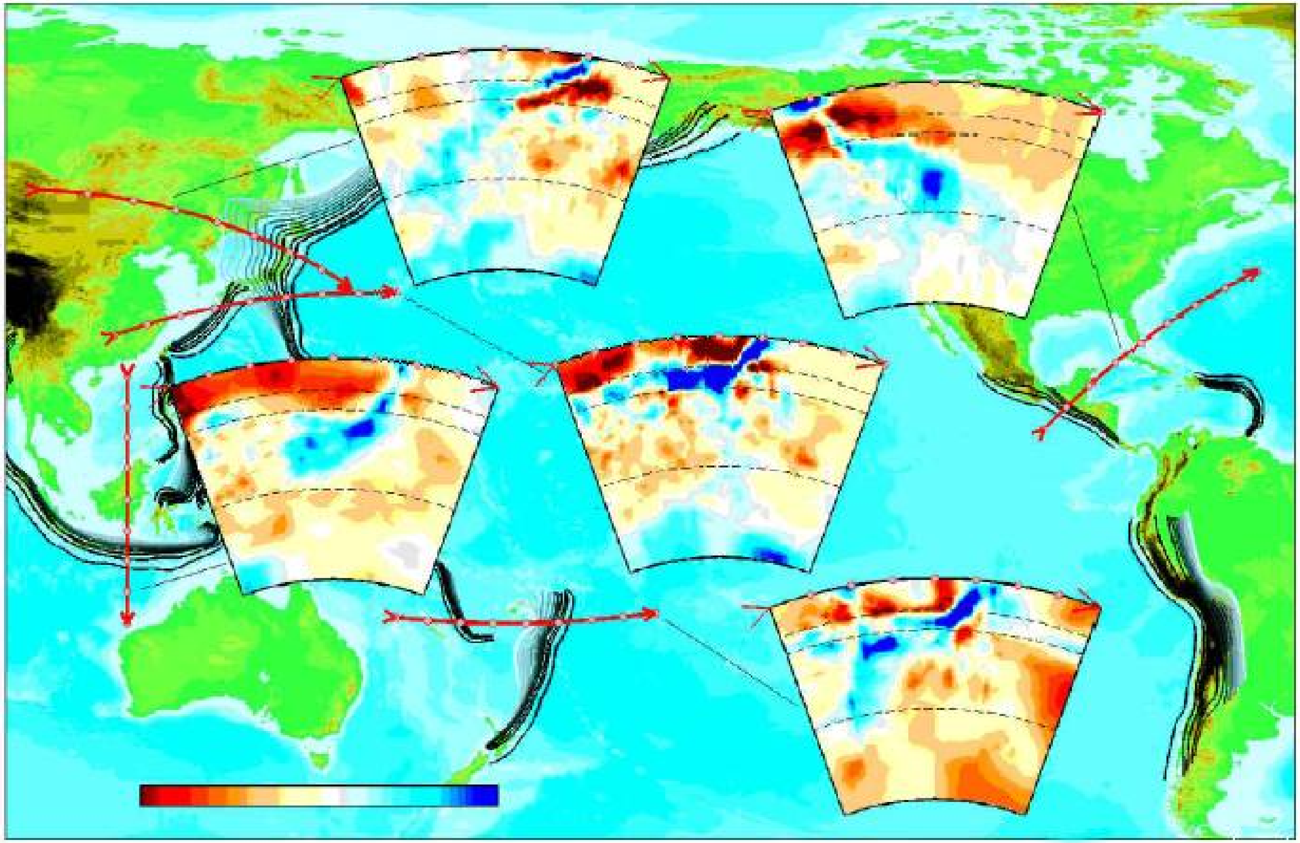
Model parameters: * Internal heating=61%; activation energy=9.21;

* LM_Viscosity/UM_Viscosity=60;

* Rayleigh number=$2{,}6.10^6$.

The Earth's convective boundary layers...

- Profil isentropique dans les zones convectives.
- Profil de diffusion dans les couches limites, mais quelles sont-elles ?
  - Surface : lithosphère.
  - Frontière noyau–manteau : couche D".
  - 660 km ? La transition de phase n'est qu'un frein partiel au mouvement !



(Albarède & van der Hilst, 2002)

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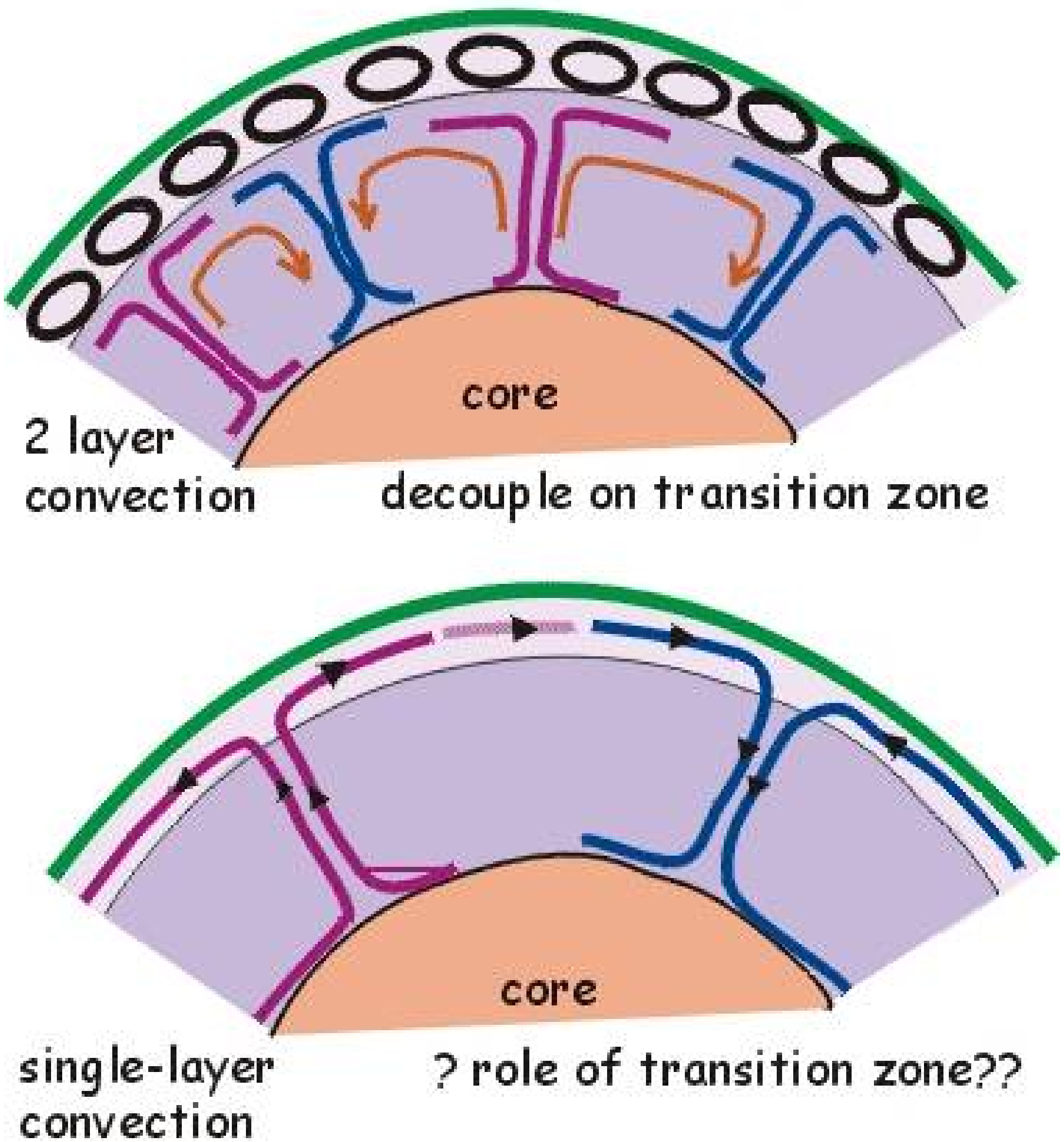
Mantle convection models

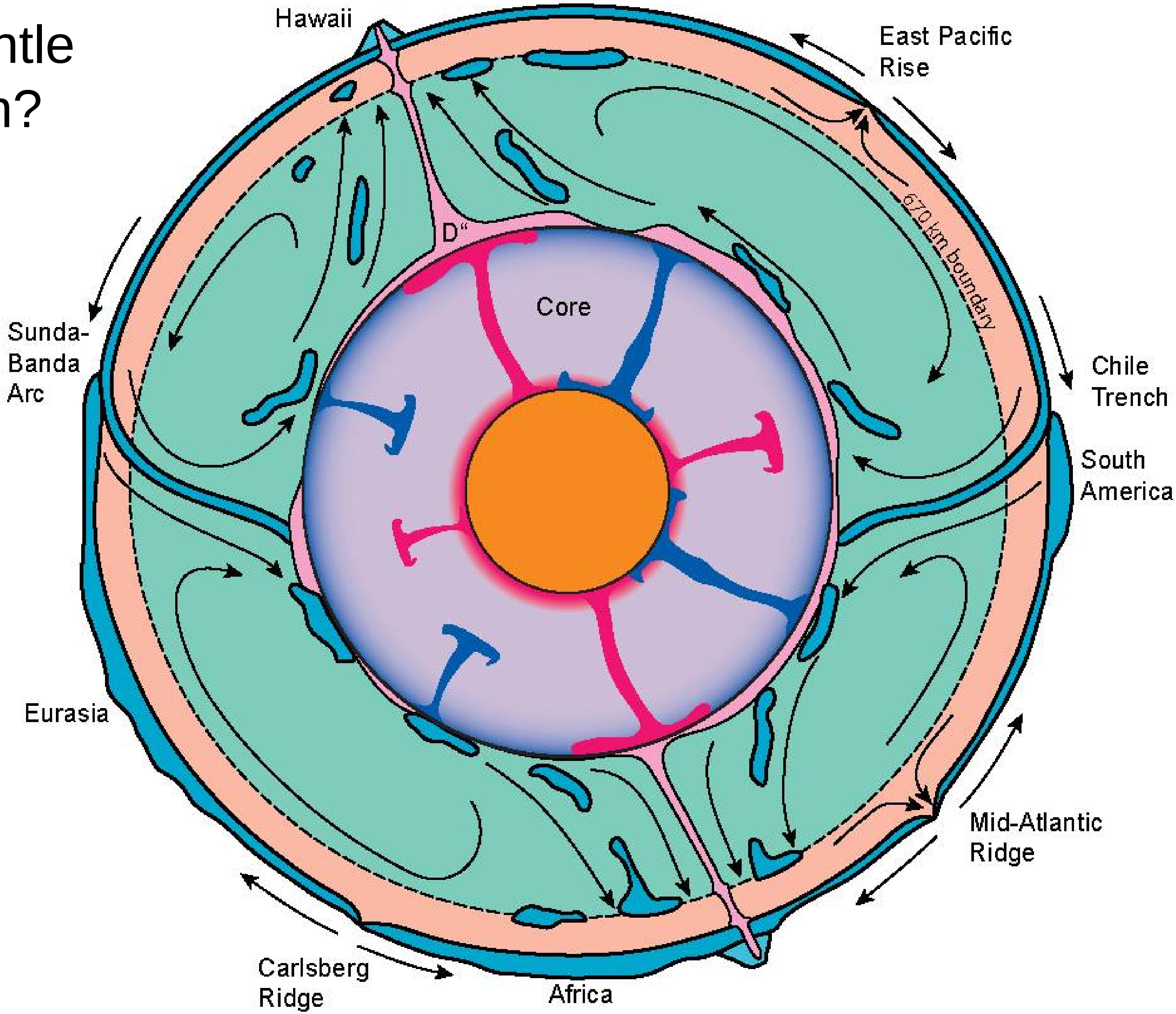


The mantle is convecting, but the isotopic differences observed between mid-ocean ridge rocks and hotspots lavas have led people to propose different levels of convection.

According to F. Albarède (CNRS, ENS-Lyon), iniital isotopes were present in a specific proportion, but they would have been dissolved in the mantle and migrated into local refractory reservoirs, preserved by the global convection currents.

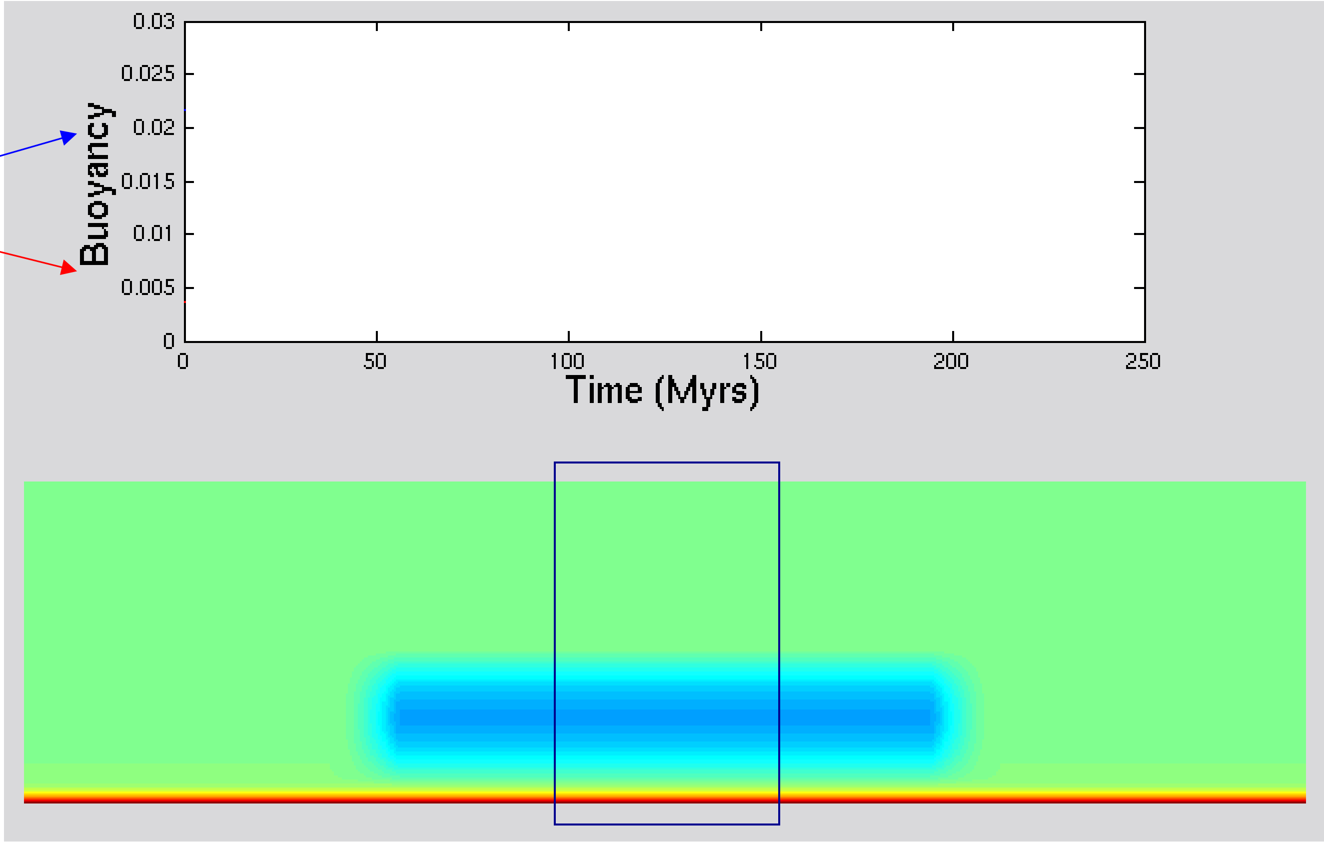
Refractory reservoirs may enrich in He and Ne molten mantle rocks differently.

Is the 670 km transition a barrier to whole-mantle convection?
Maybe?
Partly?
No?



Example of lithosphere -mantle -core coupling

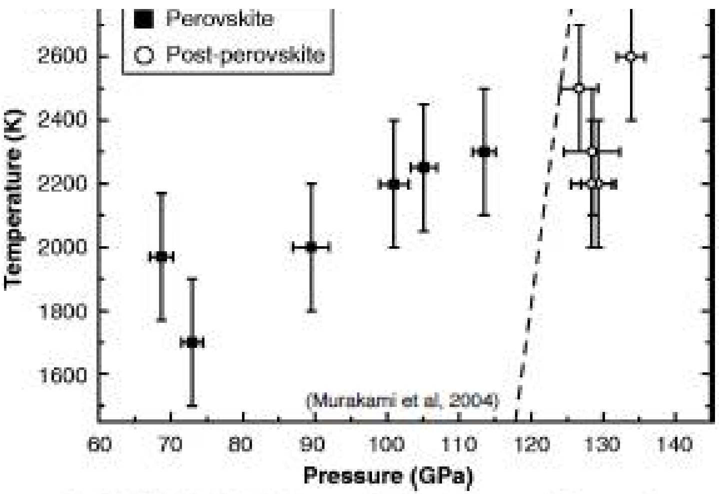
Flottabilité
- Plaque
- Plume



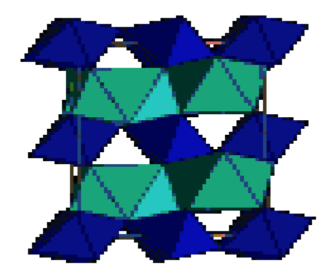
Modèle de développement d'un SUPER-Plume du à la présence d'une plaque oceanique froide en base de manteau: cette plaque fait couvercle, jusqu'à ce que le materiel dessous deviennent suffisamment chaud (LEGER) pour percer au travers.

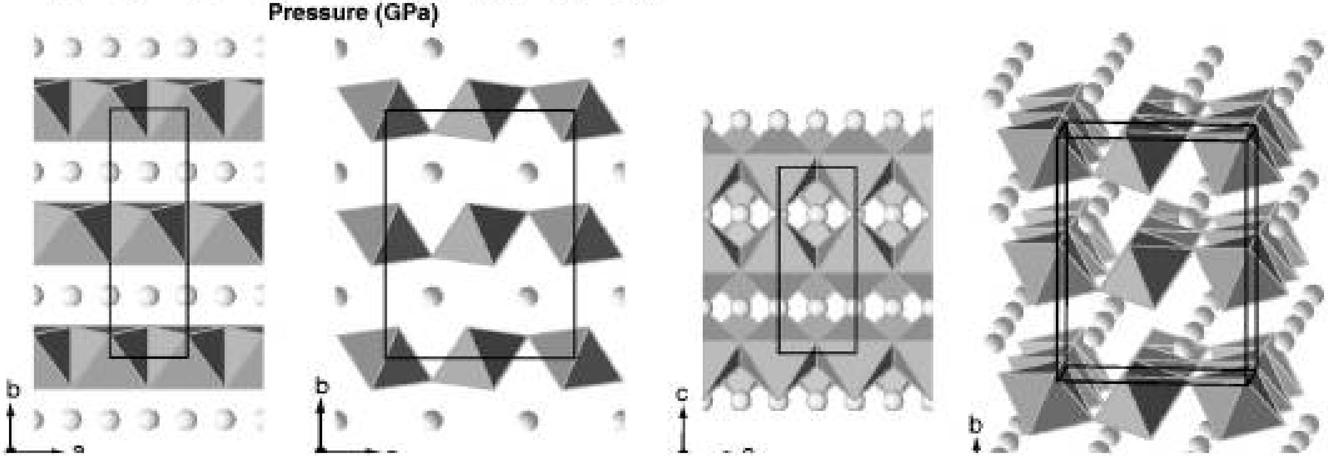
The D” Layer

This D'' layer is still a mystery. A rock called post-perovskite would be a good candidate to compose this layer which separates the lower mantle from the core. It is a rock similar to a peridotite (the dominant rock of the mantle), but richer in Fe and metal materials. It s of the type $MgSiO_3$, at pressure and temperature conditions of about 130 GPa and 2300°C.



- Phase découverte en 2004.
- Explique la discontinuité à ∼ 2750 km de profondeur (sommet de la couche D”).





The core

P and S waves studies show that the core cannot be completely liquid, despite the slow velocities. An allow of Ni and Fe built in laboratoty allows to show that the solid core would behave like a granular material (sand), like a polychrystalline solid with many defects.

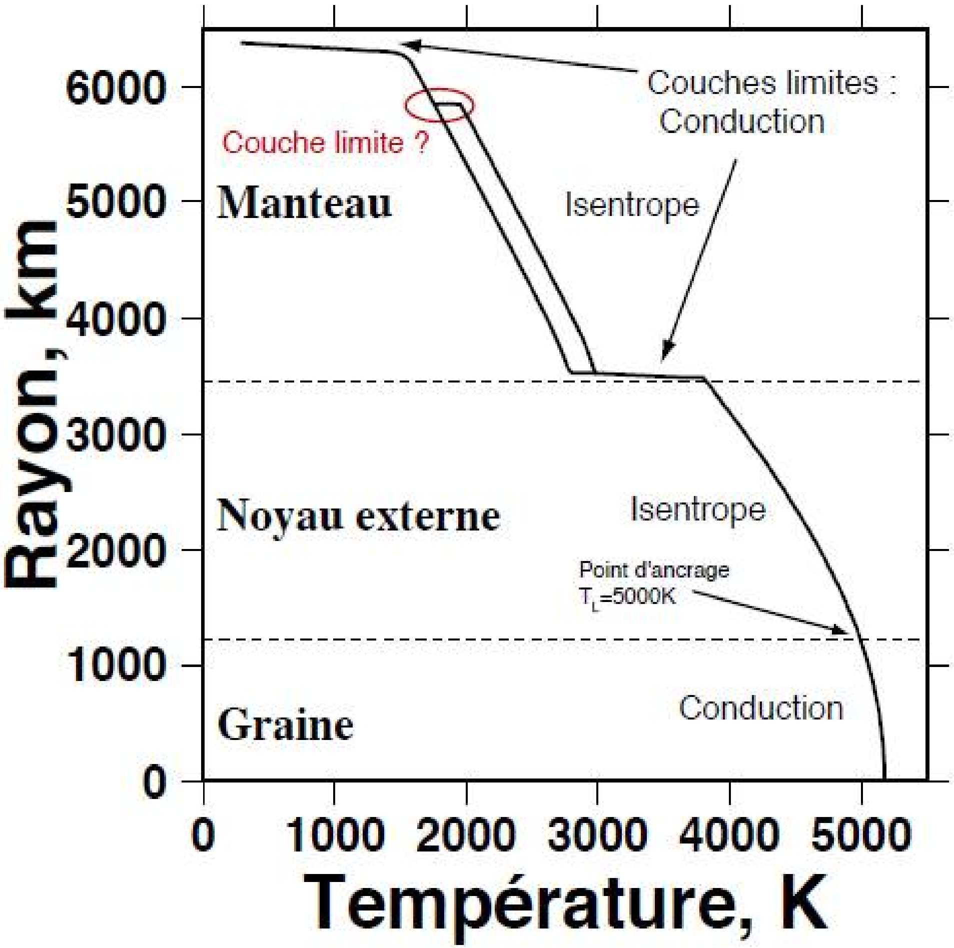
Thermal convection in the core is reenforced by a chemical convection , due to the cristallisation of the liquid Iron, the remnant liquid enriches in light materials. $Ra \sim 10^{25}$.

The internal core cristallises and grows : if it convects, it is a solid state convection like for the mantle and with slow velocities. In turn, this cristallisation increases the efficiency of the convection of the liquid core, whereas in early times, only thermal convection occured.

- To preserve the same convective efficiency as today, the heat flow at the CMB had to be much greater, or dissipation much less.
- The age of the solid core is controled by the heat flow at the CMB, which is also constrained by ohmic dissipation (magnetic field).

The Earth's Geotherm : summary

- Profils de conduction dans la graine et les couches limites.
- Profil isentropique dans chaque zone convective.
- Points d'ancrages fournis par les transitions de phase (410, 660, 2750, 5150 km de profondeur).
- Couche limite partielle à 660 km : effet encore mal contraint.
- Possibilités d'anomalies chimiques à la base du manteau avec un effet thermique potentiellement important.



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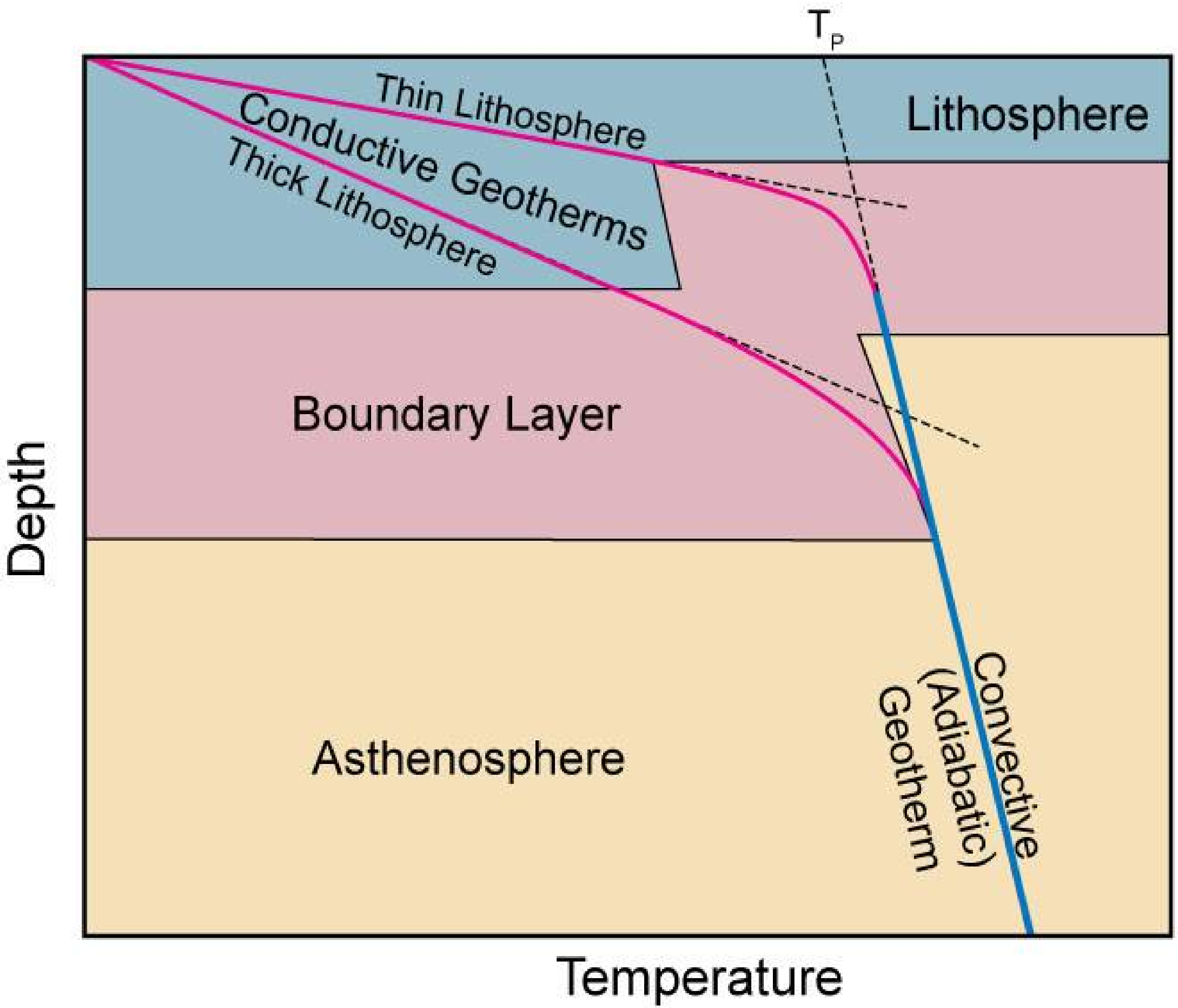
Geotherm of the upper boundary layer

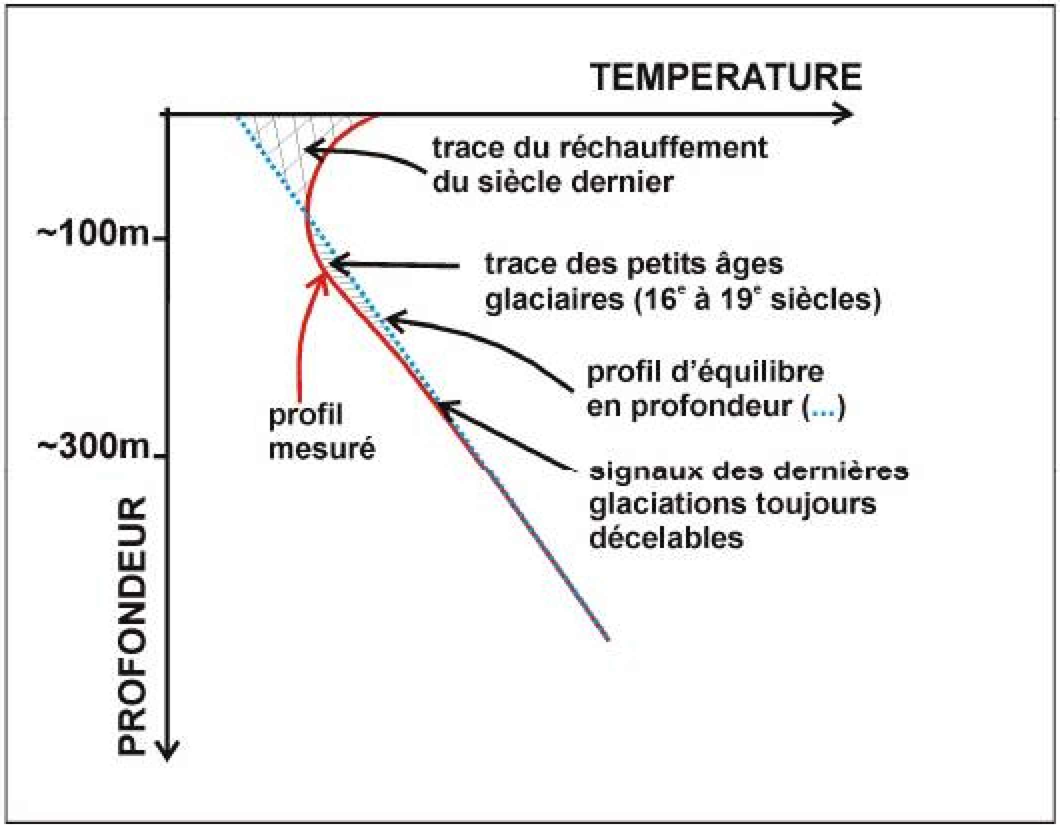
Thinner lithosphere allows convective heat transfer to shallower depths, resulting in a **higher** geothermal gradient across the boundary layer and lithosphere.

T_P : potential temperature, simply extrapolated adiabatically from the T and P base of the boundary layer to the surface.

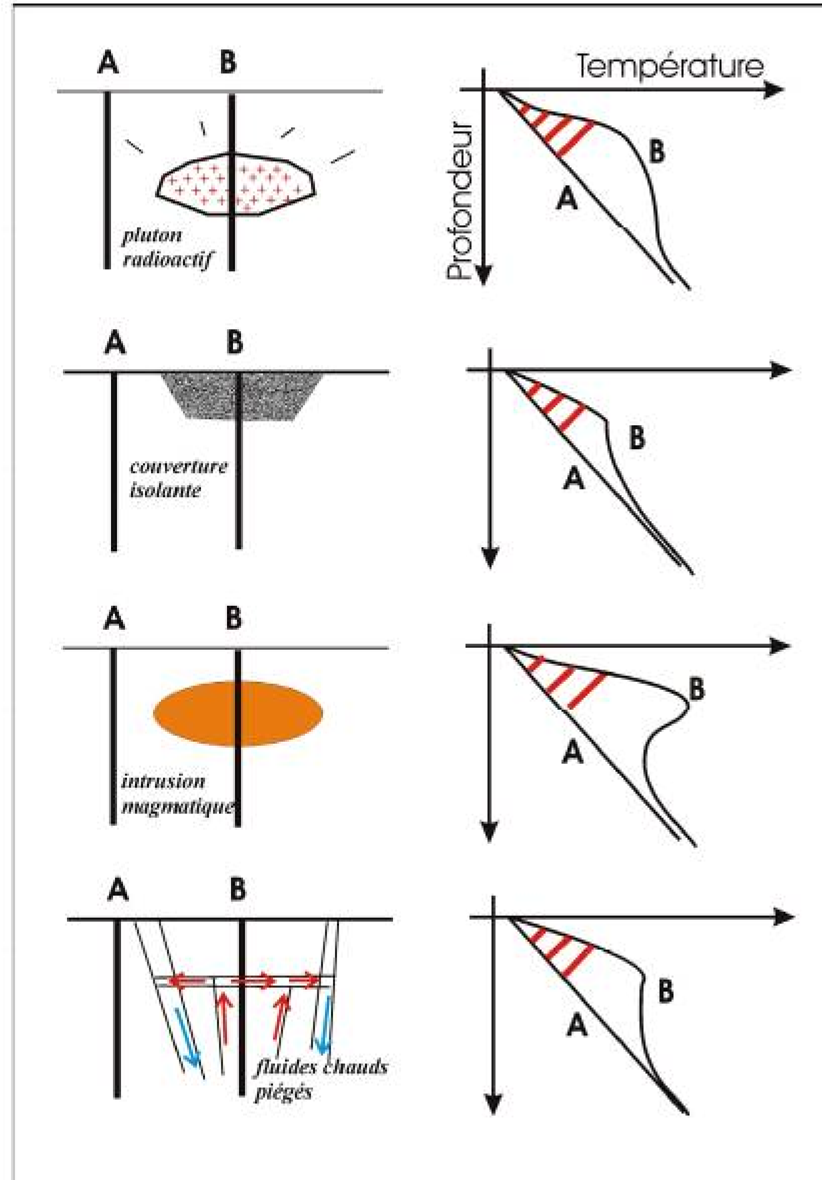


a) Temperature T

Allure typique d'un GEOTHERME dans les premières centaines de mètres de profondeur

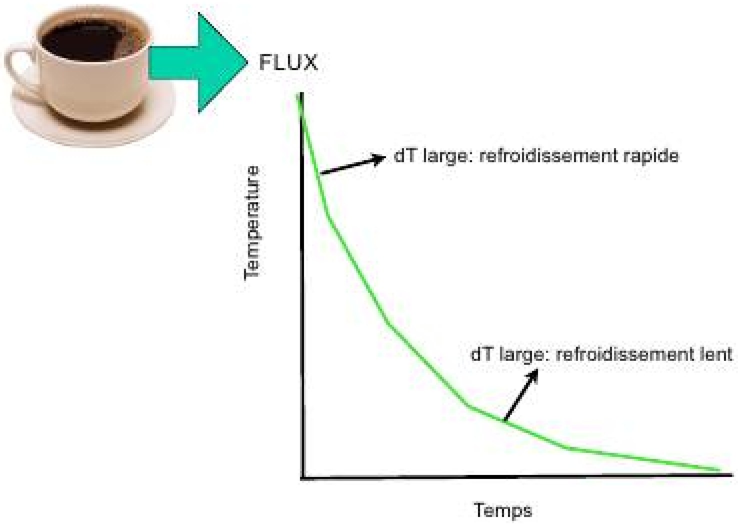


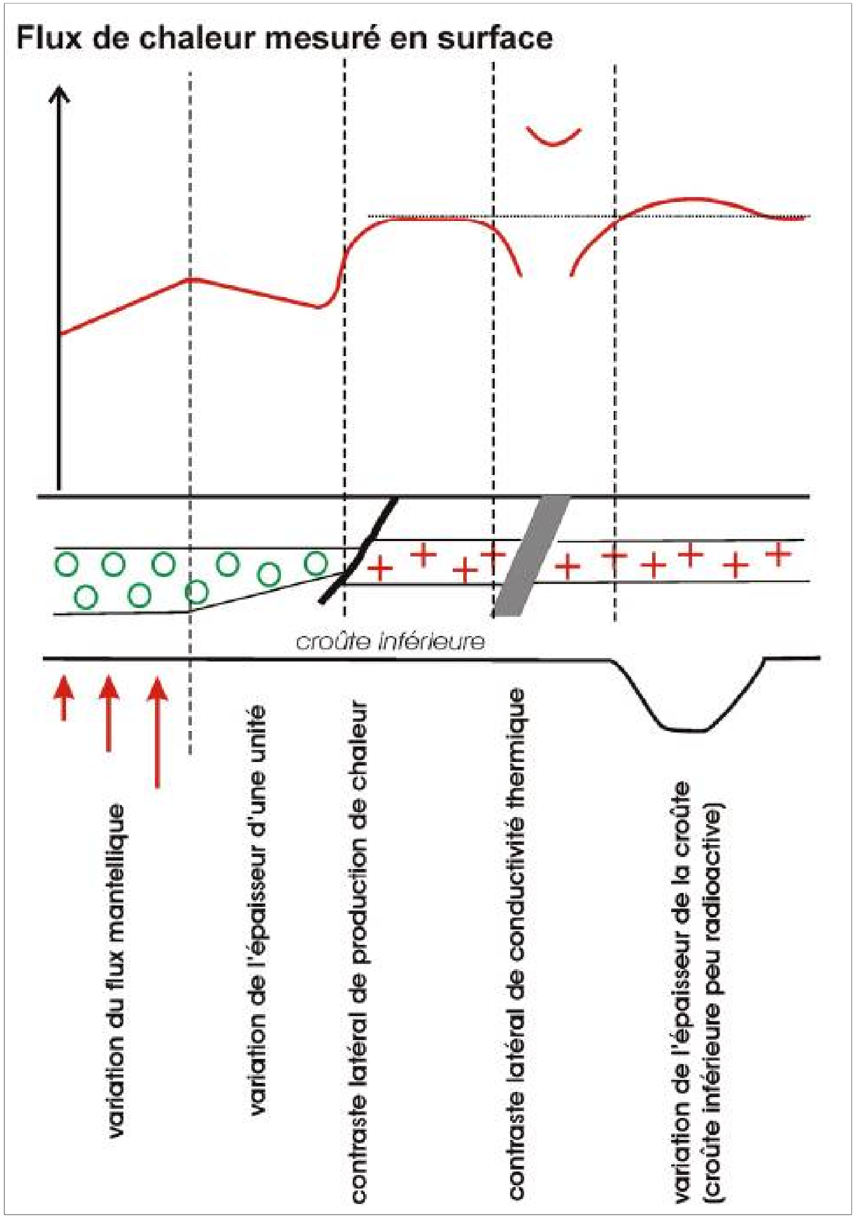
Cas géologiques dans lesquels on peut reconnaitre un réservoir de chaleur dans le géotherme B par rapport au A “normal”



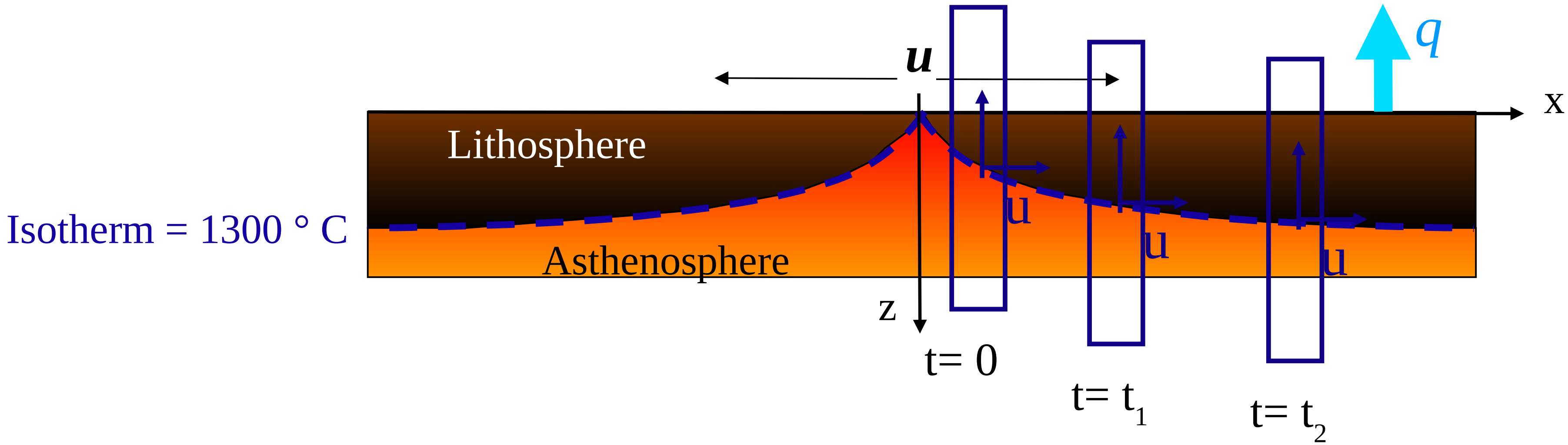
b) Flux de chaleur q (loi de Fourier)

Causes de variations du flux de chaleur en l'absence de magmatisme





Oceanic heat Flow – cooling model



An oceanic lithosphere is created and moves at velocity ***u***,
and its age is ~ ***x/u*** (***x*** : distance ridge)

The older the oceanic plate, the colder it gets, the “thicker” it becomes

The outgoing heat flow ***q*** decreases as the oceanic plates gets further from the ridge.

On résout l'équation de diffusion en 2 dimensions, supposant $A=0$ (pas de production radioactive), et que le champ de temperature ne change pas a l'interieur d'une colonne $dT/dt = 0$.

L'equation de la chaleur à résoudre est: $$\frac{k}{\rho c_p}\nabla^2 T = u\nabla T$$

Or $u=\partial x/\partial t$, et on retrouve l'équation transitoire: $$\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial z^2}$$

Pour résoudre cette equation, on fait un “changement de variable” $$\eta = \frac{z}{2\sqrt{\kappa t}}$$

On fait apparaitre la fonction ***erf :*** $$erf(\eta) = \frac{2}{\sqrt{\pi}}\int_0^\eta e^{-x^2}dx$$

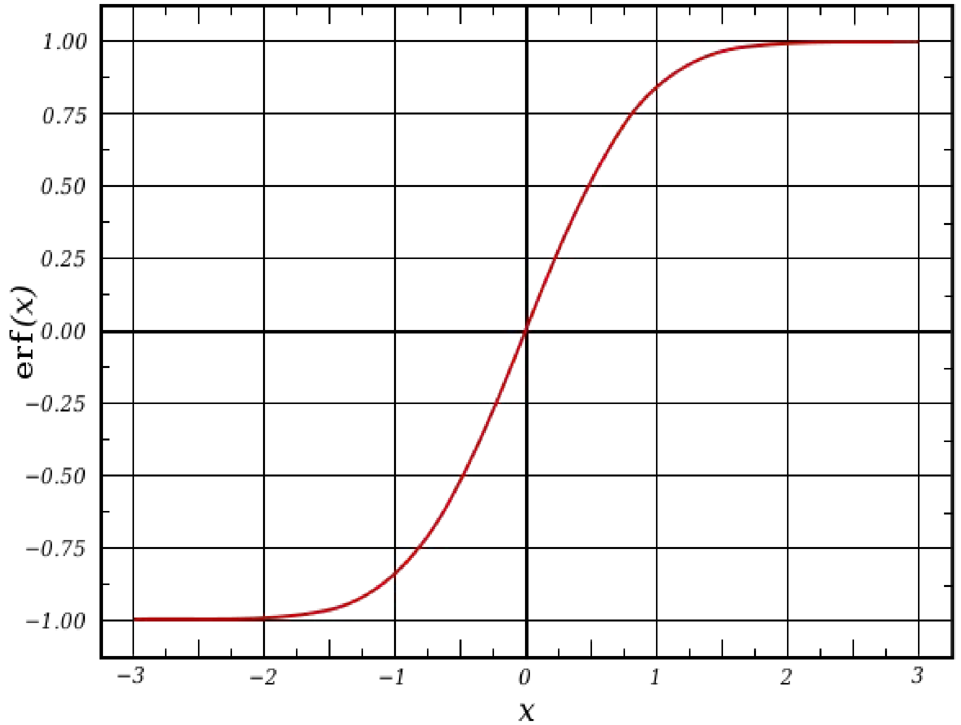
Et si on se donne aussi les conditions aux limites :

* à la dorsale $x=0$, $T=T_a$ (asthenosphere),
* en surface $z=0$, $T=0$, ...

On obtient la solution : $$T = T_a erf(\frac{z}{2\sqrt{\kappa t}})$$

La fonction erreur erf

$$\mathrm{erf}(z) = \frac{2}{\sqrt{\pi}} \int_0^z e^{-\zeta^2} d\zeta$$



Quelques propriétés:

L'inverse de erf(x), pour x allant de -1 a +1:

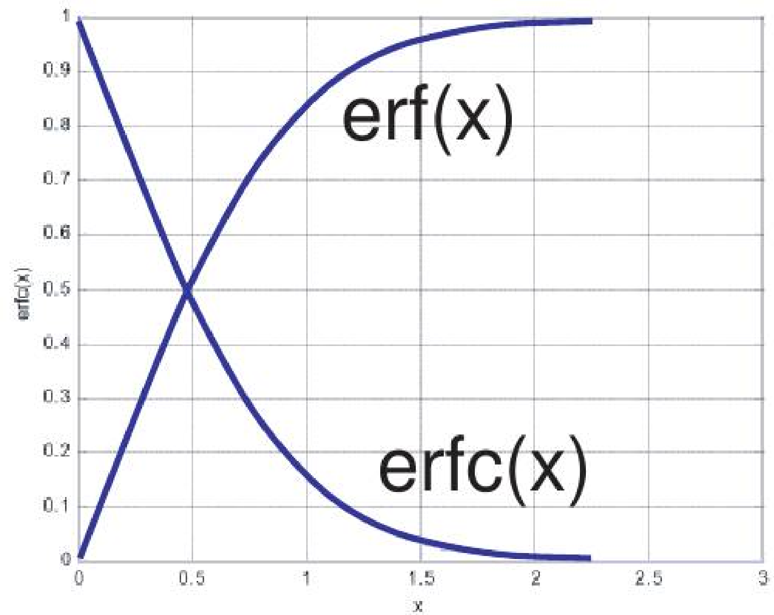
$$\mathrm{erf}^{-1}(x) \approx \frac{x}{|x|}\sqrt{\sqrt{\left(\frac{2}{\pi a} + \frac{\ln(1-x^2)}{2}\right)^2 - \frac{\ln(1-x^2)}{a}} - \left(\frac{2}{\pi a} + \frac{\ln(1-x^2)}{2}\right)}$$

La dérivée de erf(x): $\frac{\mathrm{d}}{\mathrm{d}z}\mathrm{erf}(z) = \frac{2}{\sqrt{\pi}} e^{-z^2}.$

La fonction d'erreur complémentaire **erfc**:

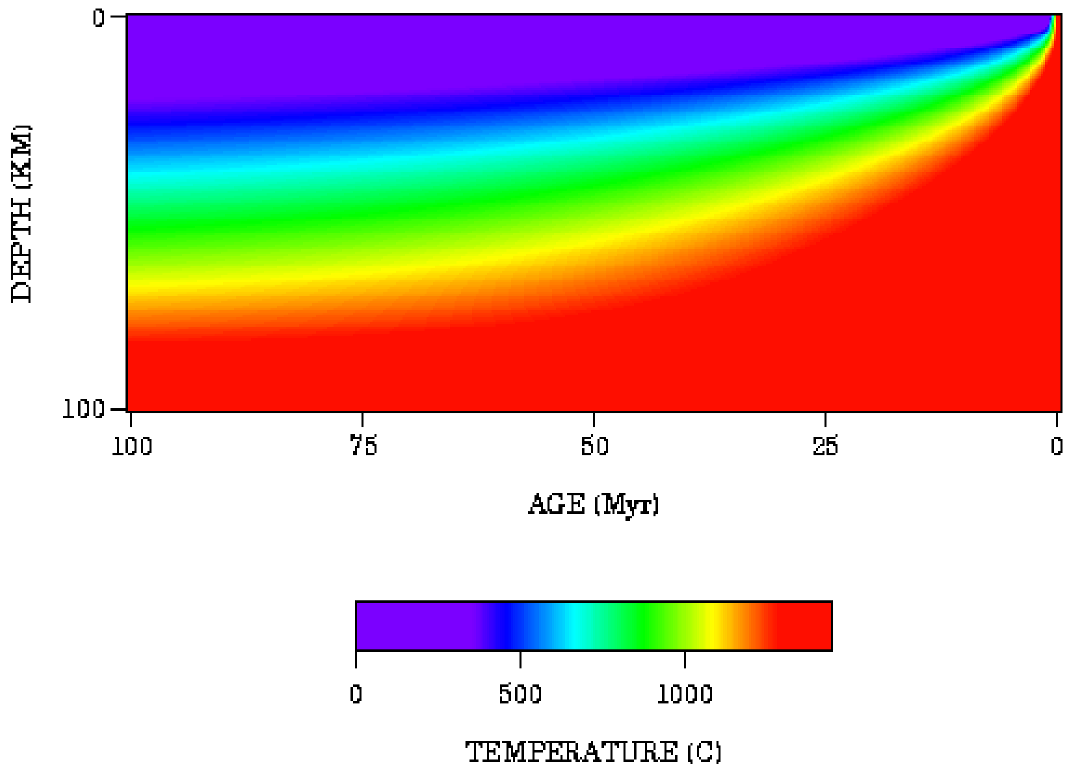
erf(z) +erfc(z)=1

$$\mathrm{erfc}(z) = 1 - \mathrm{erf}(z) = \frac{2}{\sqrt{\pi}} \int_z^{\infty} e^{-\zeta^2} d\zeta$$



ISOTHERMS - LINES OF CONSTANT TEMPERATURE - DEEPEN AS THE SQUARE ROOT OF PLATE AGE

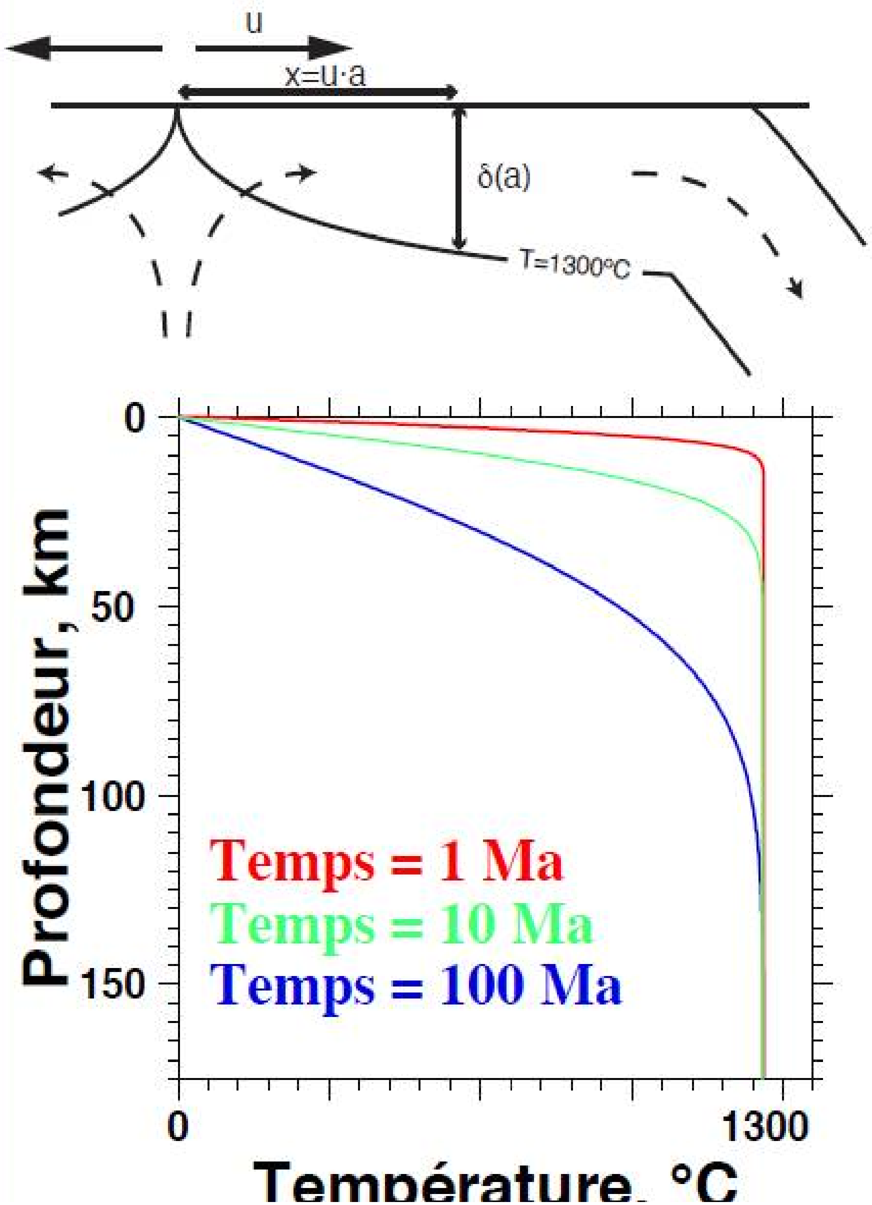
LITHOSPHERE DEFINED AS REGION BELOW ISOTHERM 1300° C



AN OCEANIC LITHOSPHERE *COOLS & THICKENS* MOVING AWAY FROM RIDGE

SIMILAR BEHAVIOR FOR COOLING OF A LAVA POND

Cooling of oceanic lithosphere



- Initialement (aux dorsales) $T = T_M$ (à déterminer).
- Refroidissement par diffusion au contact de l'eau durant le déplacement horizontal.

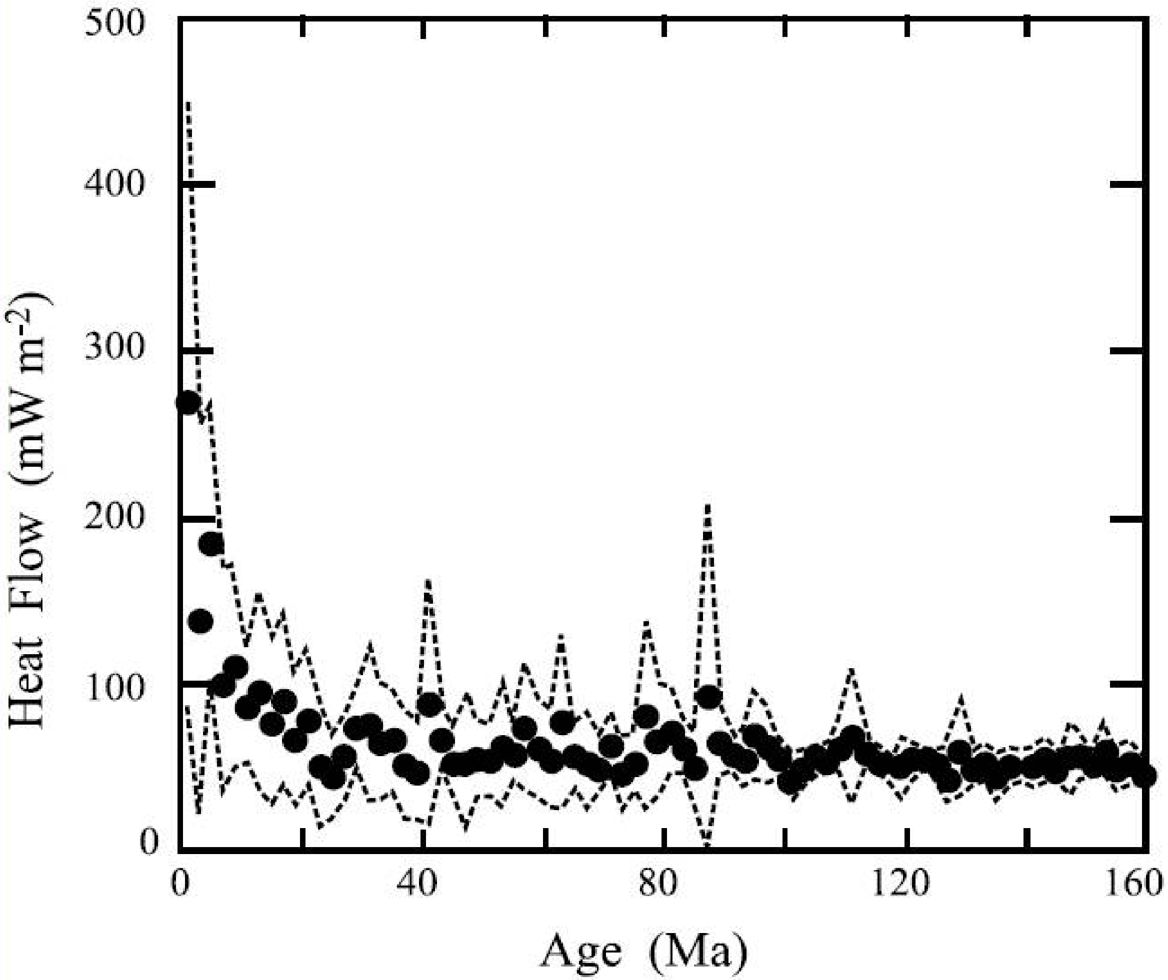
$$T = T_M \operatorname{erf} \frac{z}{2\sqrt{\kappa t}}$$

- Flux de chaleur en surface :

$$q = \frac{k T_M}{\sqrt{\pi \kappa t}}$$

Labrosse, ENS, 2009

Oceanic heat Flow - measurements



- Sonde (∼ 10 m) enfoncée dans les sédiments non–consolidés.
- Mesure simultanée de la température et de la conductivité thermique.
- Flux de chaleur élevé près des dorsales et décroissant avec l'âge de la lithosphère.
- Dispersion importantes des mesures.

- Comment expliquer ces observations ?

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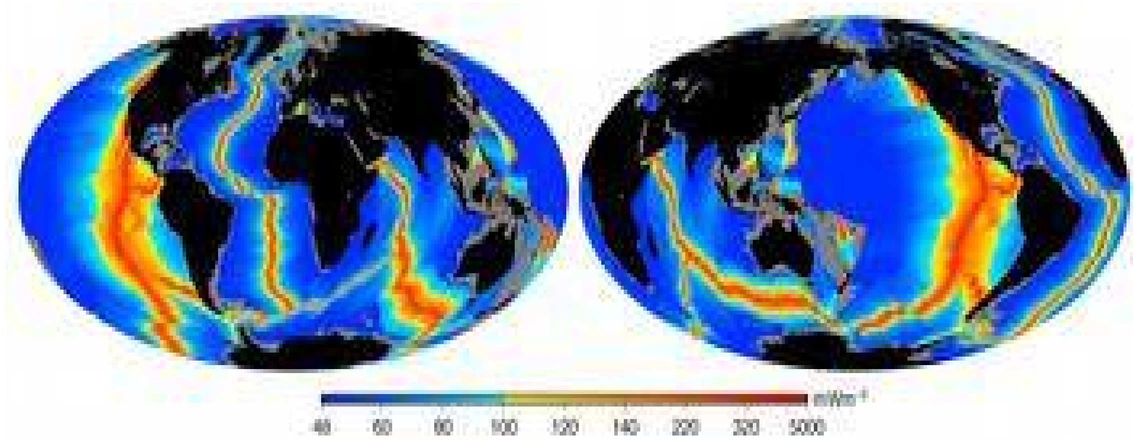
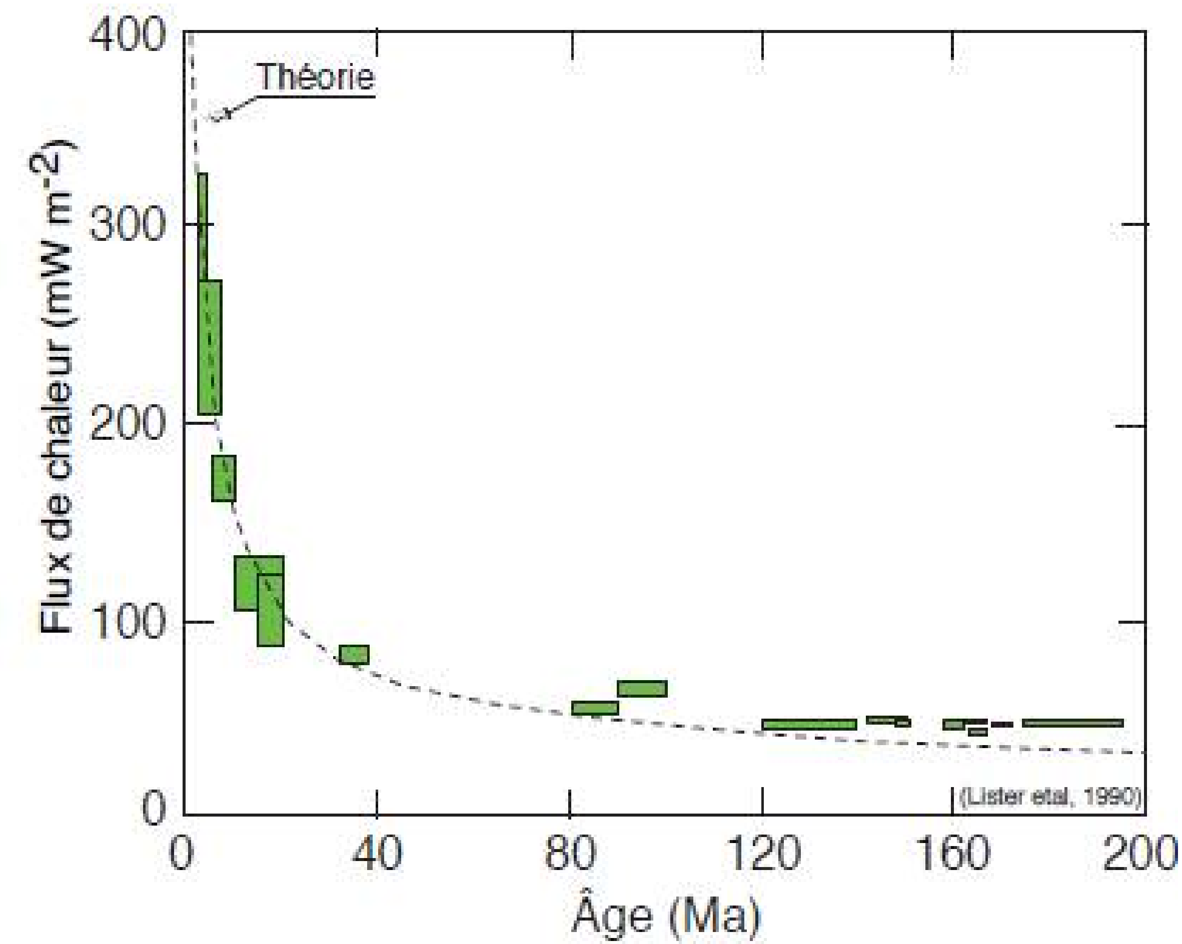


Comparaisons entre la derniere théorie (Labrosse et Jaupart, 2007) et les observations, de le flux de chaleur océanique (a=t est l'age):

$$q = \frac{490}{\sqrt{a}}$$



Se déduit grâce à la loi de Fourier, qu'on dérivee une fois qu'on connait l'expression de la Température (voir slide précédent):

$$q = -k\frac{\partial T}{\partial z}$$

Labrosse, ENS, 2009

Dynamic Causes of the Relation Between Area and Age of the Ocean Floor

N. Coltice,[1,2]* T. Rolf,[3] P. J. Tackley,[3] S. Labrosse[1,2]

The distribution of seafloor ages determines fundamental characteristics of Earth such as sea level, ocean chemistry, tectonic forces, and heat loss from the mantle. The present-day distribution suggests that subduction affects lithosphere of all ages, but this is at odds with the theory of thermal convection that predicts that subduction should happen once a critical age has been reached. We used spherical models of mantle convection to show that plate-like behavior and continents cause the seafloor area-age distribution to be representative of present-day Earth. The distribution varies in time with the creation and destruction of new plate boundaries. Our simulations suggest that the ocean floor production rate previously reached peaks that were twice the present-day value.

The distribution of ages of the ocean floor is a first-order observation that determines the evolution of Earth's surface and interior (*1*). Because heat flow and bathymetry directly depend on the age of the ocean floor (*2*), a shift in the area-age distribution profoundly modifies Earth's cooling (*3*), sea level (*4*, *5*), and consequently global climate (*6*, *7*). The characterization

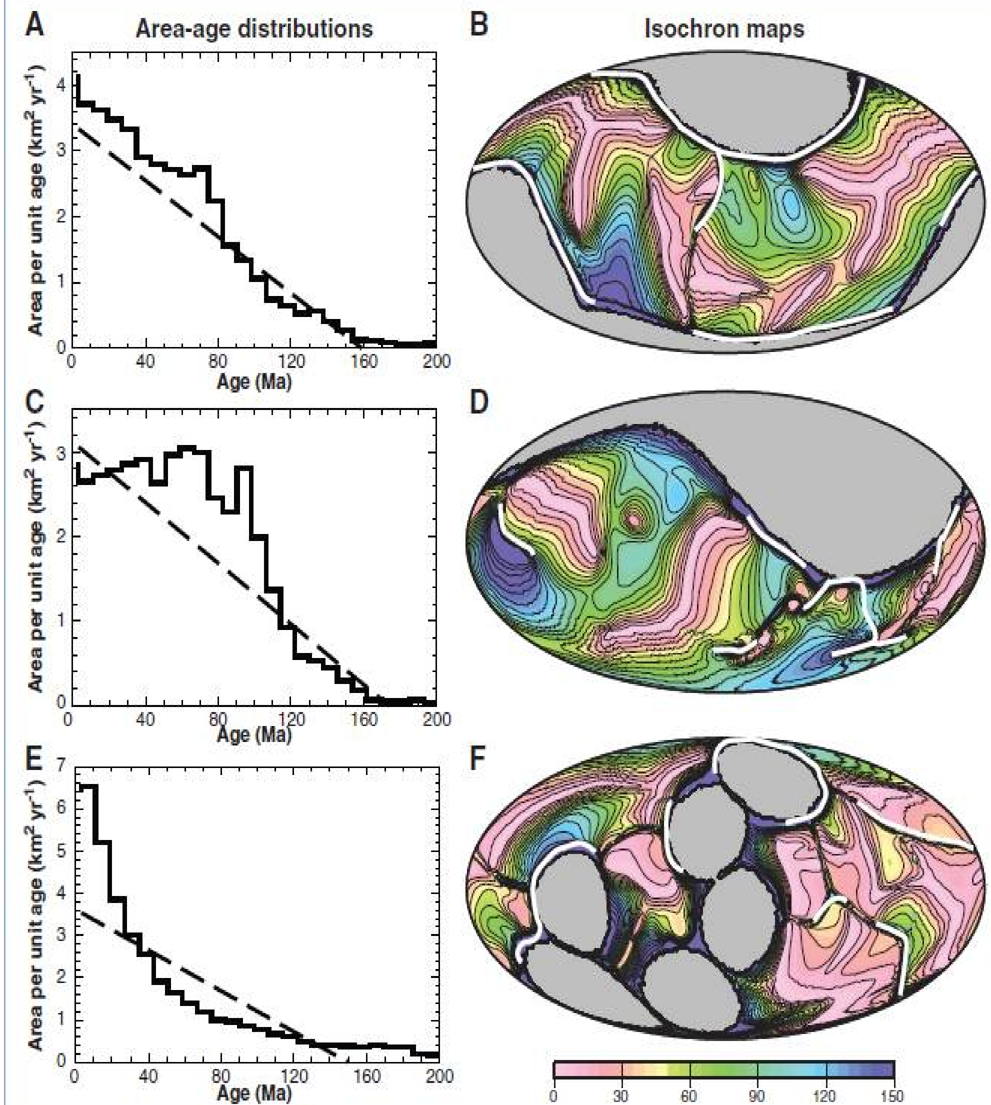


Fig. 2. Snapshots of the distribution of the area versus age of the ocean floor along with the corresponding best triangular fit in dashed lines (left) and maps of synthetic isochrons (right) computed in the 3D spherical convection models. The gray areas on the maps represent the continents, the white lines are the positions of the downwellings, and the age contours are plotted at 10-My intervals. (**A** and **B**) An example corresponding to a triangular distribution (with three continents covering respectively 15%, 10%, and 5% of the surface). (**C** and **D**) An example for a flat distribution (one supercontinent). (**E** and **F**) An example for a skewed distribution (six continents covering 5% of the surface each).