1) Flow in a lithosphere, Yield strength (TP2).

2) Diffuse and localised deformation with plate tectonics, buckling vs. subduction, Earth examples.

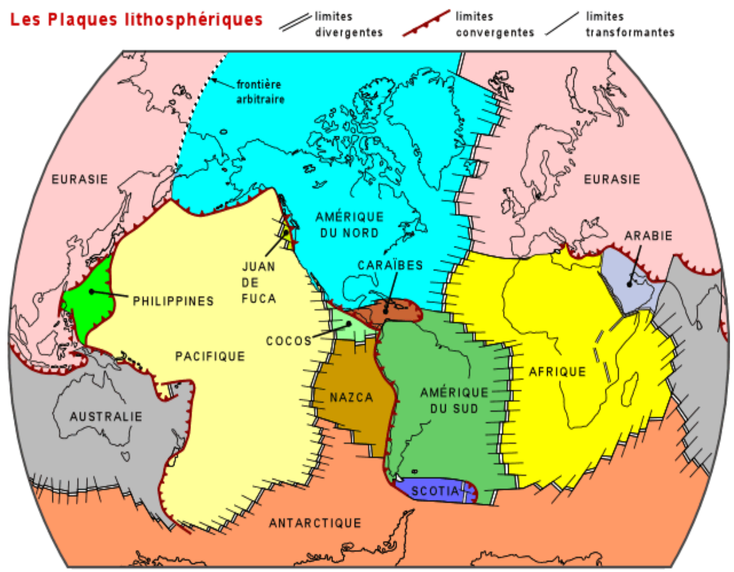
3) Observations: tectonics on other moons and planets (Moon, Venus, Mars, Io)?

4) conditions for habitability, hplanetary tectonics and the crucial effect of water on rheology (Bibliography).

Aknowledgements : Francis Nimmo, Gregor Gobalek

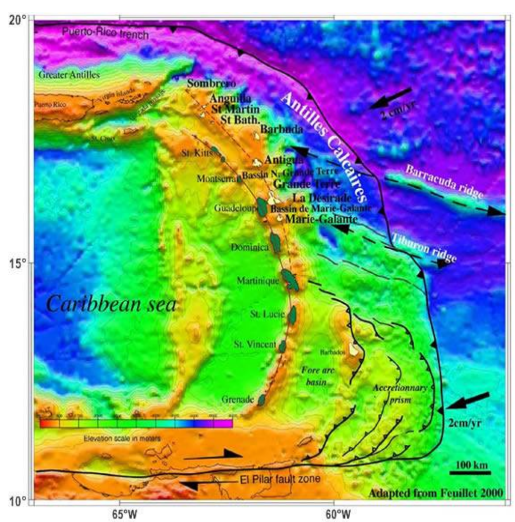
1) Behaviour of the lithosphere

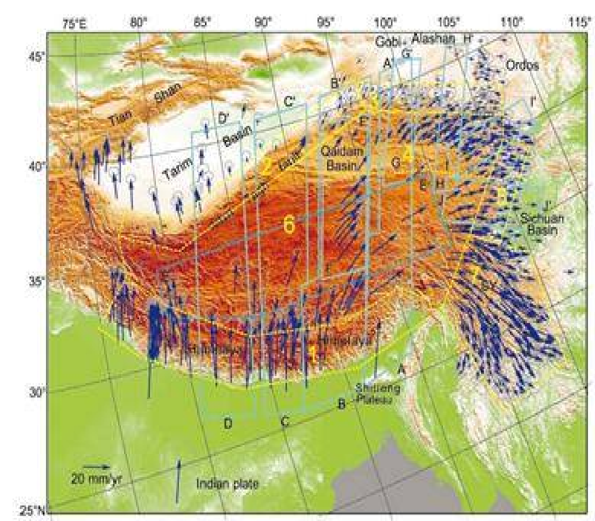
Plate Tectonics theory (1960), plates are rigid blocks that move along faults



Geodetic and geology data show that plates deform internally too :

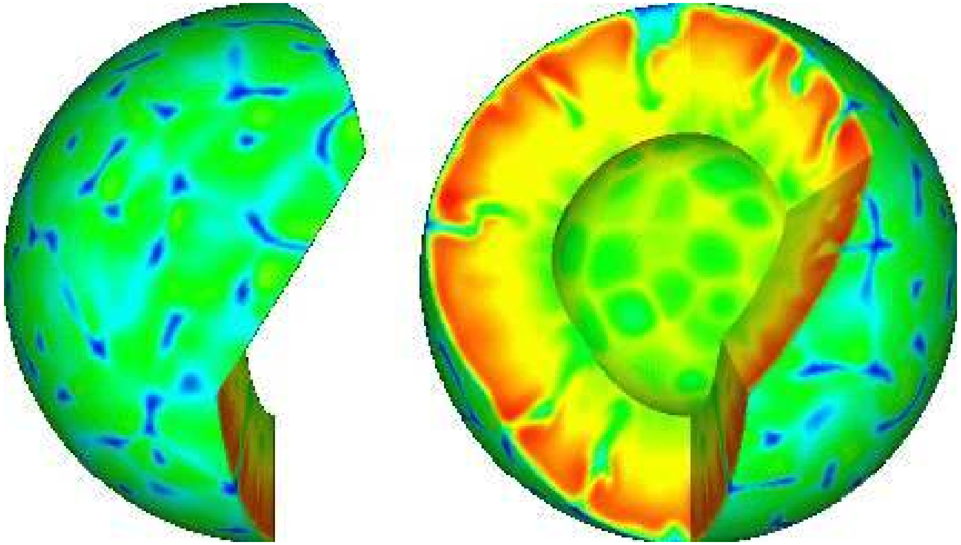
Antilles





Tibet

Examples of Geological Flow



Elasticity and Viscosity

- Elastic case – strain depends on stress (Young's mod. *E*)

$$\varepsilon = \sigma / E$$

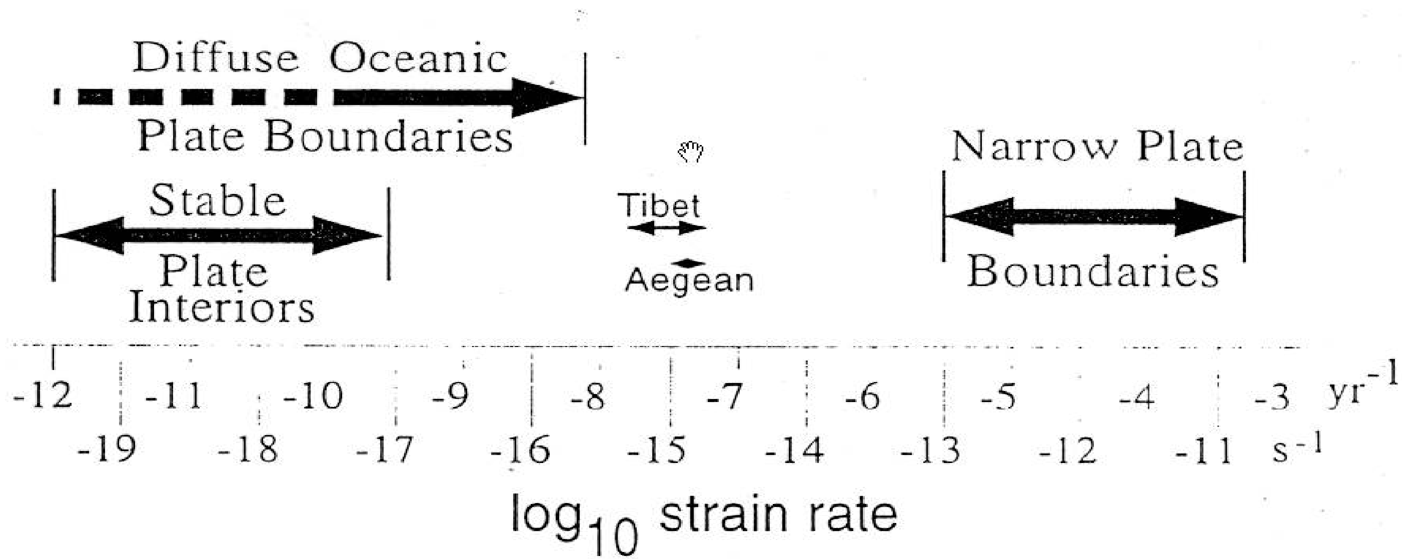
- Viscous case – strain *rate* depends on stress (viscosity μ)

$$\dot{\varepsilon} = \sigma / \mu$$

- We *define* the (Newtonian) viscosity as the stress required to cause a particular strain rate – units Pa s
- Typical values: water 10^{-3} Pa s, basaltic lava 10^{4} Pa s, ice 10^{14} Pa s, mantle rock 10^{21} Pa s
- Viscosity is a macroscopic property of fluids which is determined by their microscopic behaviour

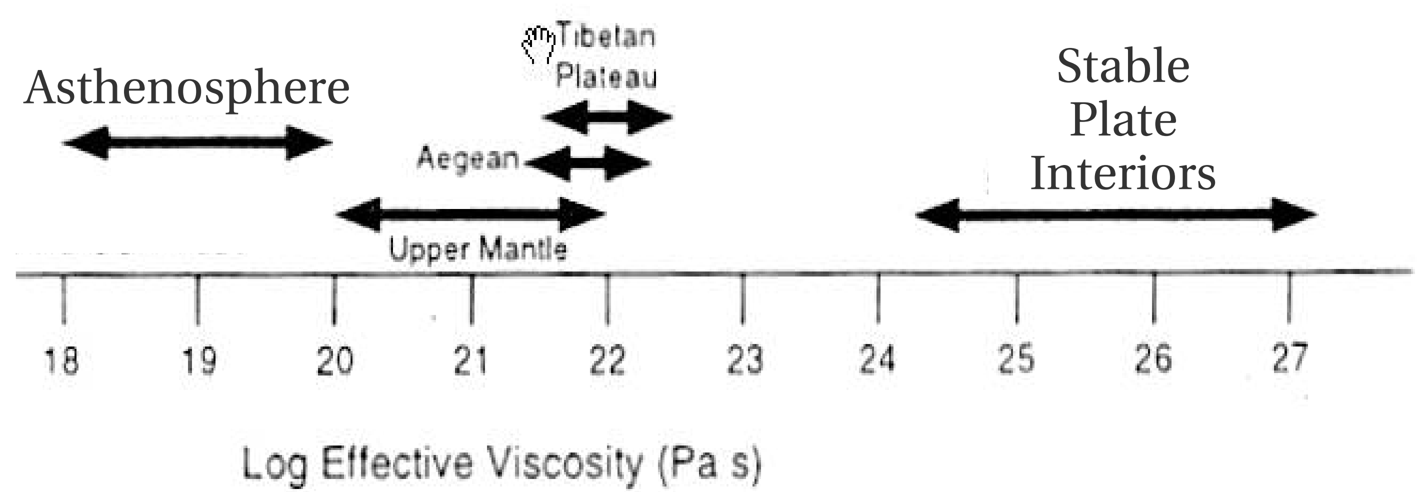
Orders of magnitud of mechanical properties in lithospheres

$\dot{\varepsilon}$



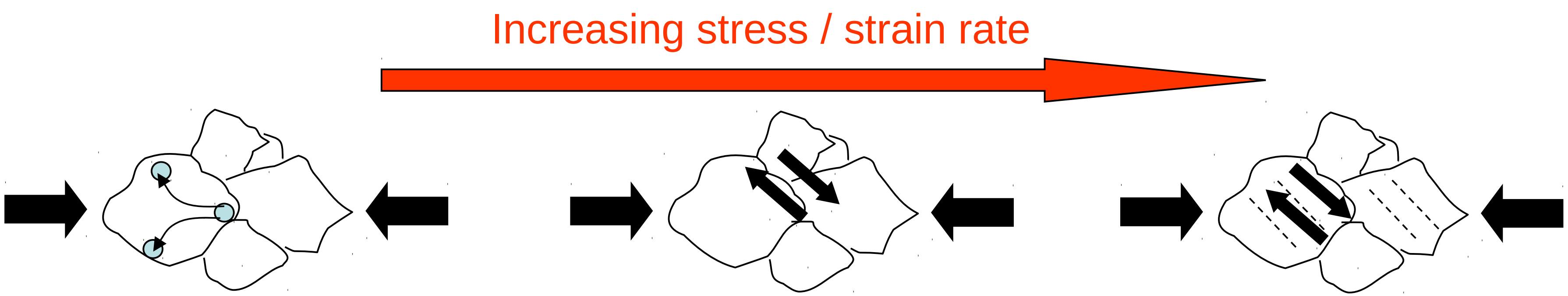
$\sigma = \mu \cdot \dot{\varepsilon}$

μ_{eff}



Flow Mechanisms

- For flow to occur, grains must deform
- There are several ways by which they may do this, depending on the driving stress
- *All* the mechanisms are very temperature-sensitive



Diffusion creep
(n=1, grain-size dependent)

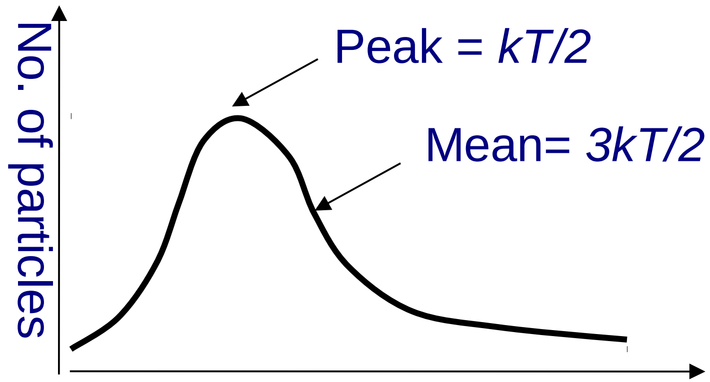
Grain-boundary sliding
(n>1, grain-size dependent)

Dislocation creep
(n>1, indep. of grain size)

Here n is an exponent which determines how sensitive to strain rate is to the applied stress. Fluids with n=1 are called *Newtonian*.

Atomic Description

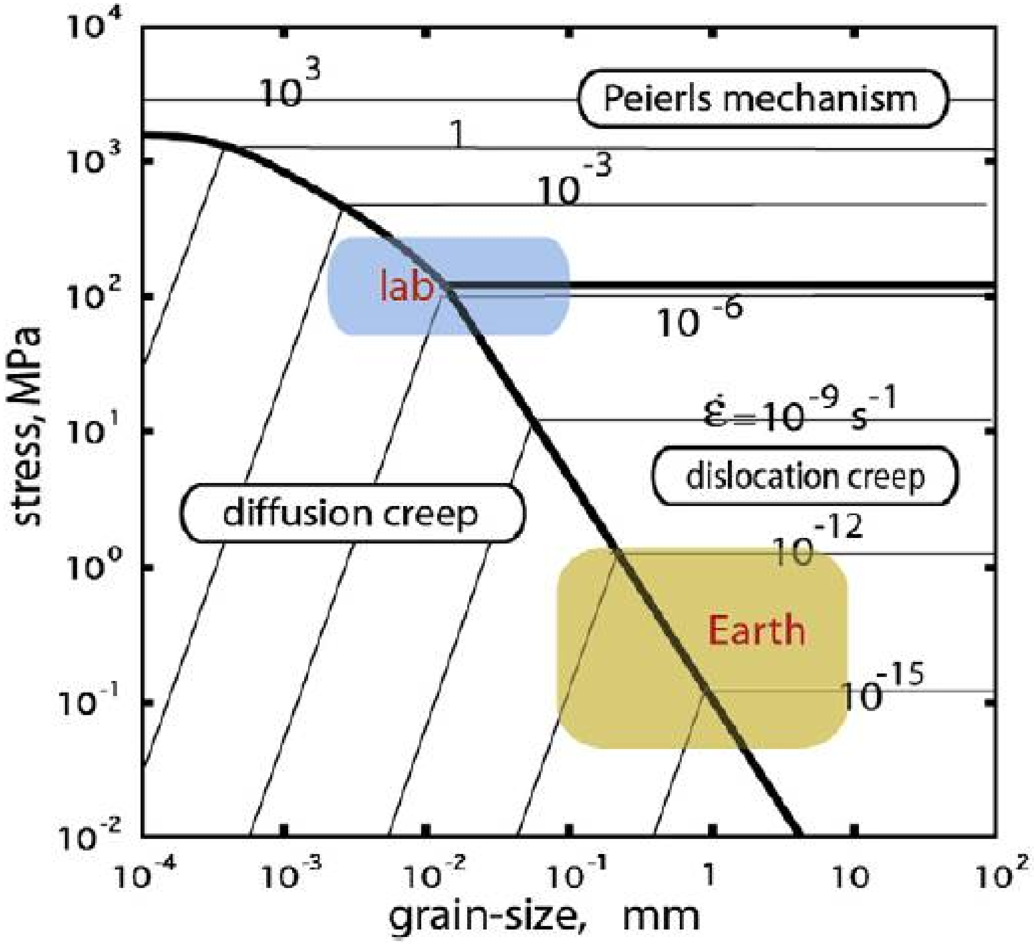
- The distribution is skewed – there is a long tail of high-energy atoms
- Atoms have a (Boltzmann) distribution of kinetic energies

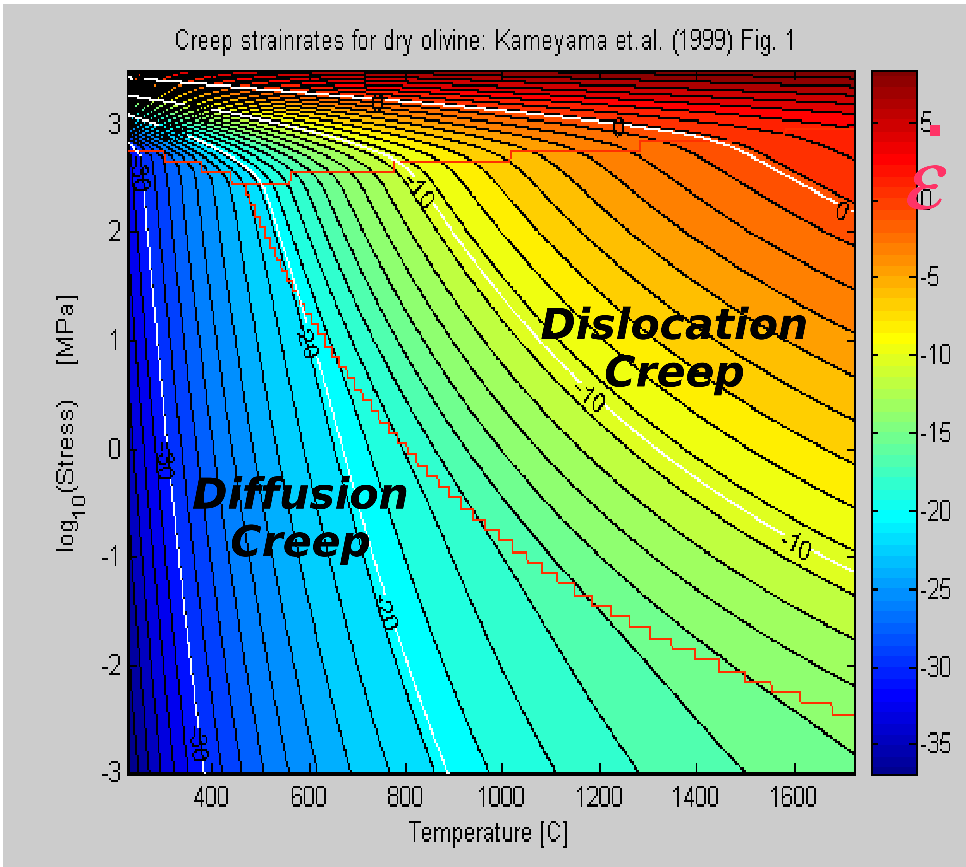


- The fraction of atoms with a kinetic energy greater than a particular value E_0 is:

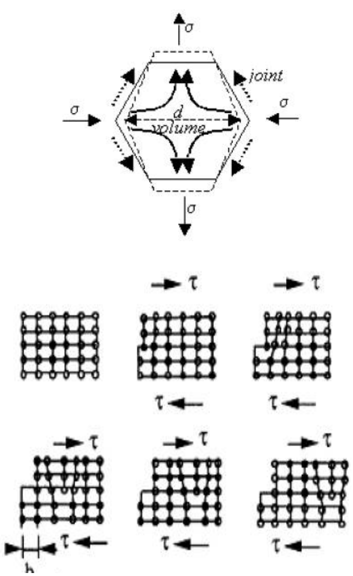
$$f\left(E_0\right)=2\left(\frac{E_0}{\pi kT}\right)\exp\left(-E_0/kT\right)$$

- If E_0 is the binding energy, then f is the fraction of atoms able to move about in the lattice and promote flow of the material
- So flow is very temperature-sensitive





From Lab experiments, effective viscosity depends on dominant mechanism :



Diffusion Creep

$$\dot{\varepsilon}_{dif}=Ad^{-p}\cdot\tau\cdot\exp\left(\frac{-Q_d}{RT}\right)$$

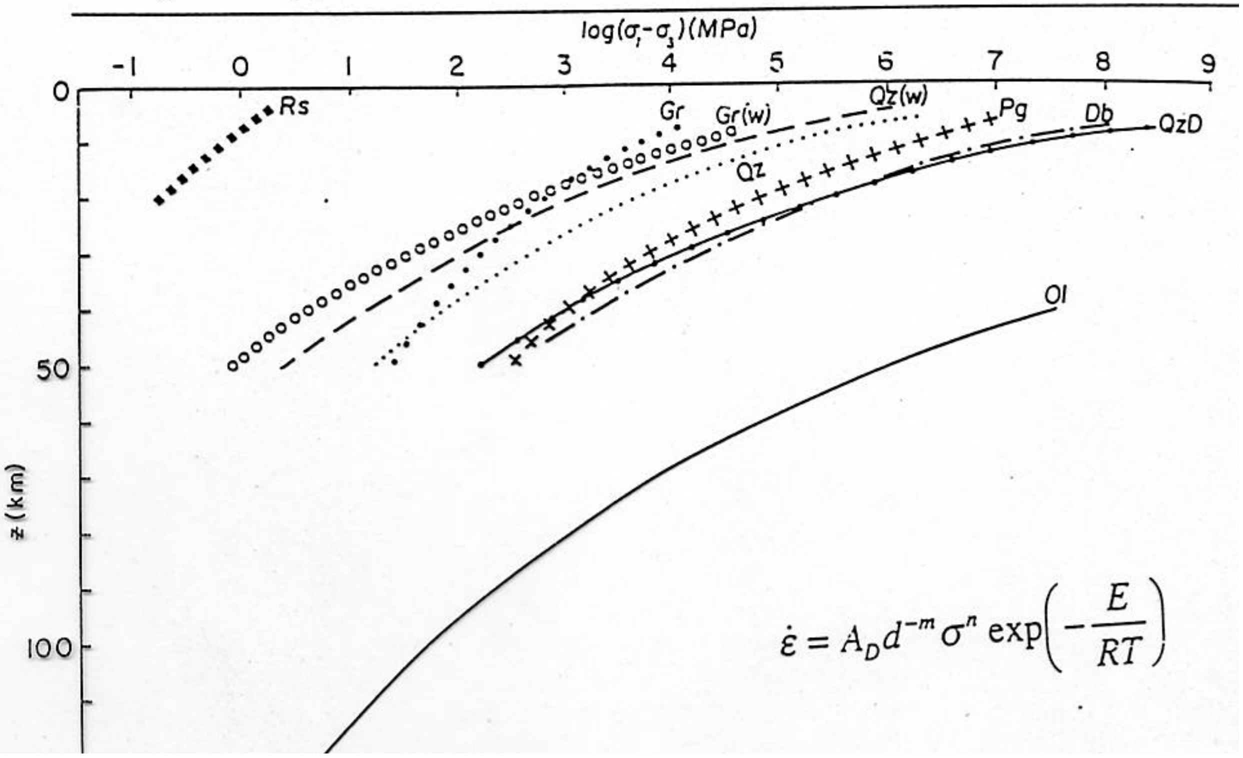
Dislocation Creep

$$\dot{\varepsilon}_{dis}=A\cdot\tau^{n}\cdot\exp\left(-\frac{Q_p+PV}{RT}\right)$$ x f(OH)

Effect of water (fugacity)...

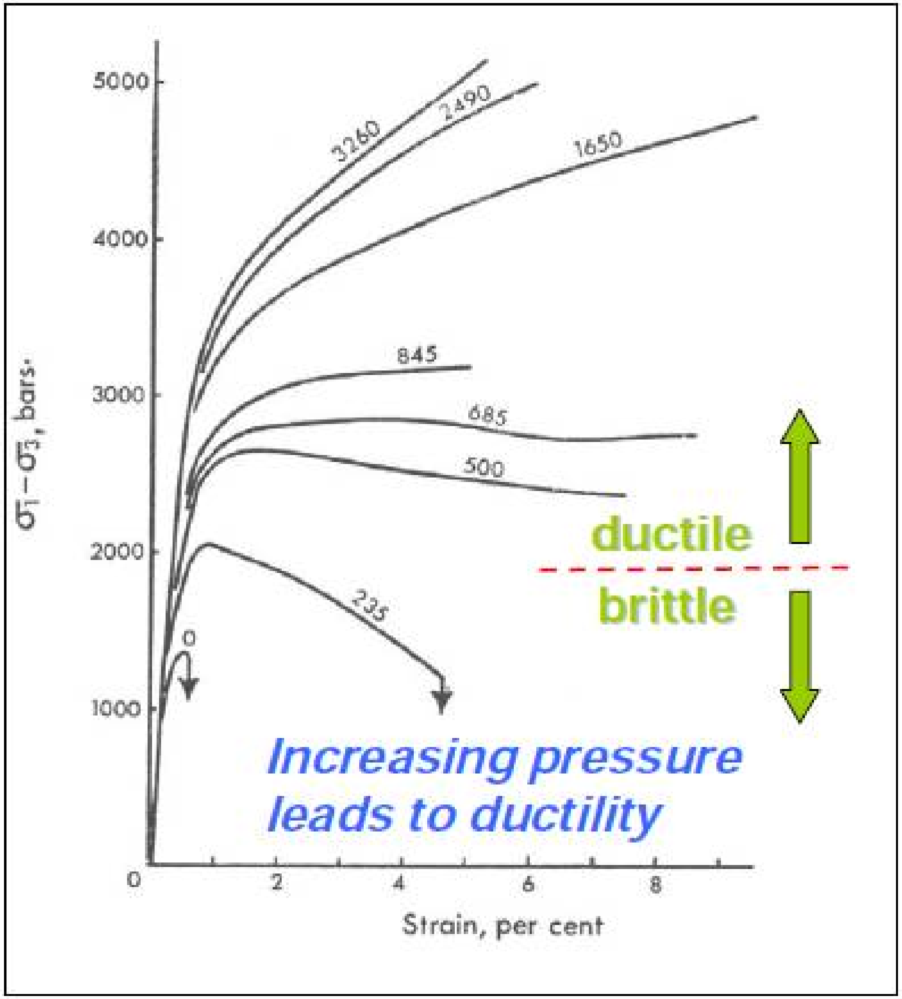
Ductile behavior depends on Temperature and composition

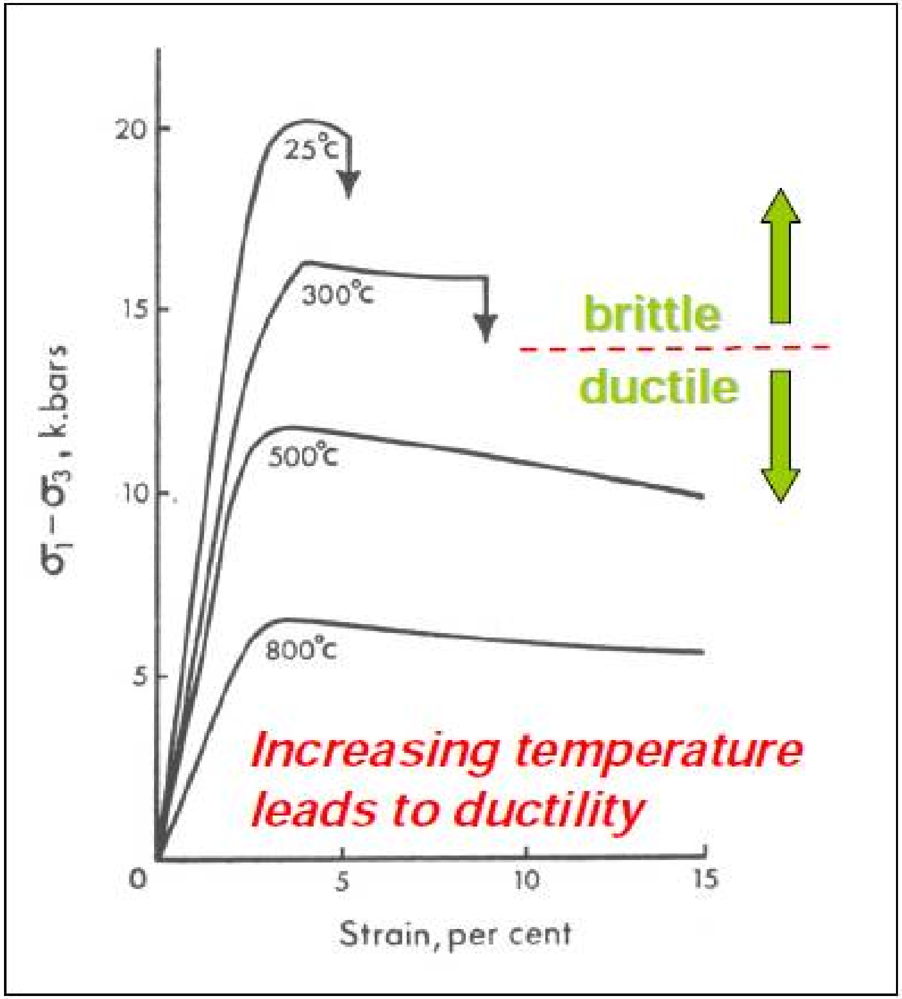
Material	A_D (MPa^{-n} s^{-1})	n	E (kJ mol^{-}
rock salt	6.3	5.3	102
quartz	1.0×10^{-3}	2.0	167
plagioclase (An_{75})	3.3×10^{-4}	3.2	238
orthopyroxene	3.2×10^{-1}	2.4	293
clinopyroxene	15.7	2.6	335
granite	1.8×10^{-9}	3.2	123
granite (wet)	2.0×10^{-4}	1.9	137
quartzite	6.7×10^{-6}	2.4	156
quartzite (wet)	3.2×10^{-4}	2.3	154
quartz diorite	1.3×10^{-3}	2.4	219
diabase	2.0×10^{-4}	3.4	260
anorthosite	3.2×10^{-4}	3.2	238
felsic granulite (*)	8.0×10^{-3}	3.1	243
mafic granulite (*)	1.4×10^{4}	4.2	445



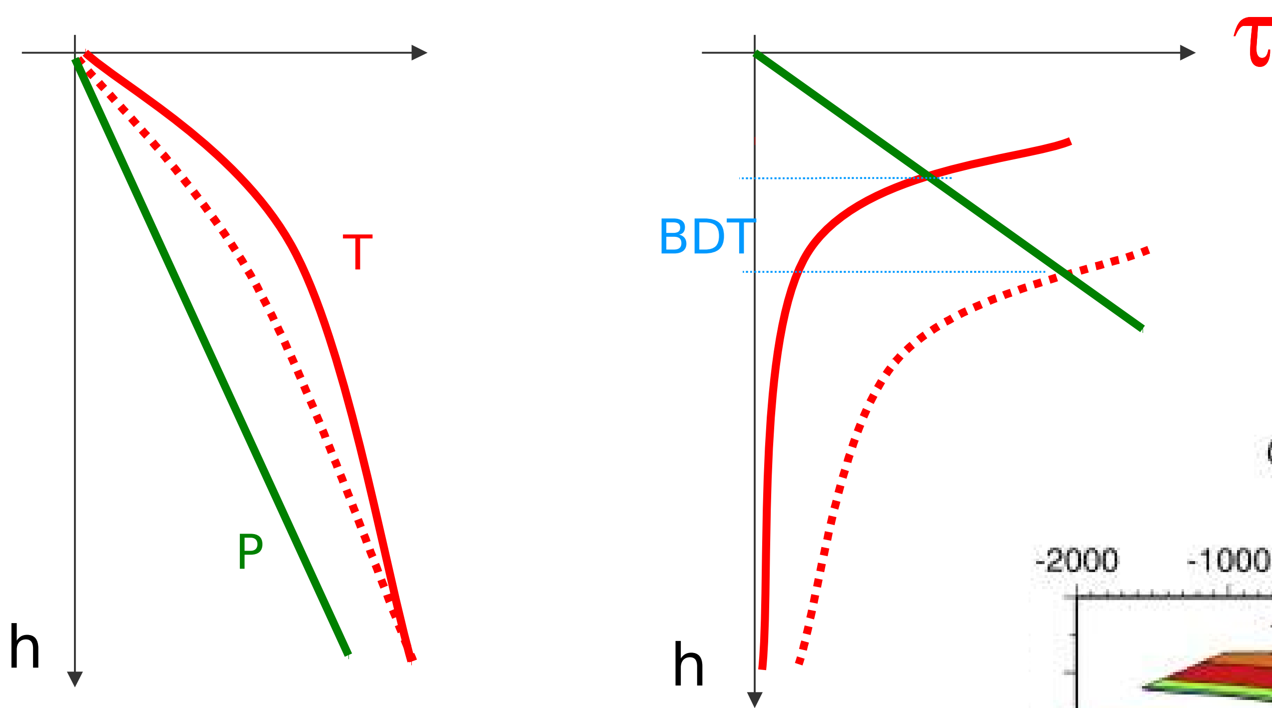
$$\dot{\varepsilon} = A_D d^{-m} \sigma^n \exp\left(-\frac{E}{RT}\right)$$

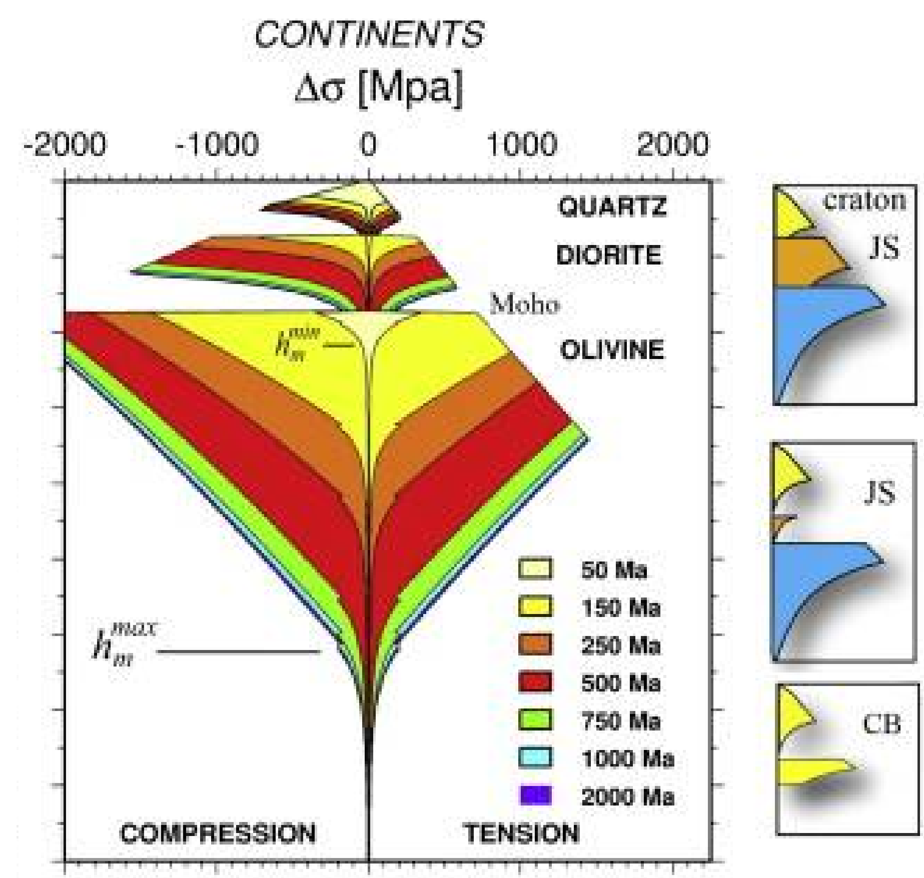
Brittle-ductile: stress-strain curves with permanent inelastic brittle and ductile deformation





Extrapolation of these laws to the lithospheric scale





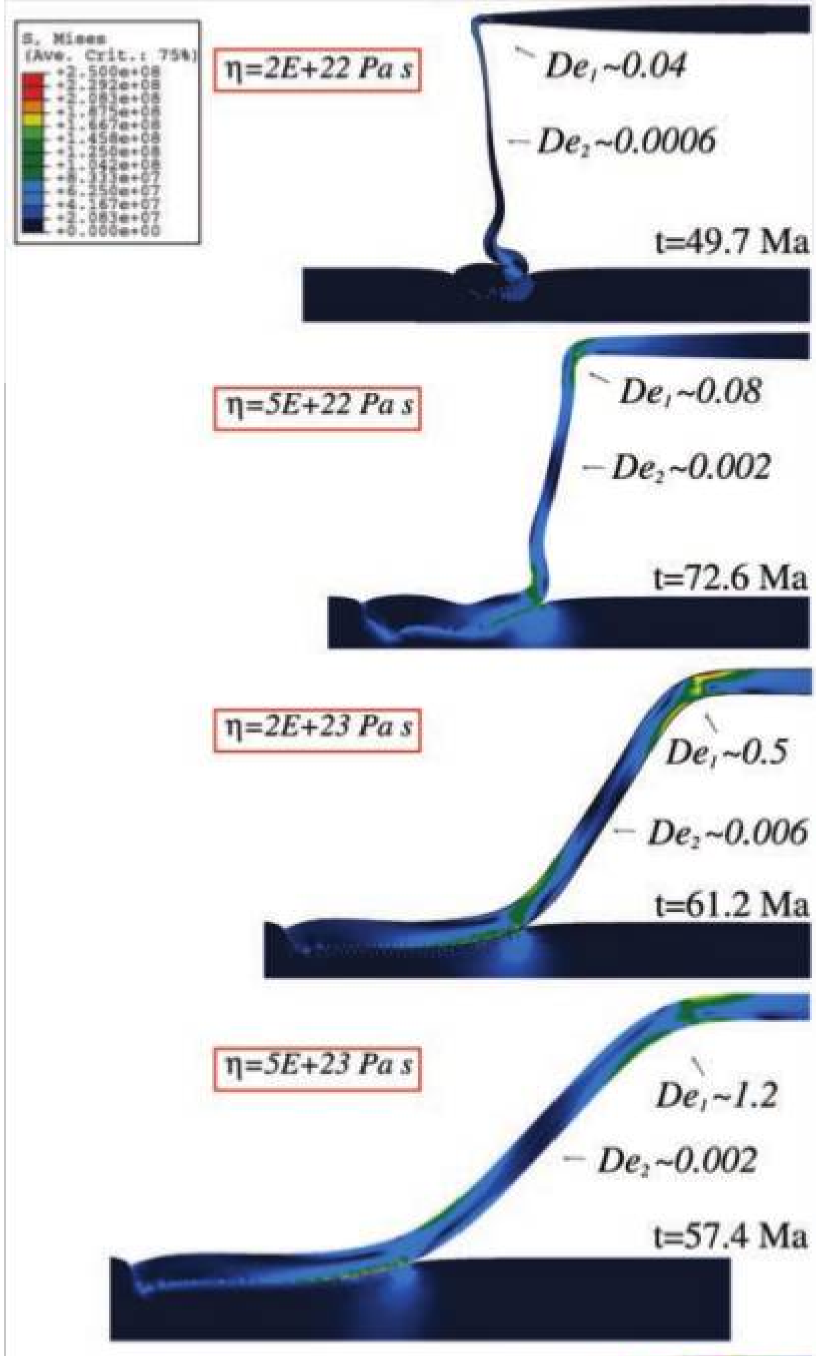
Fragile behaviour - type Byerlee

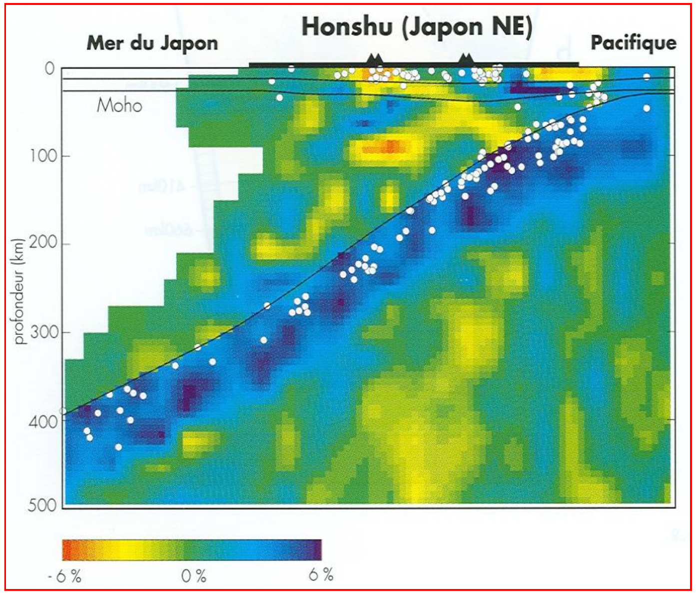
$\tau = f(P)$

Ductile behaviour- type non-Newtonian

$\tau = f(T)$

Gravitational fall of a visco-elastic slab (Morra et al., 2003)

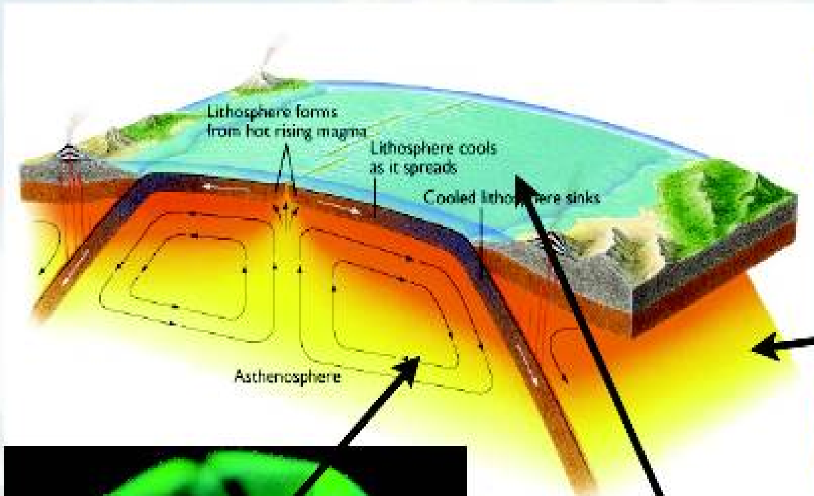


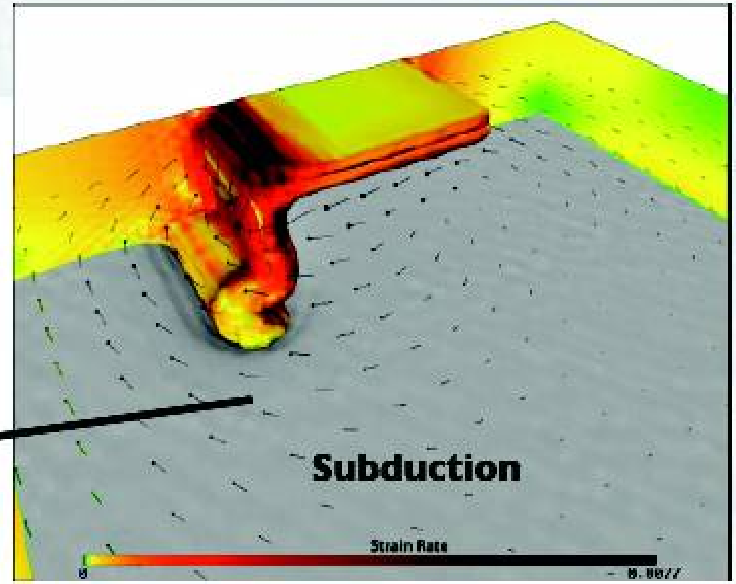


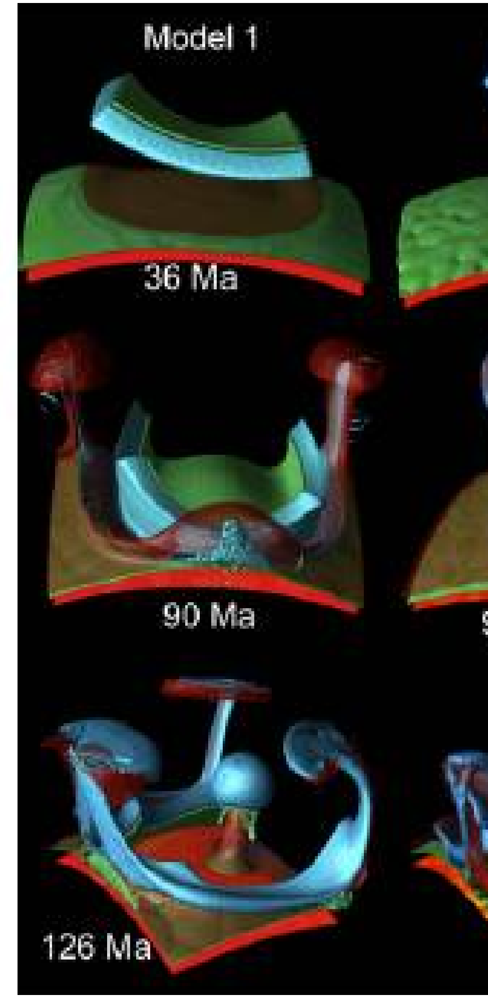
TP2: estimate strength Y in lithospheres:

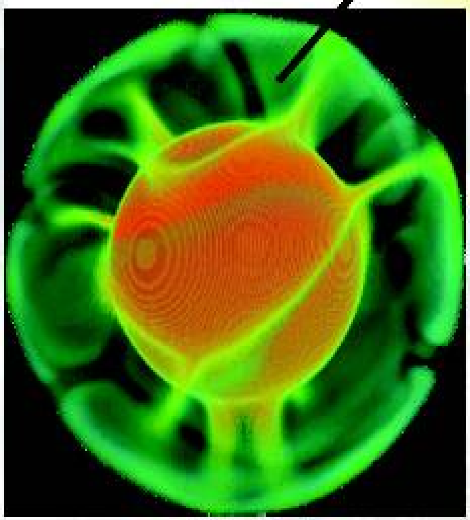
- identify composition (olivine for oceanic lithosphere)
- take thermal conductive boundary conditions (TP1)
- implement elastic-plastic yield f(P), and viscous flow laws f(P) :
  - $\tau_{ep} = \mu \cdot \sigma_n$ with $\sigma_\nu \sim P \sim \rho g h$,
  - $\tau_{vi} = (\varepsilon/A)^{1/n}.\exp(Q/RT)$, for olivine A,n,Q...
- draw the strength envelope τ (depth)
- estimate an average yield strength as Y=f(P,T), above a yield depth for which τ > 20 MPa.

Motivation

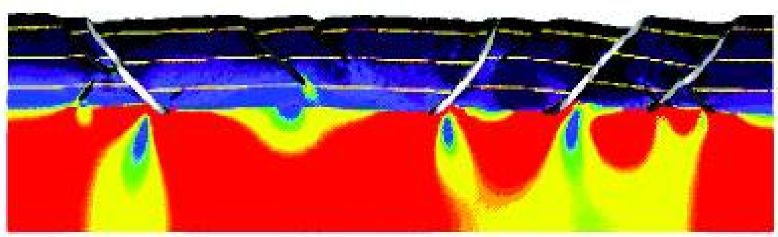




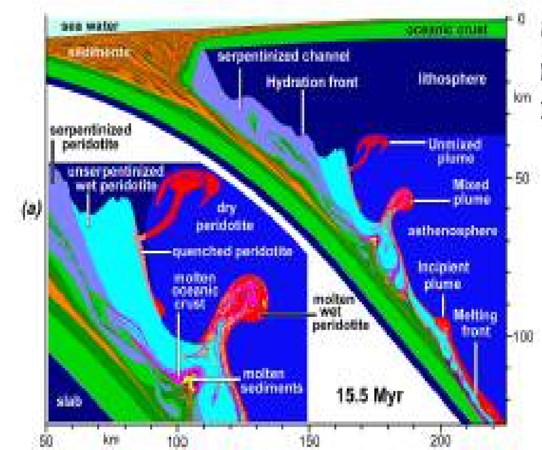




Convection in the mantle



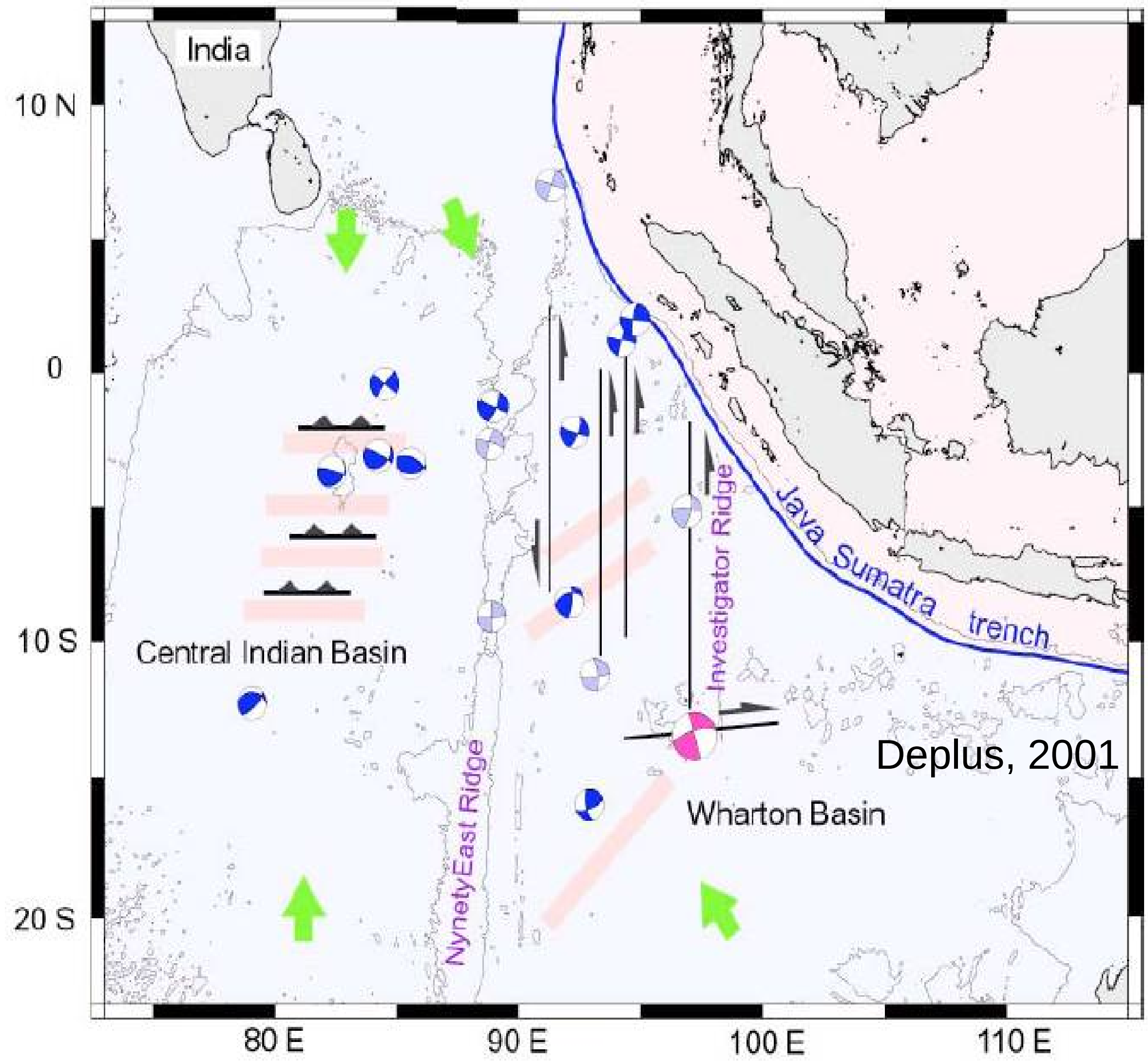
Lithospheric deformation



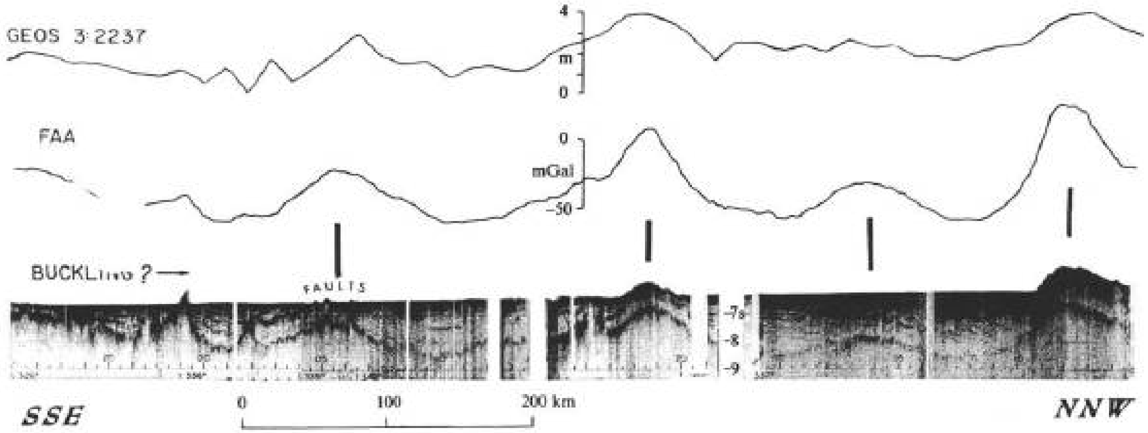
2) Diffuse vs. localised tectonic structures

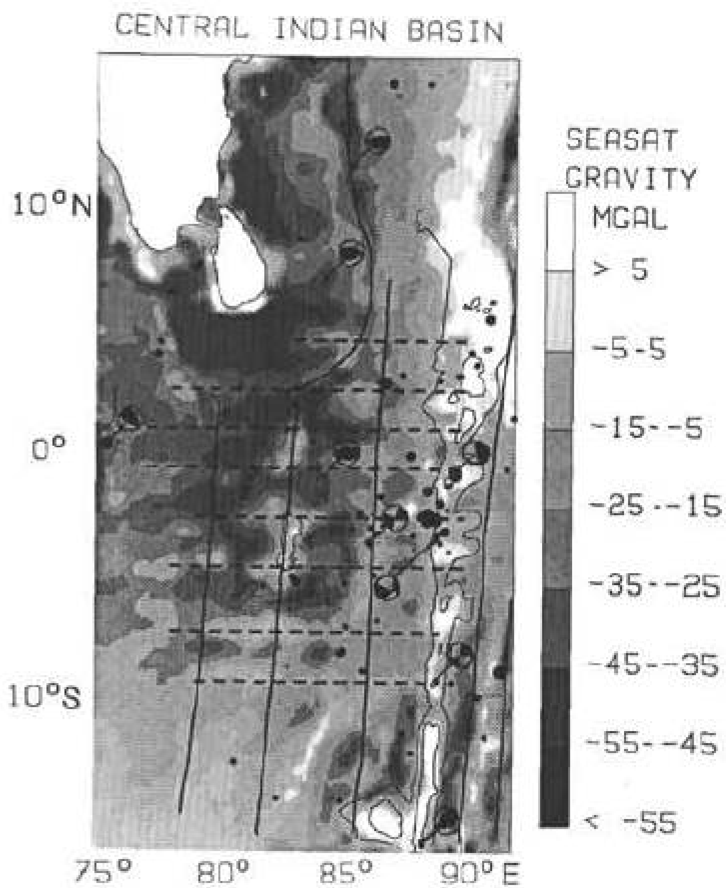
A – Diffuse buckling, the Indian ocean and other stories

1970-80: Sykes, et Weissel et al. relate seismic activity at the plaet center (magnitud 6 at 42 km depth) to a distributed compressional deformation : which cause ?

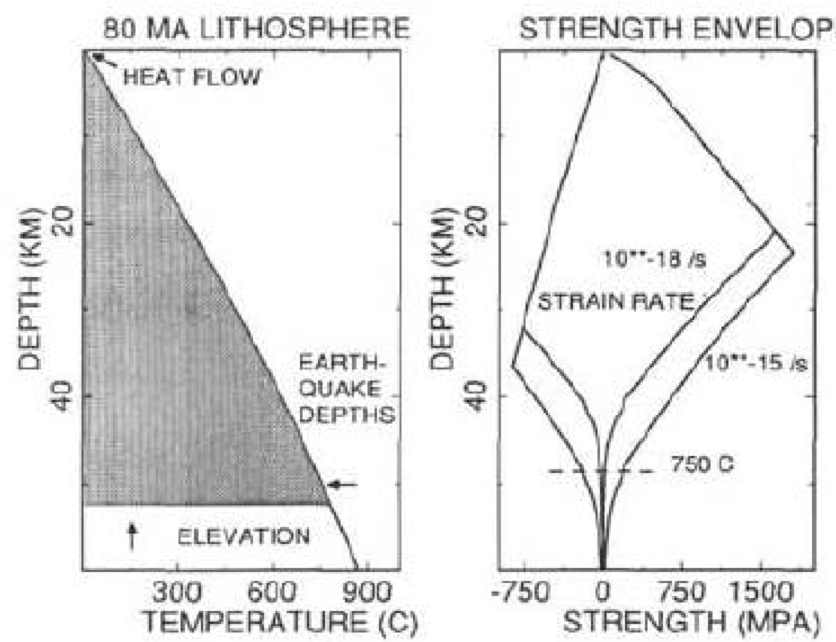


Periodical gravity anomalies



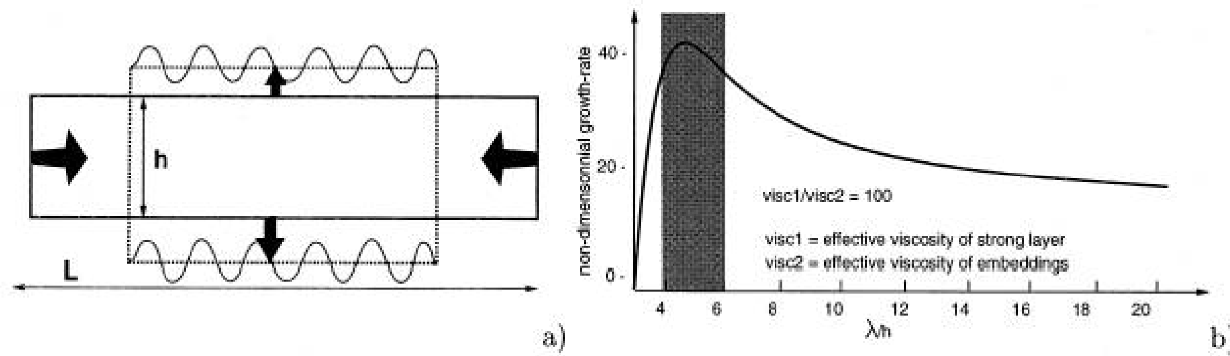


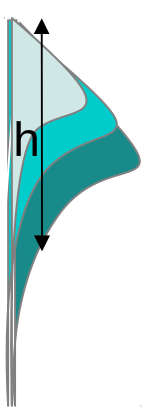
State of compressive stress

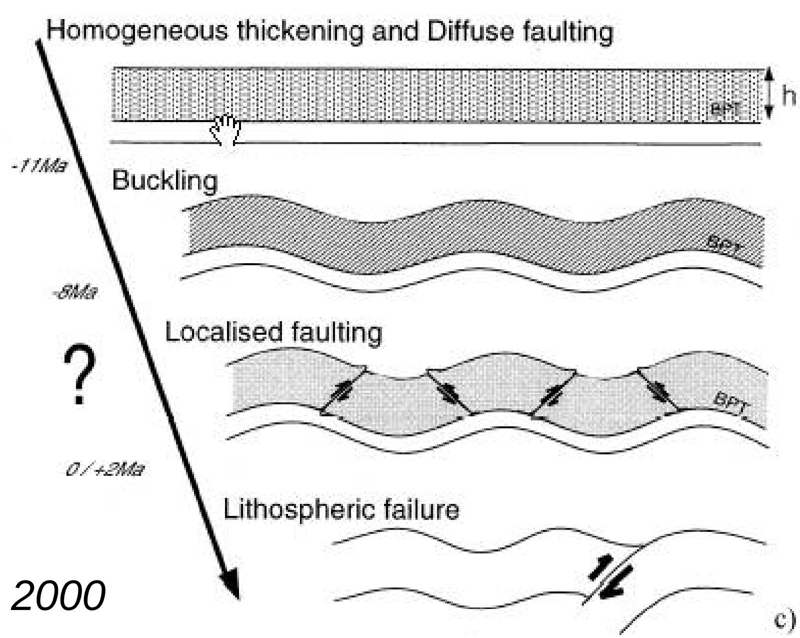


Lithospheric Buckling/folding

Elastic or viscous buckling are impossible because the timing (100Myrs) and/or the stresses (5GPa) necessary are unrealistic for the geological scale.
McAdoo & Sandwell (1985) develloped the concept of « plastic» buckling: the stress cannot increase despite continuing convervence, therefore the medium cannot continue to deform in a uniform manner. A buckling instability develops, with a wavelength linked with the layer thickness : $\lambda \sim 3\text{-}6h$

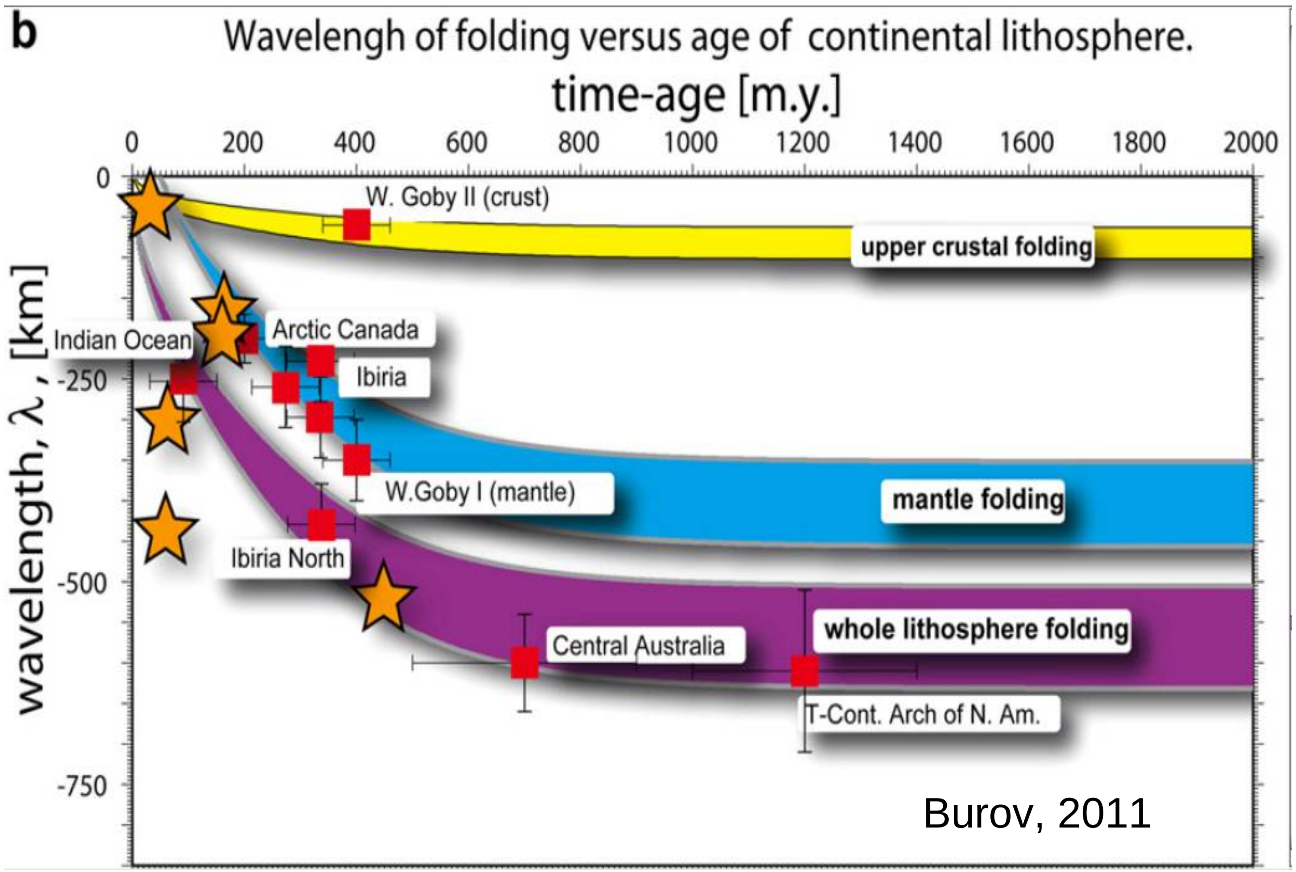




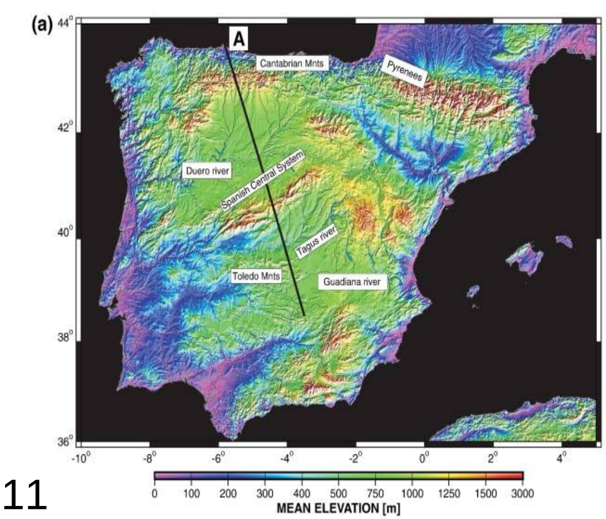


Gerbault, 2000

Resistant layers of the lithosphere buckle according to their strength and thickness, which depends on theirthermal state.

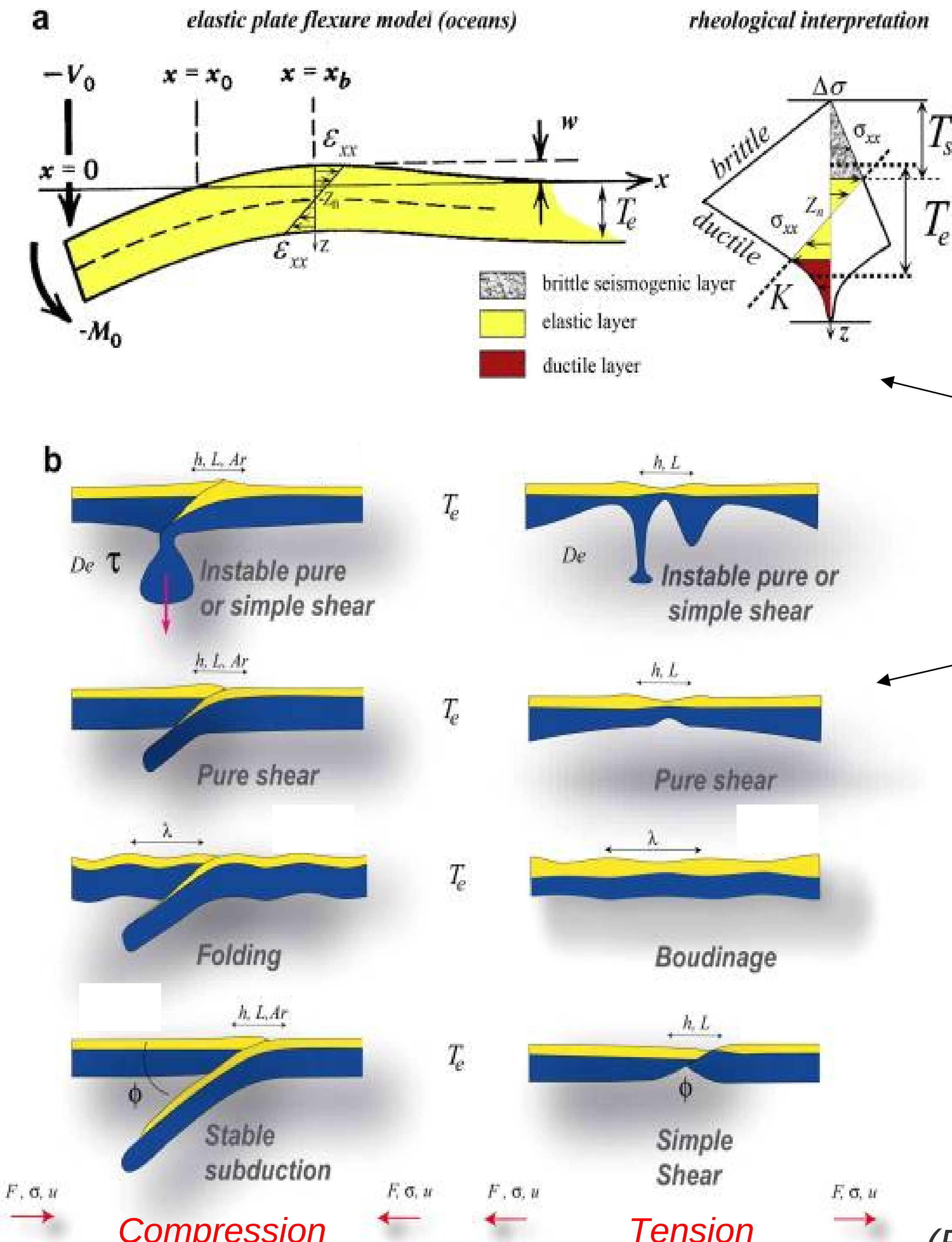


Burov, 2011



Cloetingh et al., 2011

Modes of deformation in Earth-like lithospheres



Lithospheric flexure is related to the response of the lithosphere to the vertical gravitational forces (Turcotte & Schubert, 2002).

Under large scale horizontal forcing F, relaxation and growth time of Rayleigh-Tailor or buckling instabilities are related to viscosity contrasts in the lithosphere.

h, L : vertical and horizontal scales for process induced topography,
λ : characteristic wavelength of deformation,

Argand number Ar = ρghL/F.

(Burov, 2005; Burov & Yamato, Lithos, 2008)

2 Gyrs ago, the Earth was hotter ...
=> smaller viscosity contrast …
=> were there subductions ?

F. Cagnard et al. / Precambrian Research 187 (2011) 127–142 139

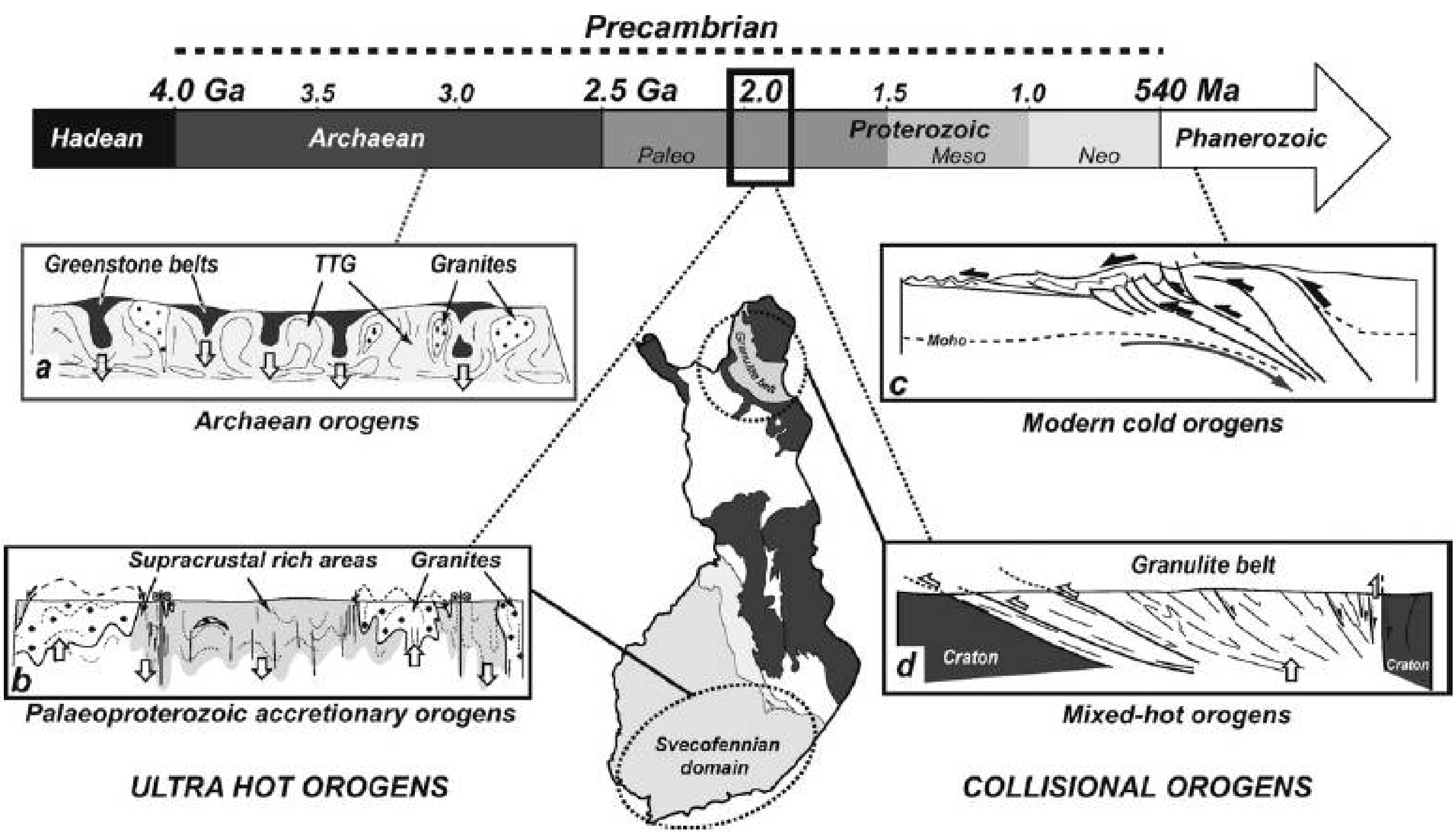
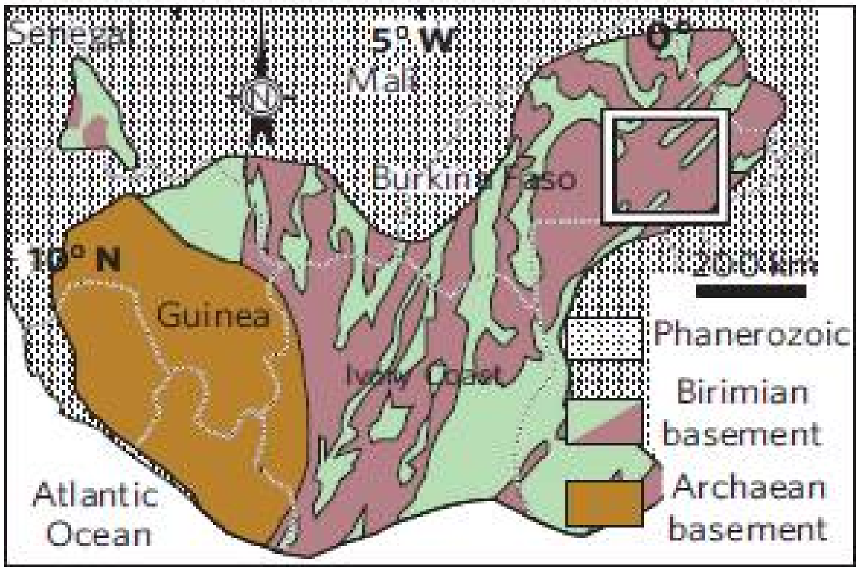


Fig. 9. Schematic cross sections illustrating different orogenic styles developed through time. (a) and (b) Archaean and Palaeoproterozoic accretionary orogens (modified after Choukroune et al., 1995; Cagnard et al., 2007). (c) Modern-type orogen. (d) Mixed-hot orogen (this study). Schematic map of Finland is modified after Korsman et al. (1997).

West african craton : folds or subduction ?



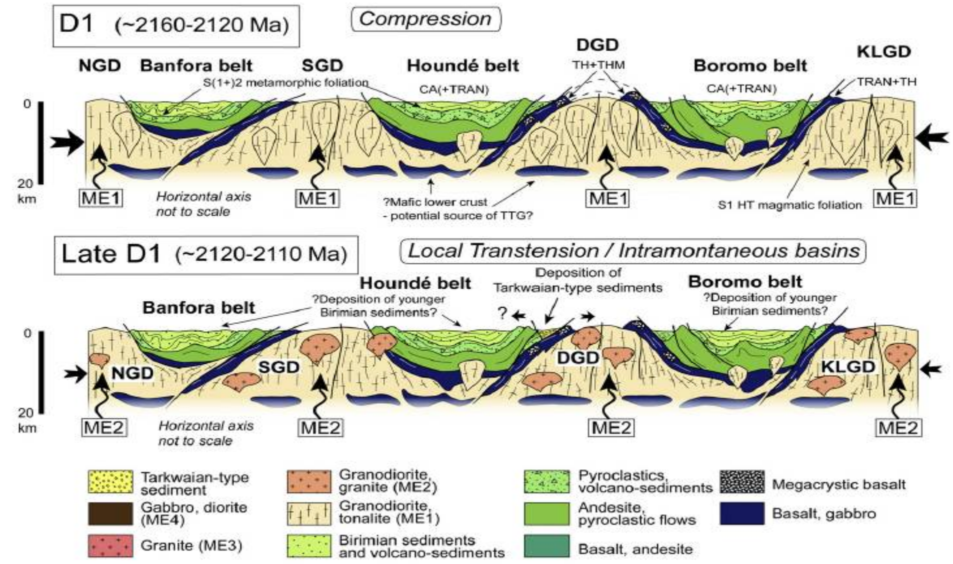
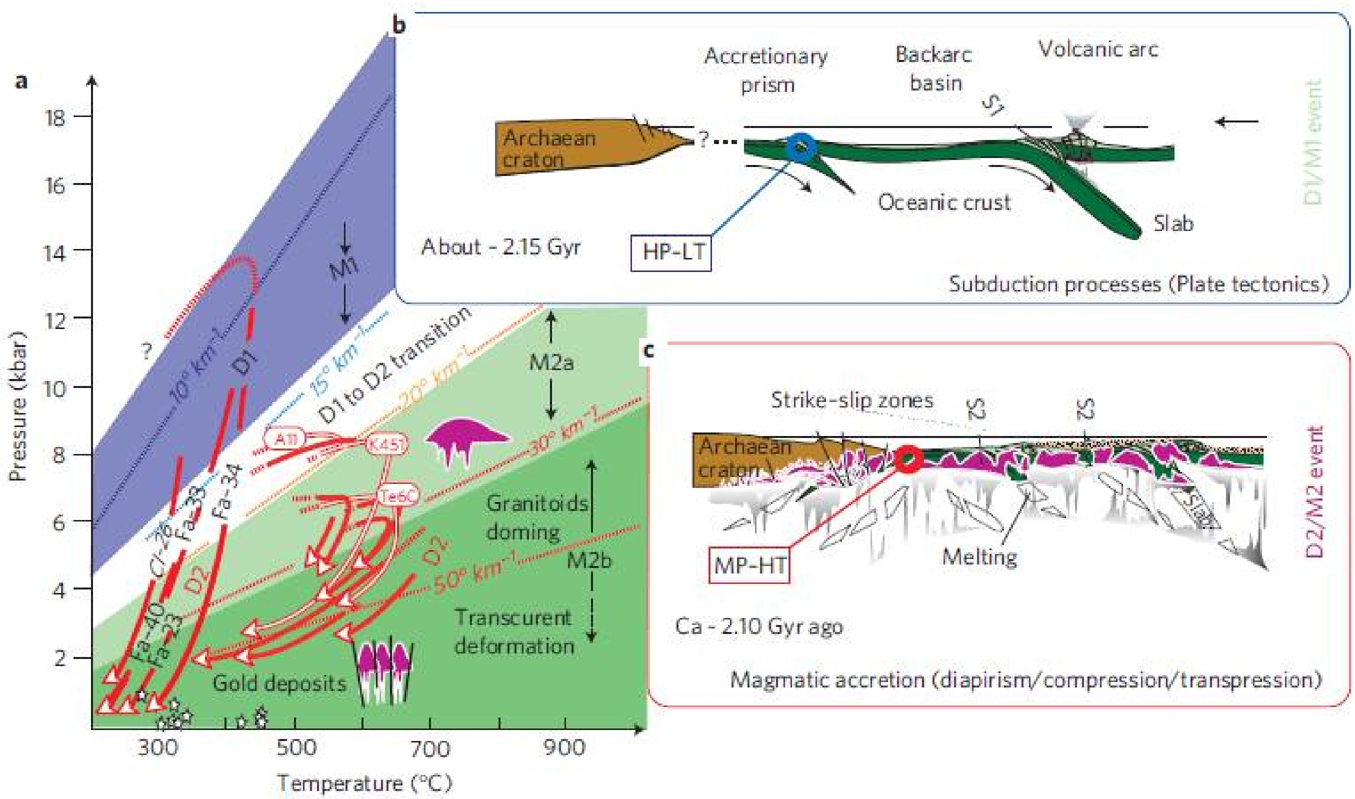


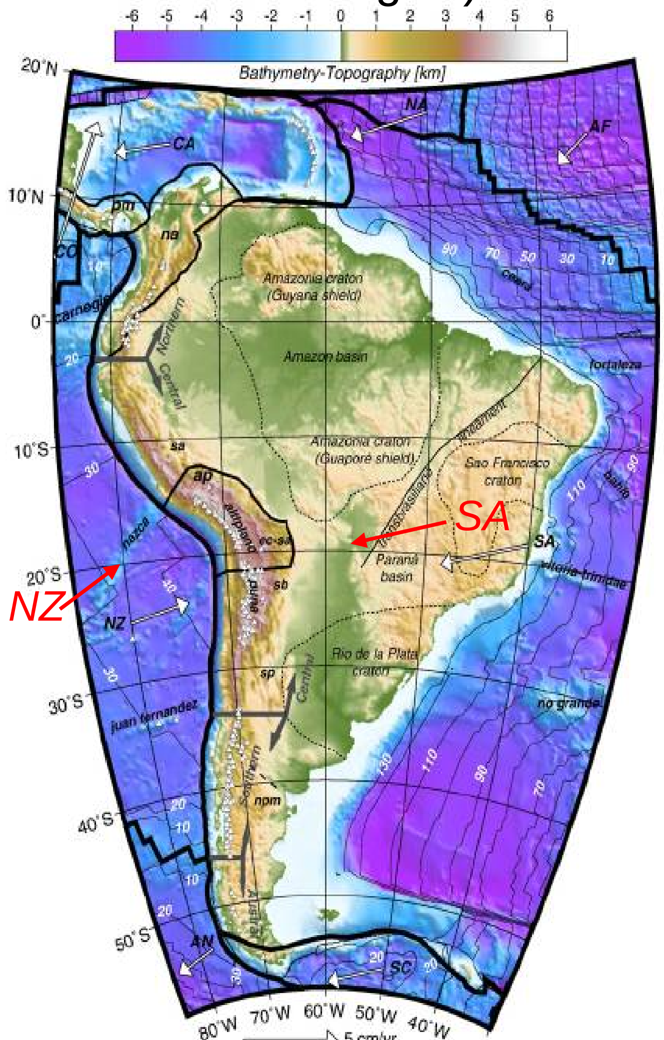
Fig. 14. Tectonic scenario for western Burkina Faso during the Eburnean orogenesis. The surface corresponds to the present-day erosional level.



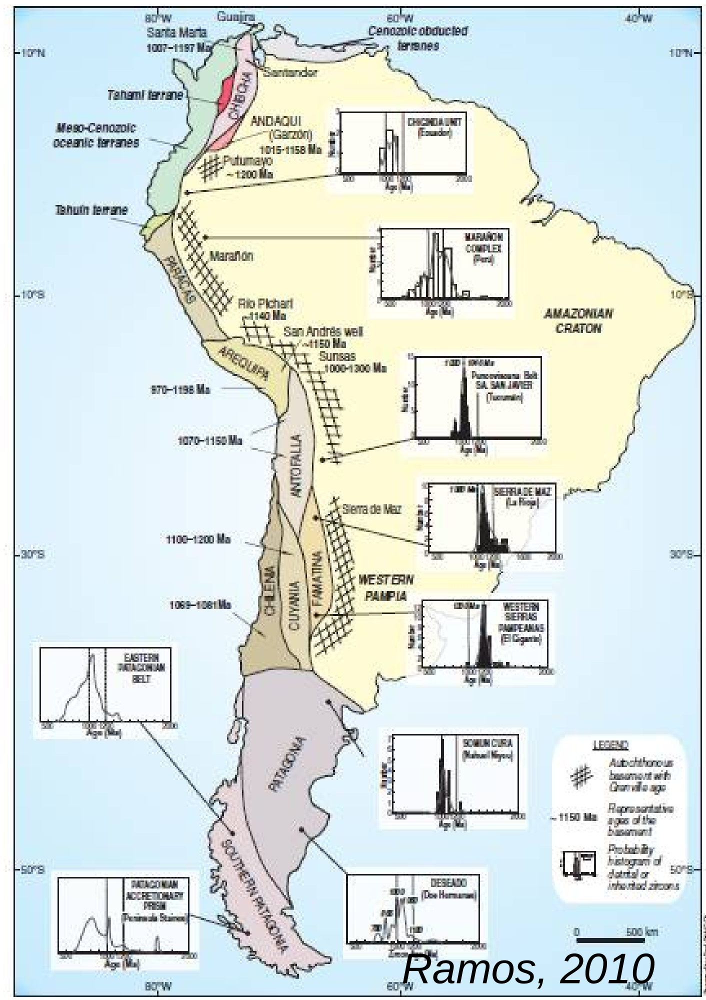
Baratoux et al., 2011,
Ganne et al., 2011,
etc ...

B- Large-scale localised deformation : Subduction : the Andes and other stories

Nazca subducts under south America at 7 cm/yr
(vitesse de croissance des ongles)



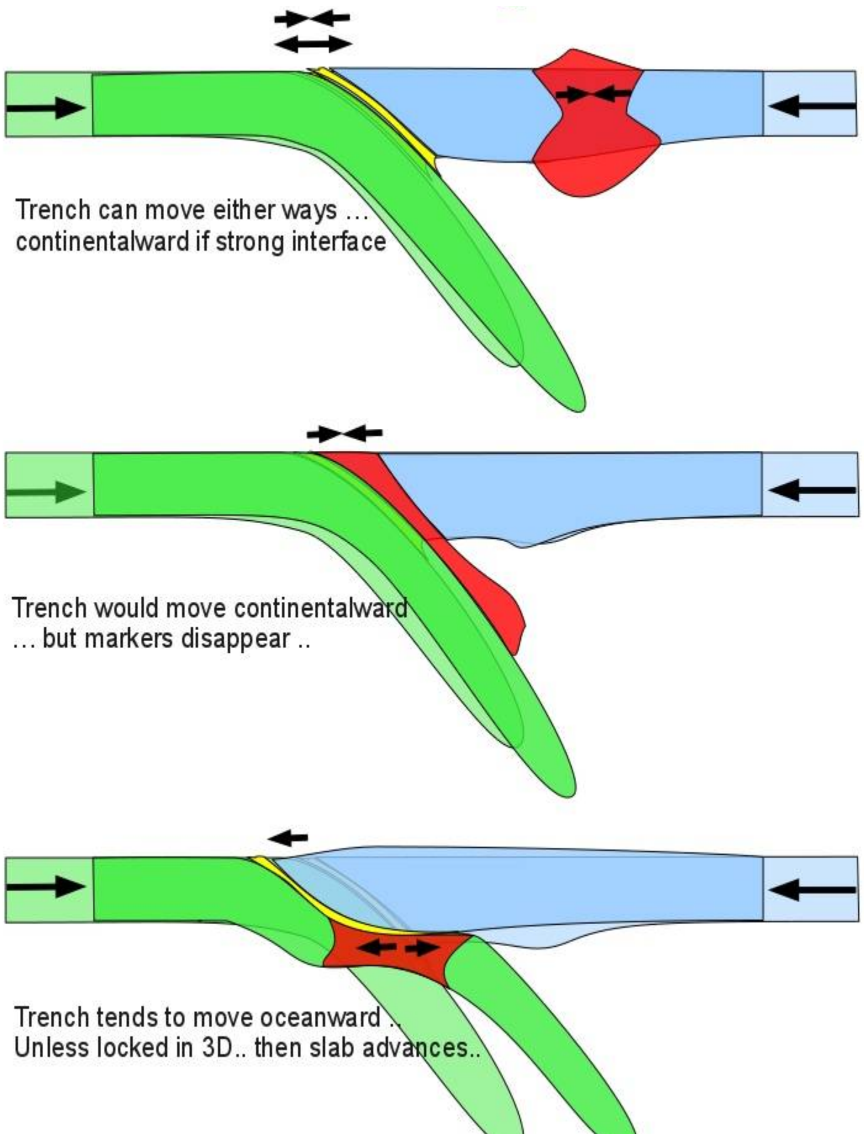
Tassara, 2012



Ramos, 2010

Topography, changes, slab depth changes, geology (behaviour) change

La convergence entre plaques s' accomode par du raccourcissement là où elles sont le plus faible mécaniquement



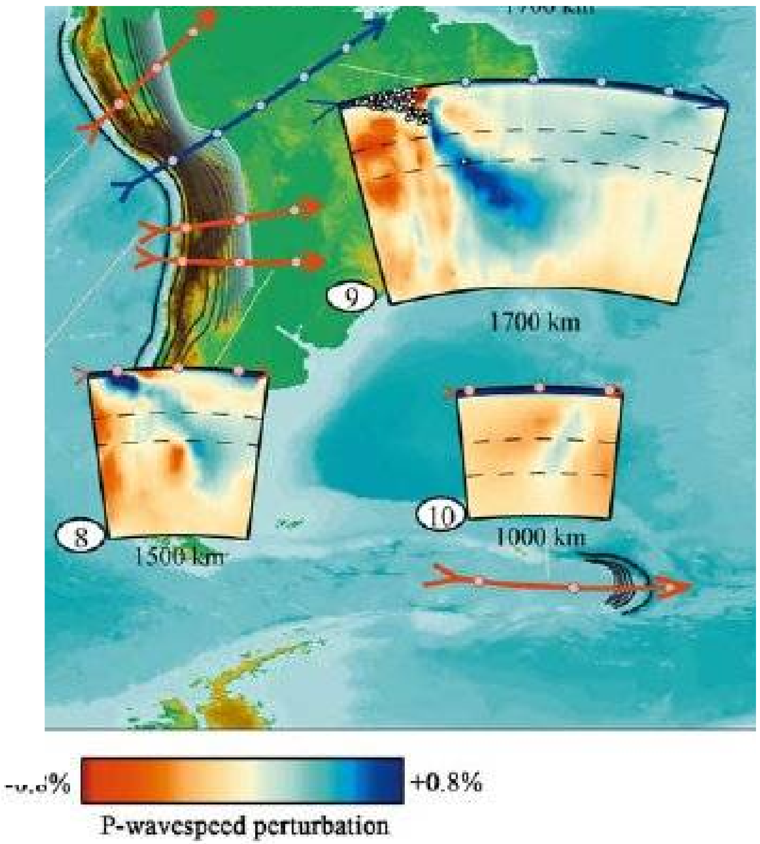
a) un arrière arc faible
> déformation intraplaque
(plus distribué).

b) une faible friction d'interface
> glissement relatif au contact
(plus localisé).

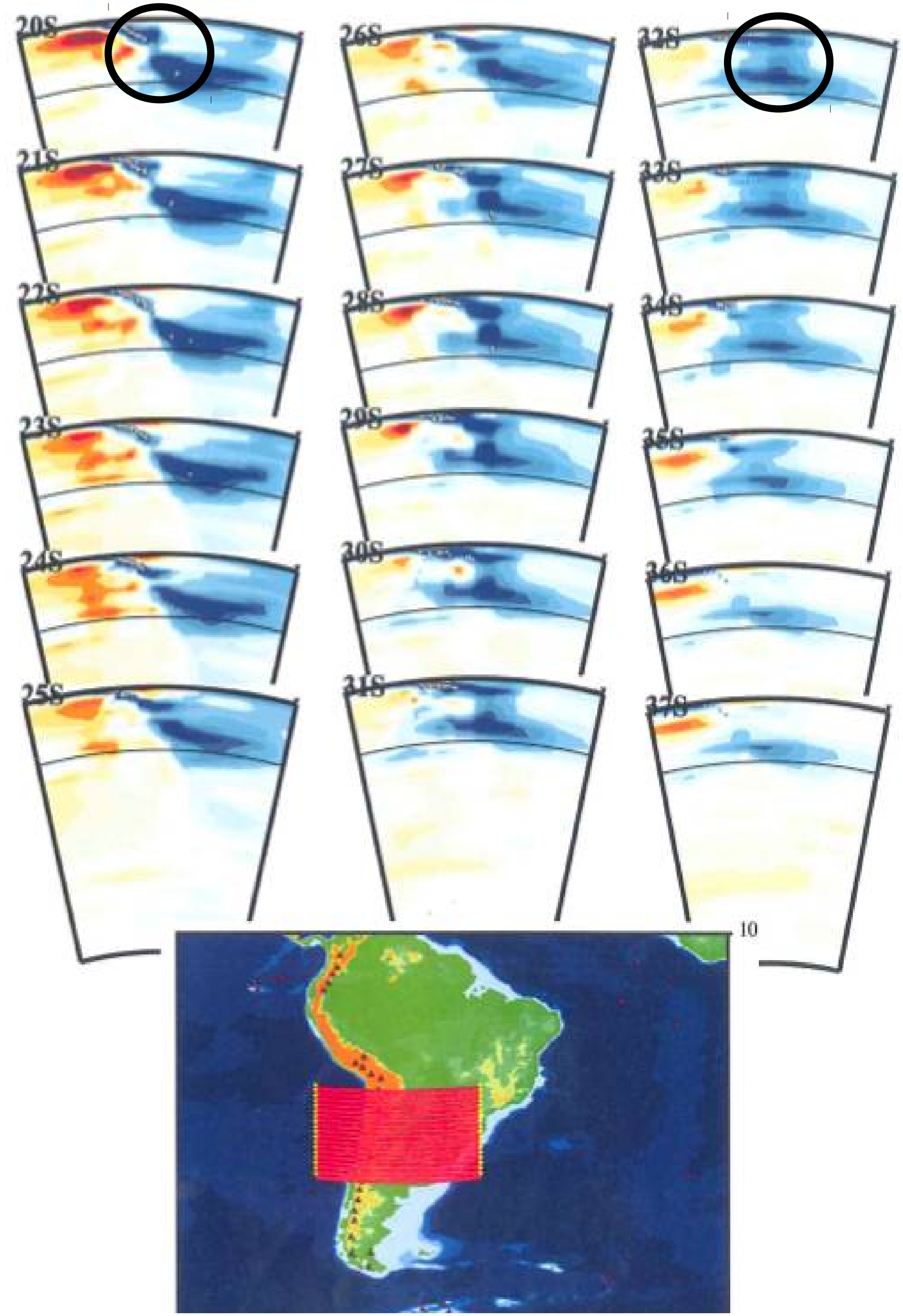
c) un slab faible
> se déforme/ se rompt

Seismic tomographies are blurry
.. what is the slab doing ?!

- below 600 km (Li et al., 2008)
- or not (Fukao et al., 2009) ?

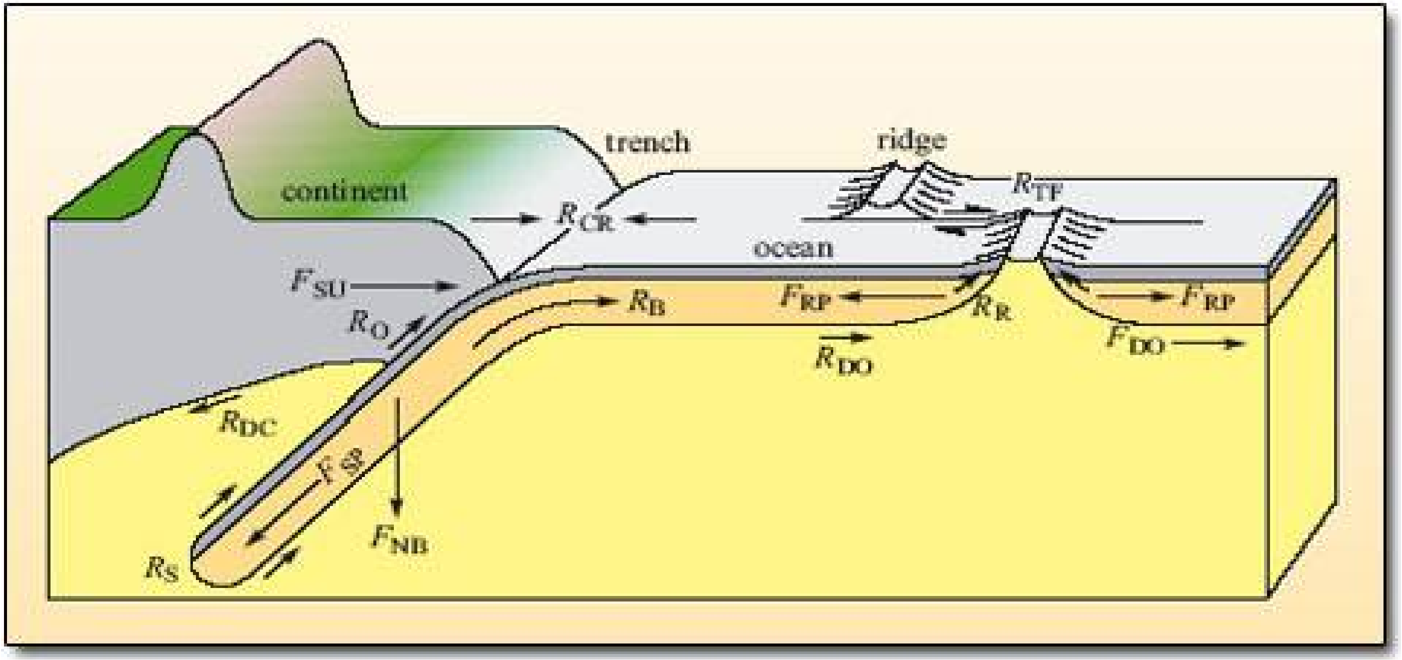


Li et al., 2008



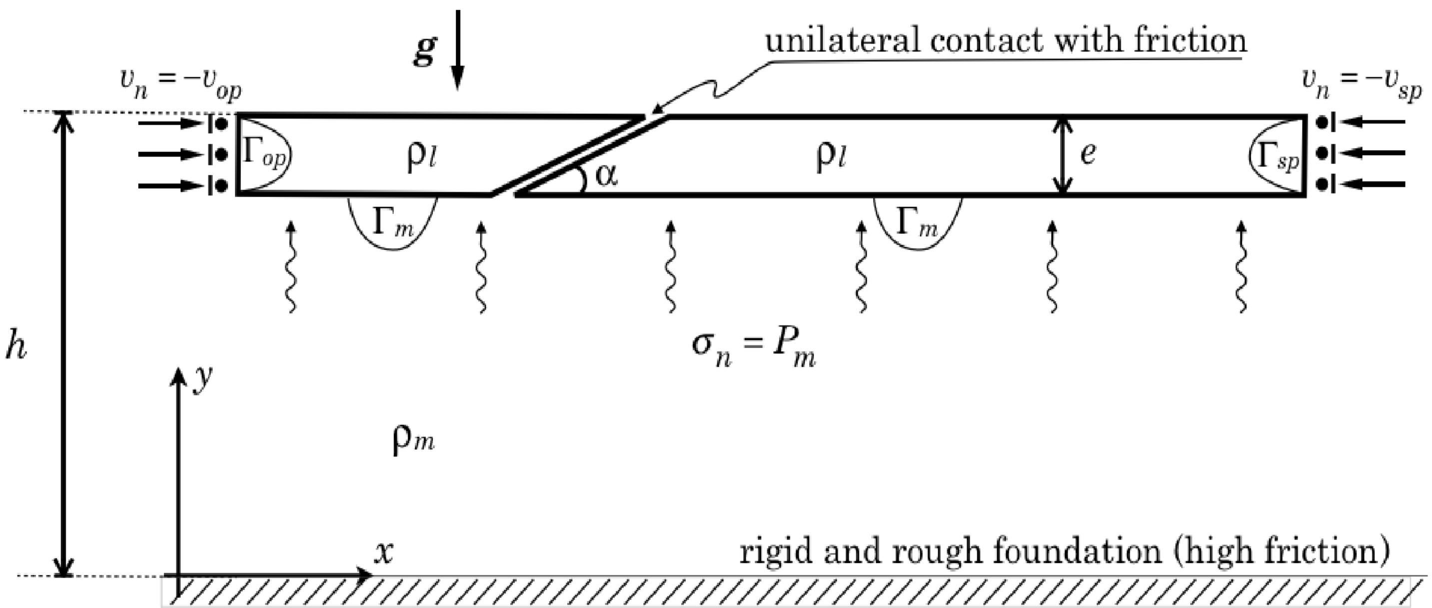
Pers.comm. M. Obayashi (from Fukao et al., 2009)

Our work (Gibert, Gerbault, Hassani, Tric, 2012)



Forces involved

- Driving Forces *Fi*
- Resisting Forces *Ri*.

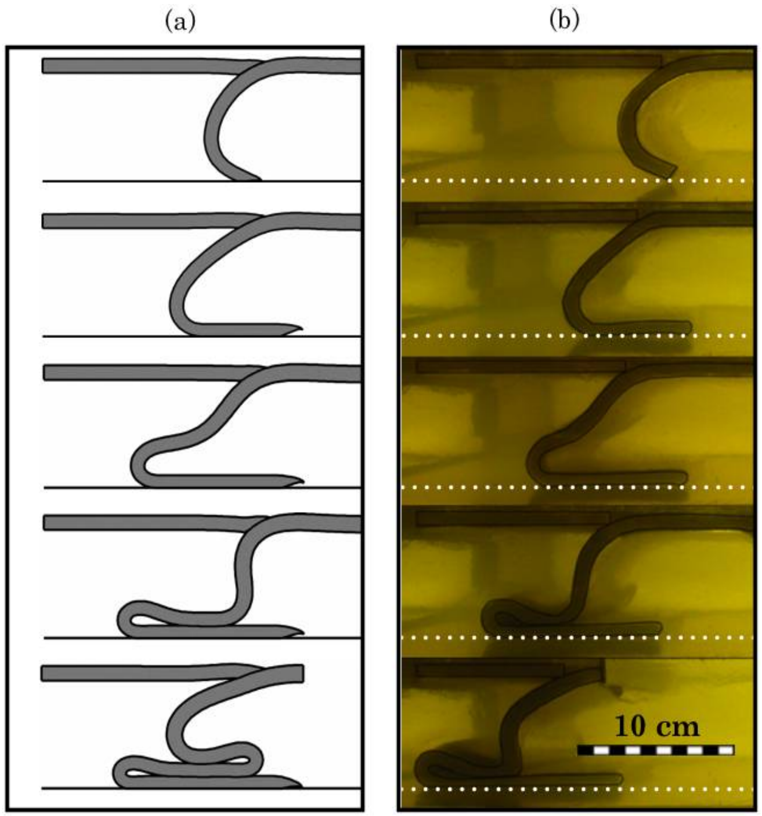


Hypotheses of the model:

- Imposed plate motion *Fop, Fsp*
- Inviscid mantle Rd=0
- Impenetrable discontinuity at 660km depth.

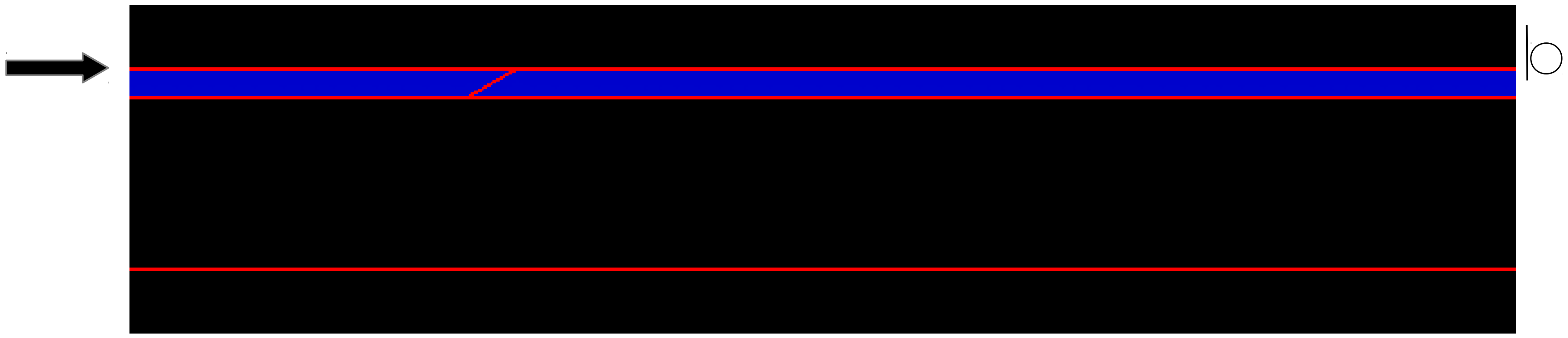
Numerical model :

ADELI (Hassani et Chery, 1998) Dynamical Relaxation with FEM.



Comparison of the numerical and analog models (Guillaume et al., 2009):

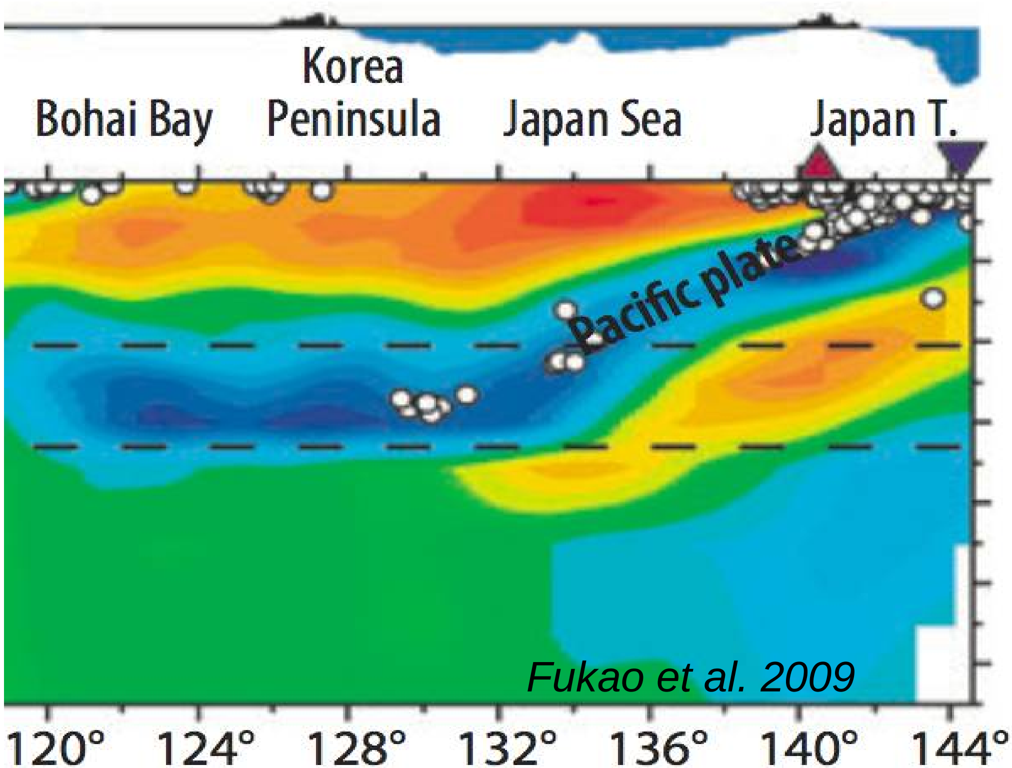
Very similar evolution, except
- fixed trench in a)
- basal friction is fixed in a).



4 modes of subduction appear depending on plate boundary velocities :
* Style 2 : $v_{op} < 0$ → the slab lies backwards (/forward)
* Cyclicity: $v_s = v_{sp} + v_{op} > |v_{op}|$ → the slab lies and folds (/does not fold)

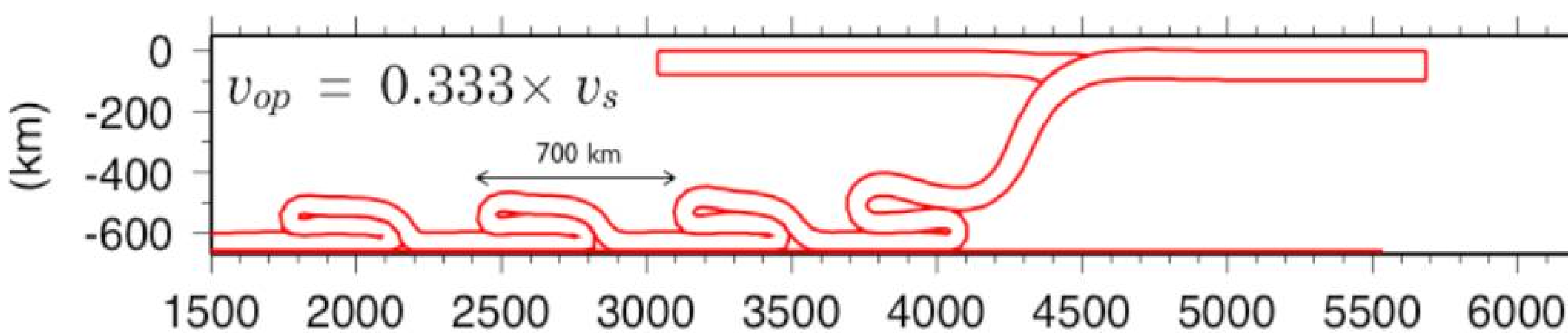
Application to – a) Pacific/Eurasia

Current velocities (Nuvel-1A) : v_{op}=2.2cm/yr (Eurasia) v_{sp}=6.5 cm/yr (Pacific)



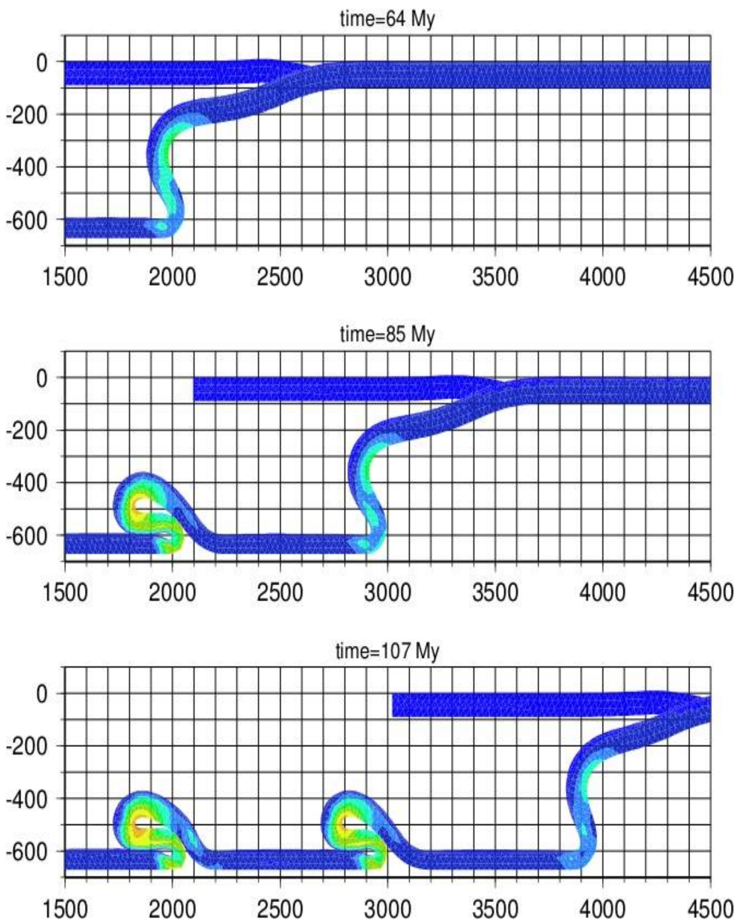
Fukao et al. 2009

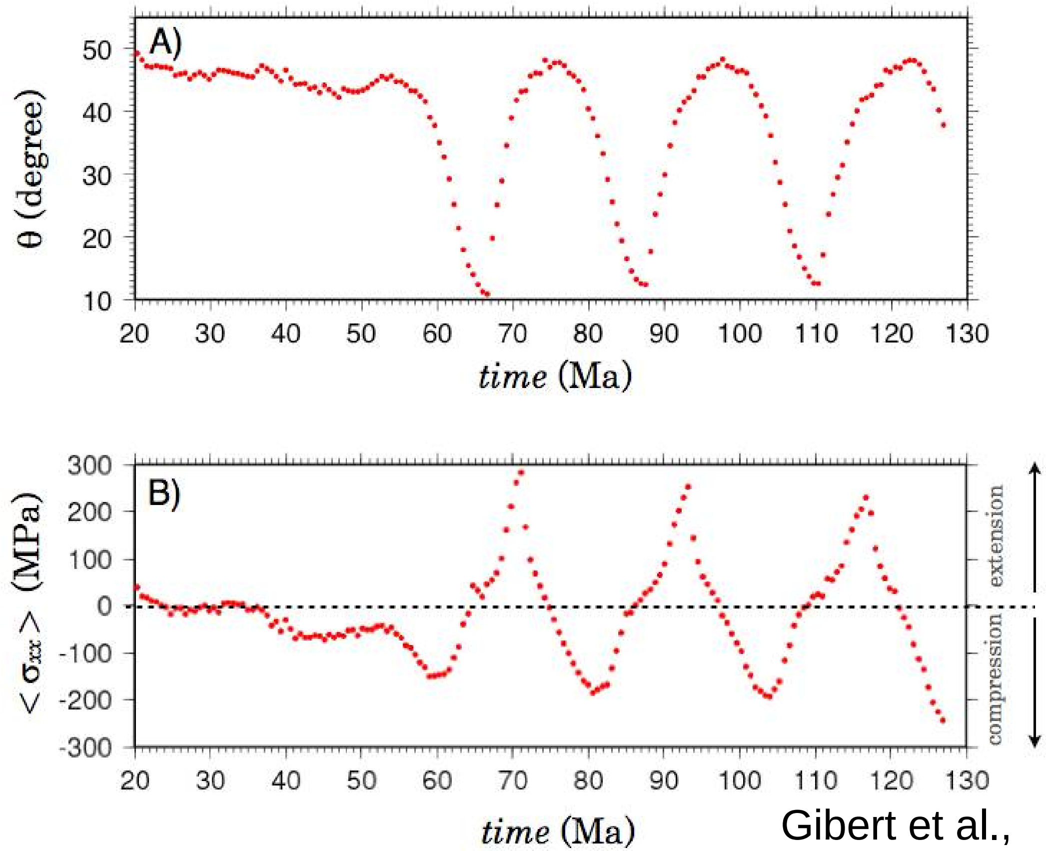
Le slab Pacifique sous la Chine semble avoir une double épaisseur sur la discontinuité à 660 km: plissements ou bien diffusion du signal tomographique ?



Application to cases – b) The Andes

Current velocities (Nuvel-1A) : v_{op}=4.3 cm/yr (South america) v_{sp}=2.9 cm/yr (Nazca)





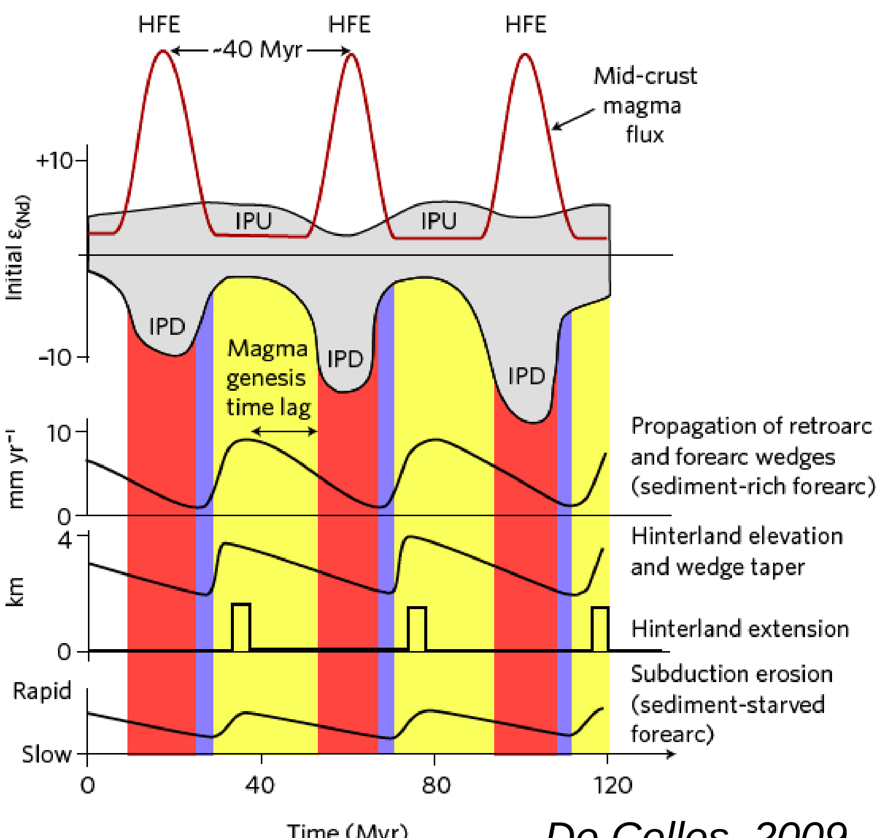
Gibert et al., GJI.2012

* Cycles are of ~22Ma and flat slope (10°) holds for ~4.3Ma (periods of volcanic gaps).
* The differences between the model and observations (slope, timing) may be explained by the assumption of a) constant slab viscosity and b) neglection of mantle viscosity .

Temporal variations in arc volcanism, slab geometry, ...

Simultaneous periods of topography construction and magmac activity over ~40 Ma.

Related to changes in the slab's slope (De Celles, 2009, Haschke, 2007; Ramos, 2010).



De Celles, 2009

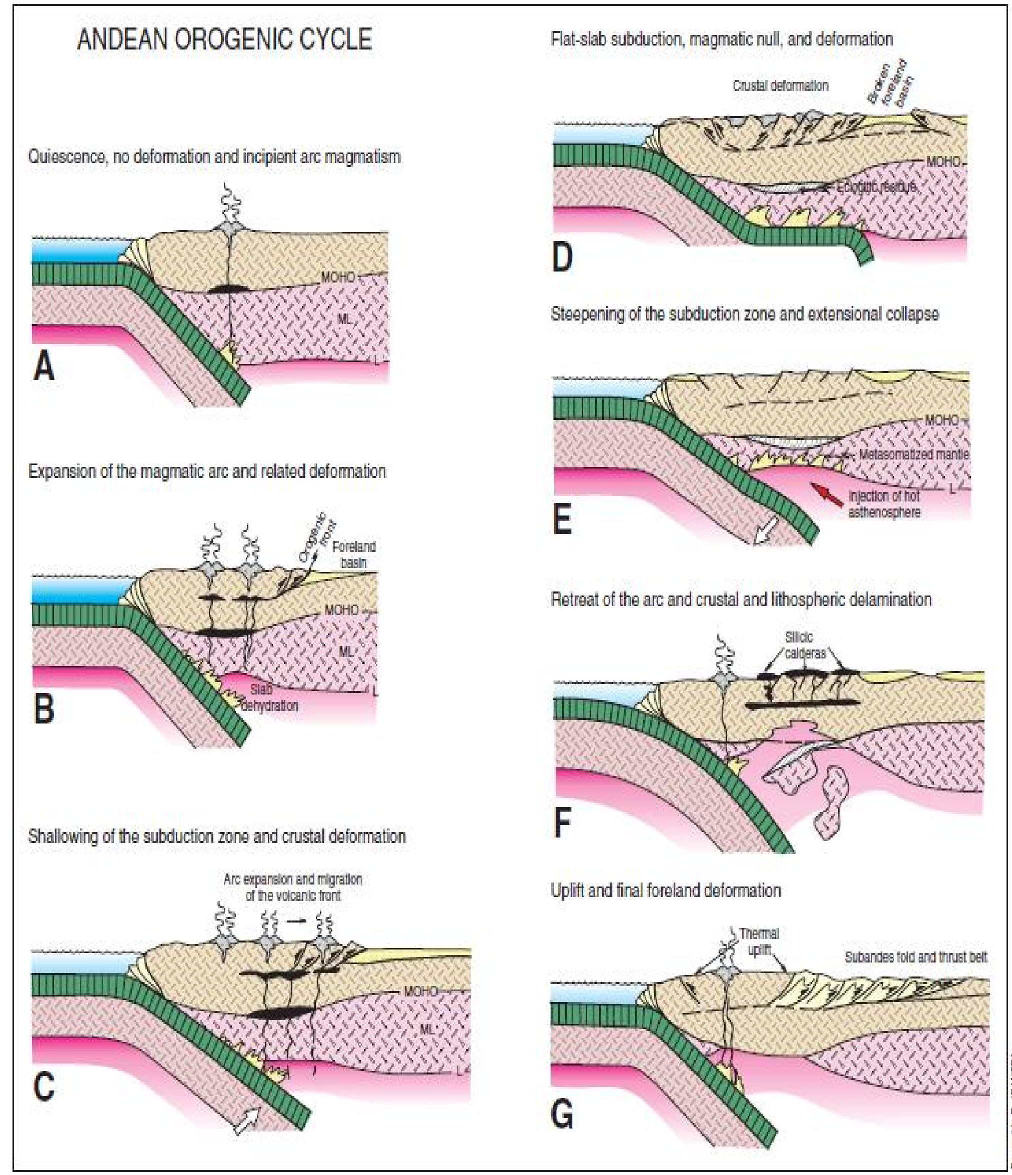


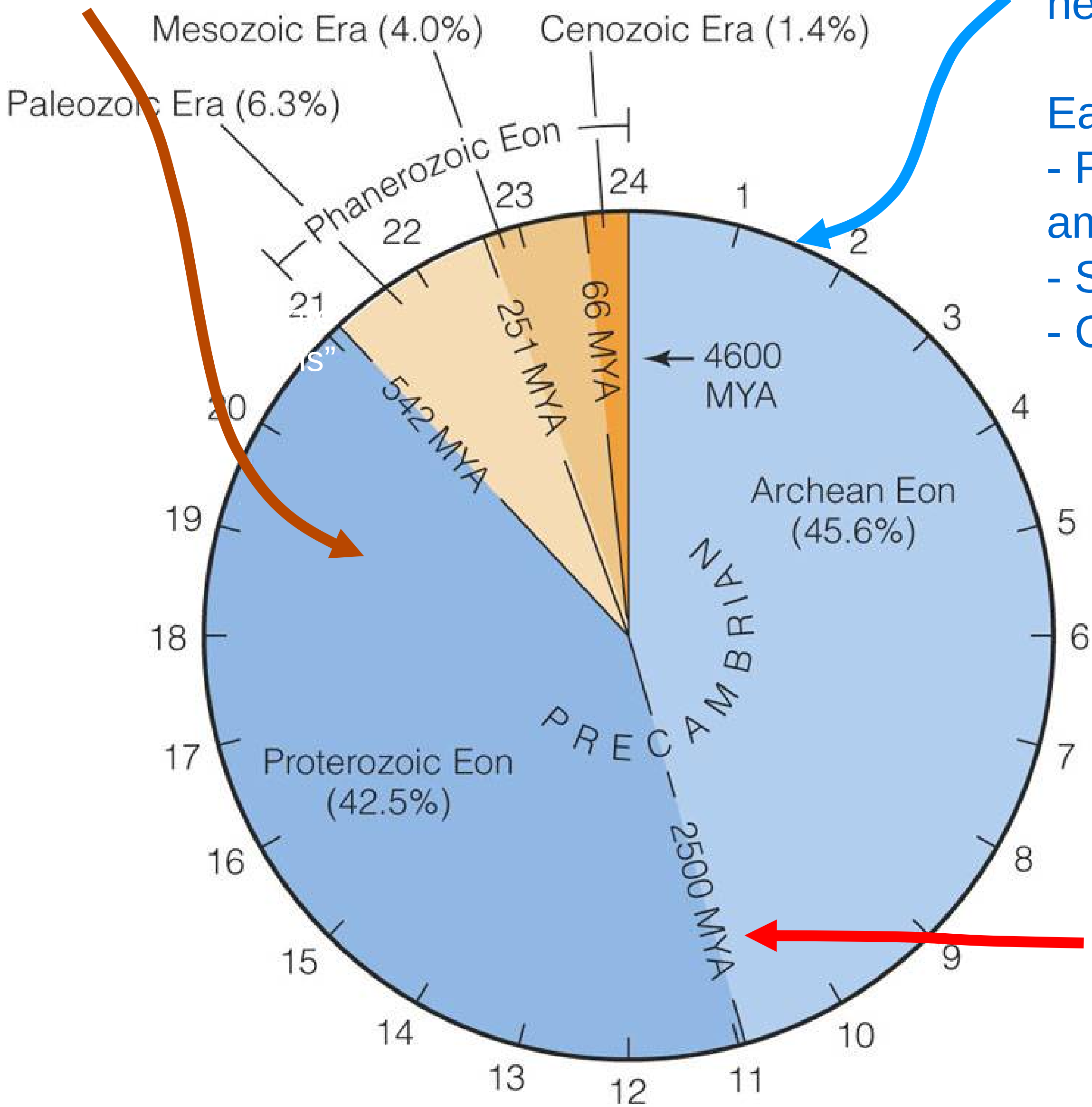
Figure 17. Idealized tectonic evolution of an Andean orogenic cycle (based on many authors; see discussion in the text). ML—lithospheric mantle

Ramos, 2010

3. Heat production decreased and slowed mantle convection
- larger convection cells
- larger plates travel farther and cool more
- Subduction and modern plate tectonics

1. Period of accretion ~10-30Ma; and then heavy bombardment

Early plates became bigger and thicker
- Recycling of oceanic crust formed large amounts of buoyant continental crust.
- Separation of Si from Mg and Fe
- Conversion of mafic to felsic material



2.Archaen-Proterozoic transition To modern plate tectonics: Period of rapid crustal growth


© 2001 Brooks/Cole Publishing/ITP

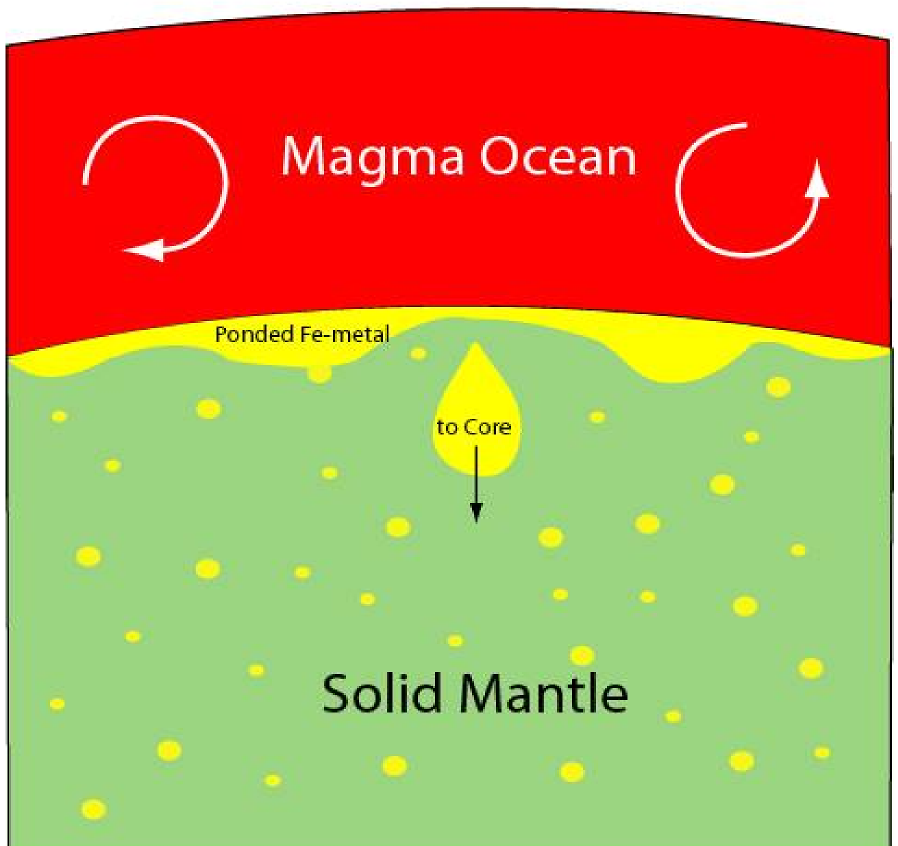
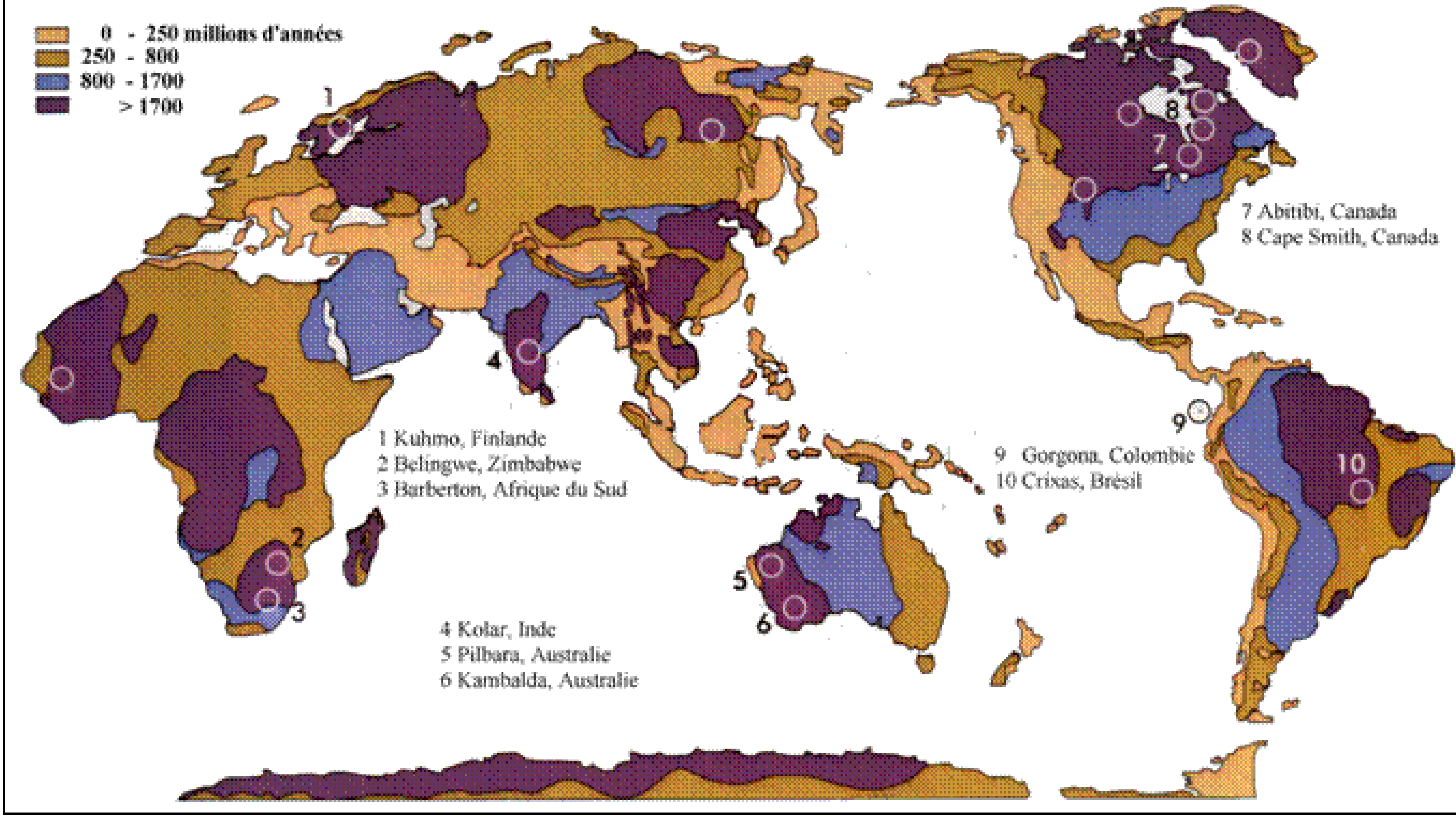
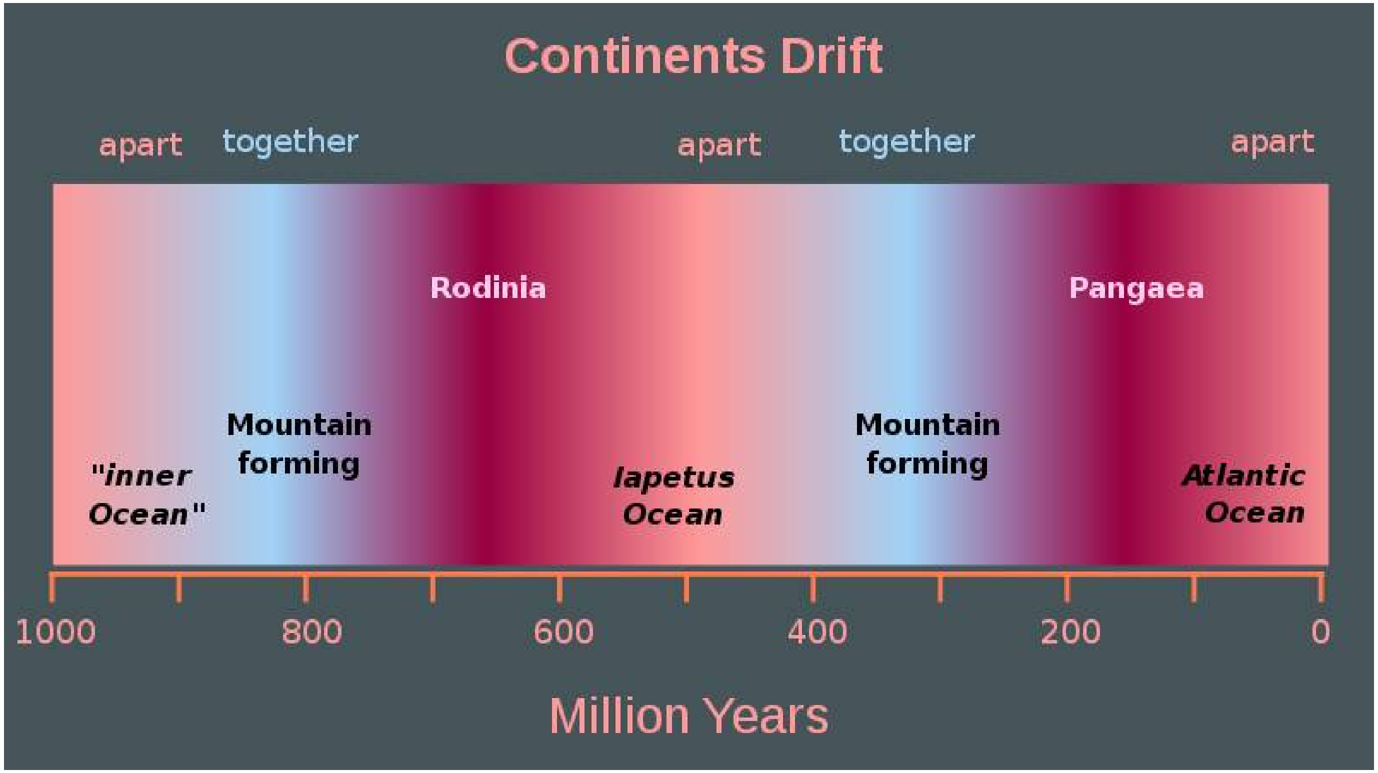

Magma Ocean
Ponded Fe-metal
to Core
Solid Mantle

Fig. 27 : l'âge de la croûte continentale ; les ronds représentent les pointements connus de komatiites



La komatiite est une roche volcanique ultramafique (ou ultrabasique) à olivine et pyroxène. Elle tient son nom de la rivière Komati, en Afrique du Sud. Leur formation implique un taux de fusion partielle pouvant atteindre 50 % et des températures de fusion de l'ordre de 1600-1650°C (contrairement aux 1250-1350°C des basaltes actuels). Elle est aussi très riche en MgO (18 à 35 % soit trois à quatre fois plus qu'un basalte classique).

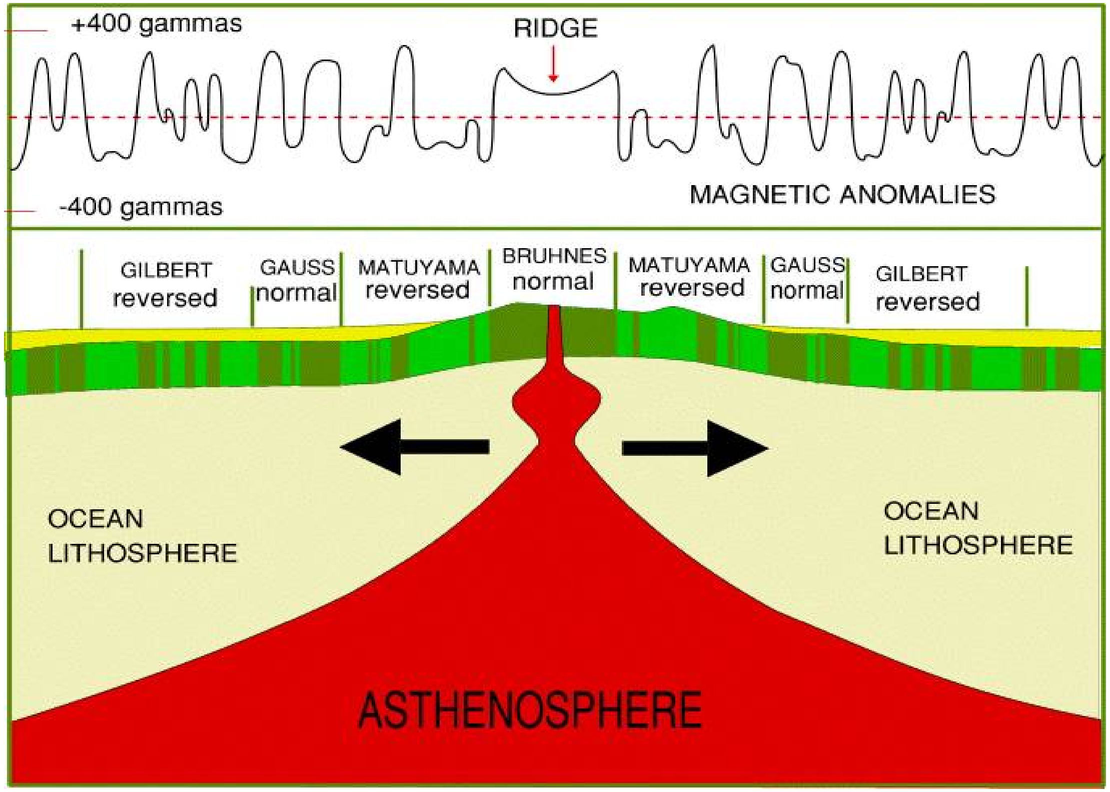
* Sur Mars, le rover Spirit en découvrit de probables dans le cratère Gusev.



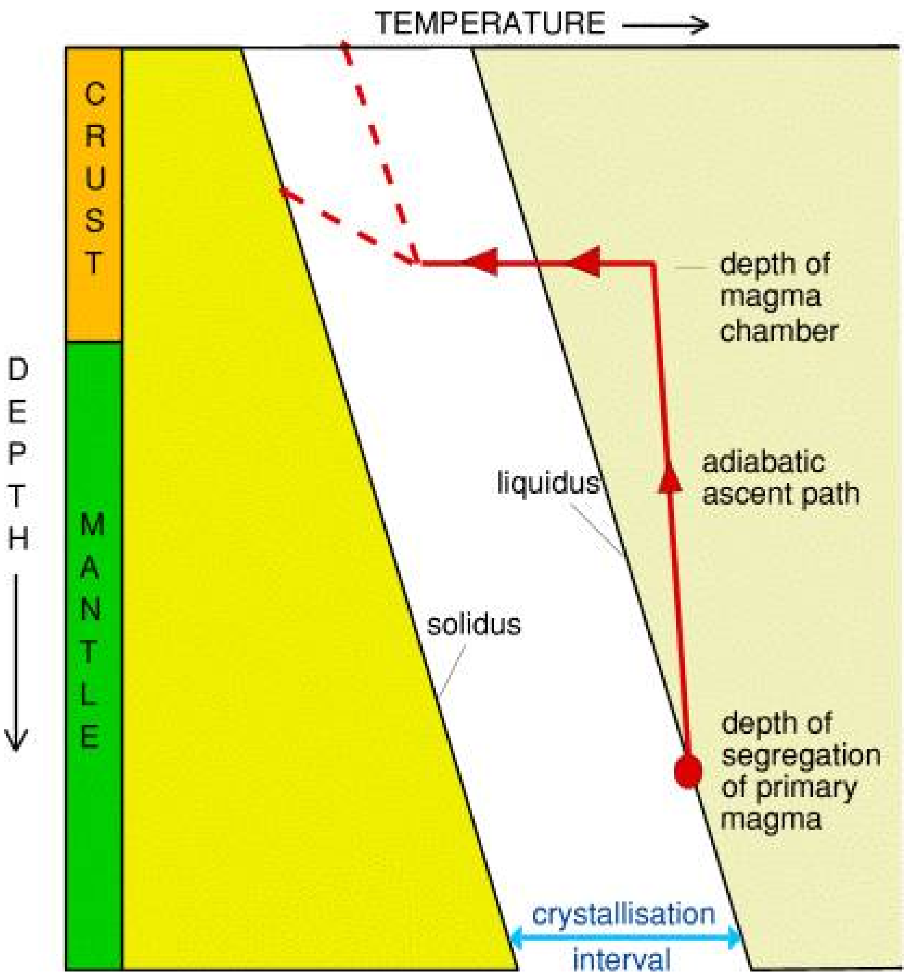
Les supercontinents regroupent la quasi-totalité des terres émergées à leur époque:
- PANGEE (300 à 180 millions d’années).
- RODINIA (1,1 milliard à 750 millions d’années).
- COLUMBIA (1,8 à 1,5 milliard d’années).
- UR (3 milliards d’années, plus petit que l'Australie, mais unique à son époque).
- VAALBARA (~3,6 ou 3,3 milliards d’années) comprenant le craton du Kaapvaal et de Pilbara.

Le terme de supercontinent désigne une masse continentale regroupant tous les continents actuels. Le plus ancien supercontinent connu, la Rodinia, se serait fragmenté il y a 750 millions d’années. Ces fragments se rassemblèrent au paléozoïque pour former la Pangée, qui se divisa ensuite en deux autres supercontinents, la Laurasia au Nord et le Gondwana au Sud.

Il semblerait que les supercontinents se forment par cycles, tous les 400 à 500 millions d’années : **c'est le cycle de Wilson**.



The uprising mantle crosses the geotherm and begins to melt, and as the solidus temperature of mantle falls with decreasing pressure, the temperature of the melt increases relative to this solidus, thus **melting** with decompression.



The amount of melt generated will be limited by the latent heat of fusion (which is high for silicates), and by the melting range of mantle peridotite, between 1100- 1700°C. The magma may enter a chamber in the oceanic crust and begin **crystallising**.

What does Plate Tectonics have to do with Climate?

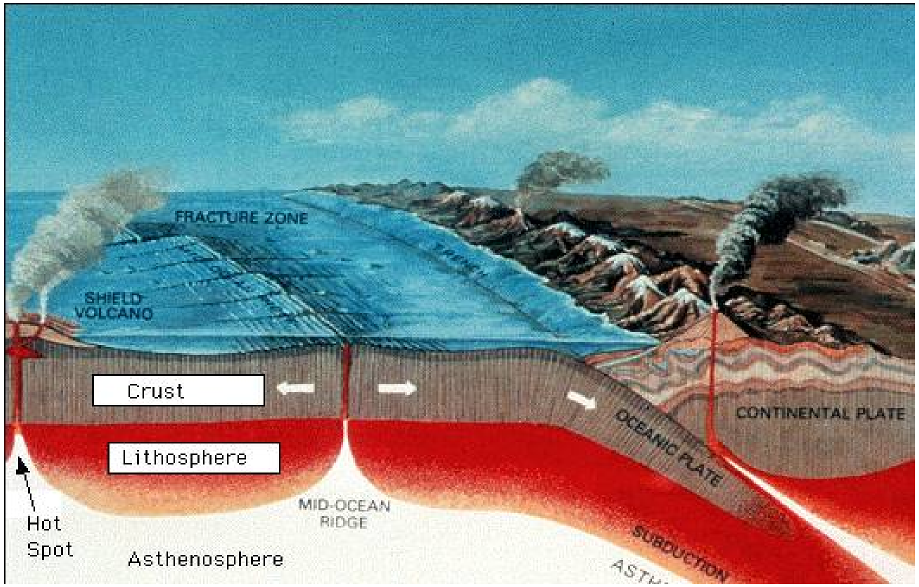
- Changes the topography
- Changes the ocean circulation
- Affects the re-cycling of volatiles

  re-cycling of water vapor is particularly important on planets besides Earth, such as Mars, Venus & Io
- In turn, climate affects the creation of continental crust & the long-term evolution of a planet

In earliest days, Earth resembled Io.

The slow buildup of continental crust over Earth's history shaped the course of its evolution.

Slippery Continents, a speciality of Earth, contributes to a recycling of volatiles

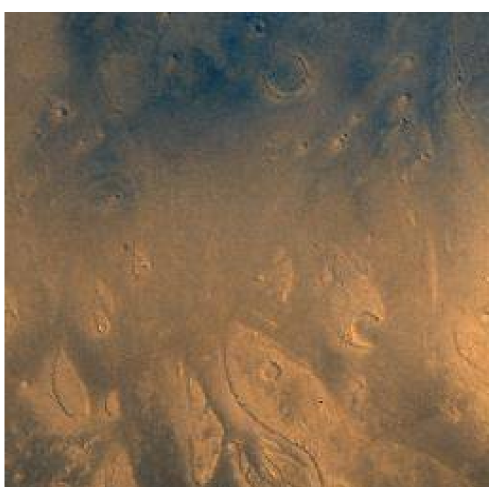


Silicate rocks are about 90% of the Earth's surface. They form in the magma chamber of a volcano and their chemistry depends upon its pressure and temperature.

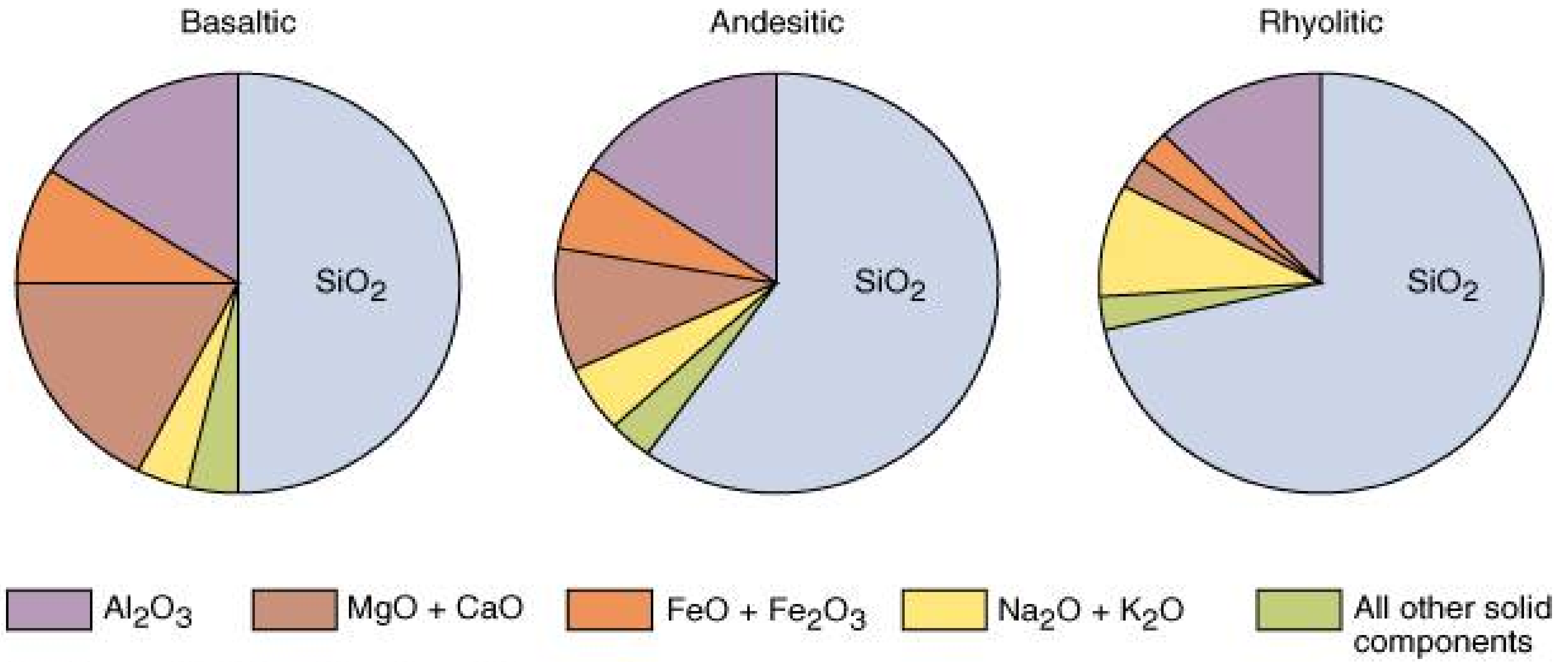
Hydrated minerals, such as kyanite, a biproduct of the breakdown of granite, help make the crust of the Earth "slippery", and so facilitate the subduction of the plates.

Subduction in turn scraps the crust and helps creating light-weight rocks (silicate-rich) that do not sink.
Subducted plates are re-melted and return to the surface as volcanoes.

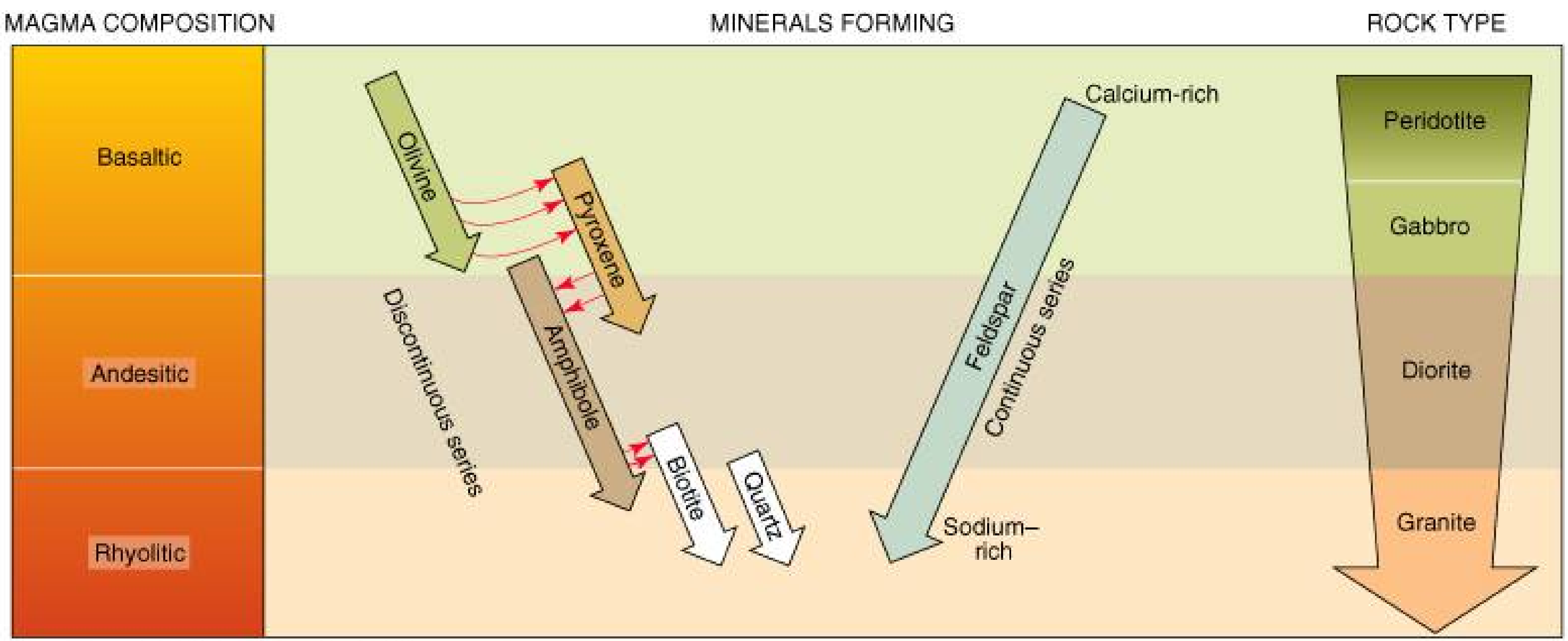
Granite vs. Gabbro



- The continental crust of the Earth is formed of light-weight rocks such as **granite** (silica-rich).
- The crust of the Moon is made of more silicate-poor rocks such as **gabbro**.
- The crust of Mars is made of basalt of as-yet unknown silica%.



Basaltic
Andesitic
Rhyolitic
SiO_2
SiO_2
SiO_2
Al_2O_3
$MgO + CaO$
$FeO + Fe_2O_3$
$Na_2O + K_2O$
All other solid components



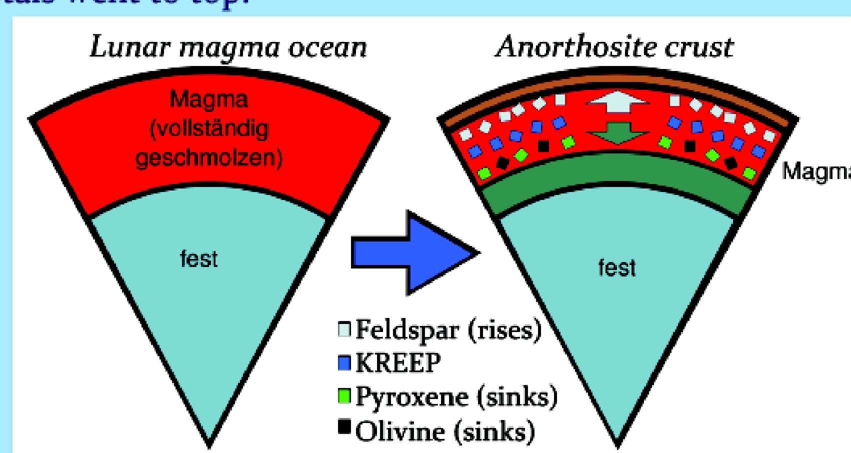
MAGMA COMPOSITION
MINERALS FORMING
ROCK TYPE
Basaltic
Andesitic
Rhyolitic
Olivine
Pyroxene
Amphibole
Biotite
Quartz
Discontinuous series
Calcium-rich
Feldspar
Continuous series
Sodium–rich
Peridotite
Gabbro
Diorite
Granite

La Lune

Highland formation

- Made of *anorthosite*, a rock normally crystallized deep inside a planet.
- Probably formed from a global ocean of molten rock, or magma ocean:

- Magma ocean several hundred km deep.
- As it cooled, crystals of different densities went to top or bottom.
- Feldspar crystals went to top.



Venus

- Venera spacecraft landed on surface in 1970s-1980s (after many failures).
- To see through the clouds need radar.
- Pioneer-Venus 1 (1978-1992), Venera 15/16 (1983) and Magellan (1991-1994), mapped surface with radar.

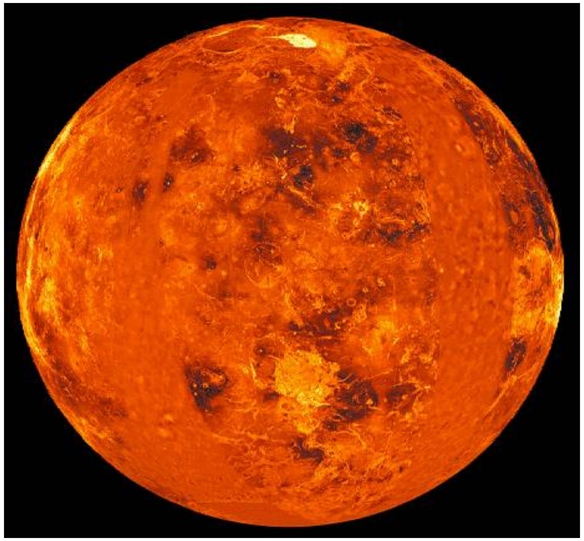
Venera surface images

Venera 13 (1982) *Venera 14 (1982)*

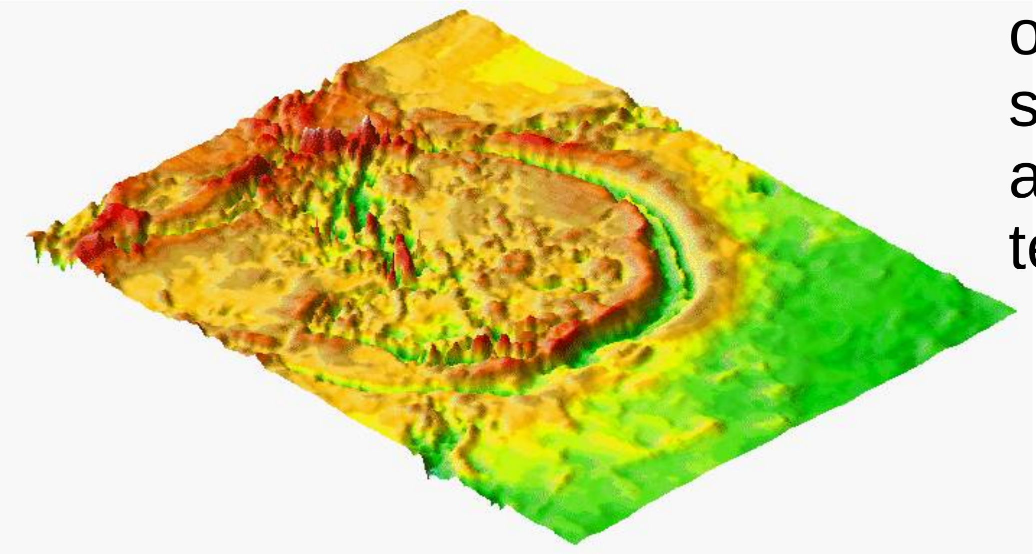
Earth/Venus : similarities & differences

	Venus	Earth
Mass	4.87×10^{24} kg	5.974×10^{24} kg
Radius	6052 km	6371 km
Average distance from Sun	108 million km	150 million km
Rotation period	243 days (retrograde)	24 hours
Surface temperature	465 °C	15 °C
Surface pressure	9.2 MPa	101 kPa
Albedo	0.76	0.37
Tallest mountain	Maxwell Montes (11 km)	Mauna Kea (10 km)
Surface composition	Basalt rock	Basalt, granite
Obliquity of axis	178 °	23.5 °
Surface gravity	8.9 m/s^2	9.8 m/s^2
Moons	None	1

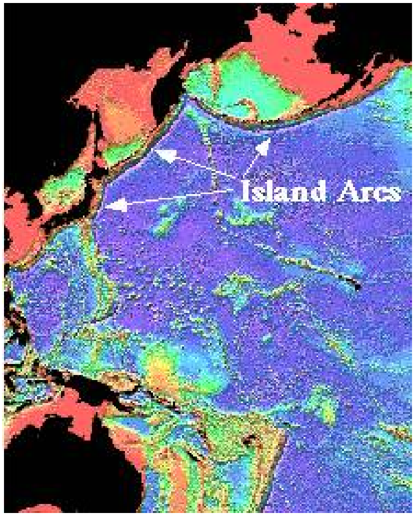
Plate Tectonics on Venus ?

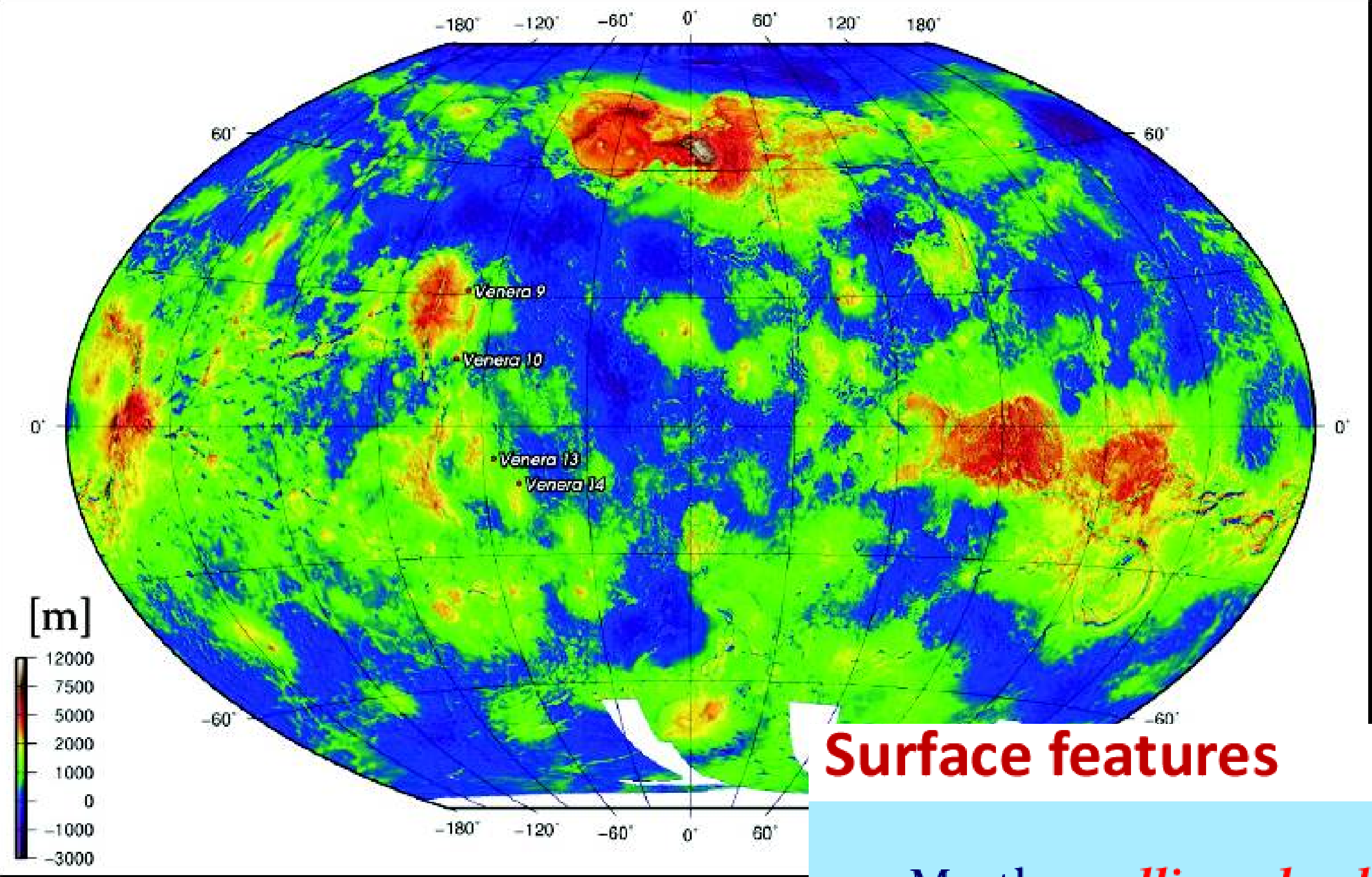


Venus has a thick atmosphere (94 bars), which reduces the efficiency in recylcing of volatiles.



There are features on the surface of Venus called "***coronae***" which strongly resemble terrestrial island arcs - a manifestation of plate tectonics.

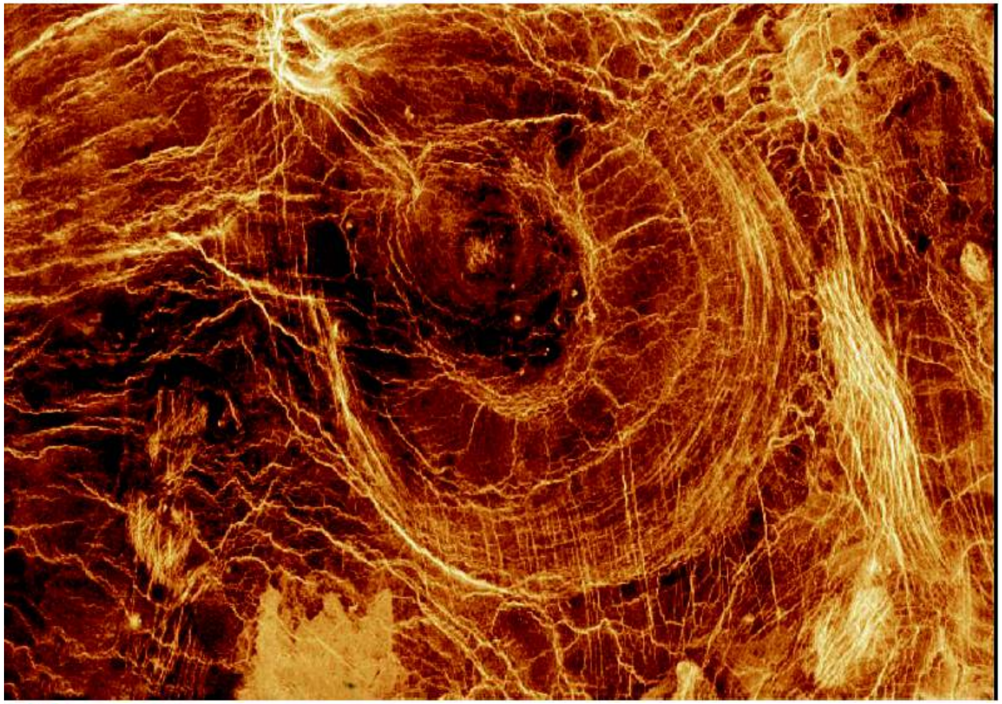




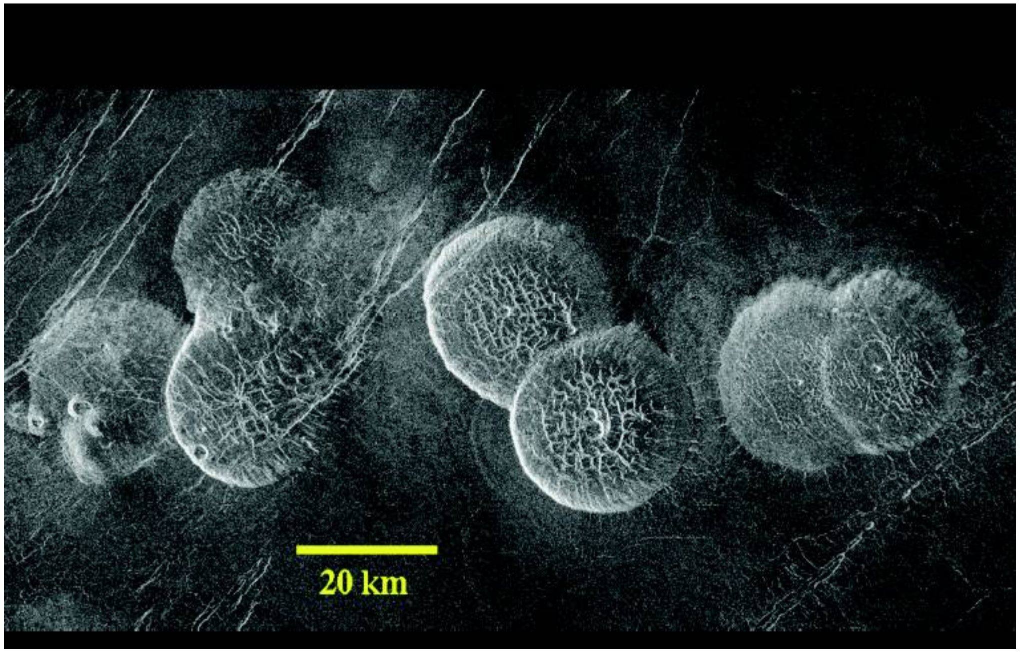
Surface features

- Mostly ***rolling lowland plains***, covered by basaltic lava
- Highland regions 8% of surface (largest Aphrodite and Ishtar Terra)
- Widespread evidences for ***crustal deformation***.
- Circular features (***coronae***, ***arachnoids***): other than volcanoes and craters, possibly rising hot material underneath.
- Volcanic features: range from calderas & shield volcanoes 100s km wide & 5 km high to farra (pancake domes).

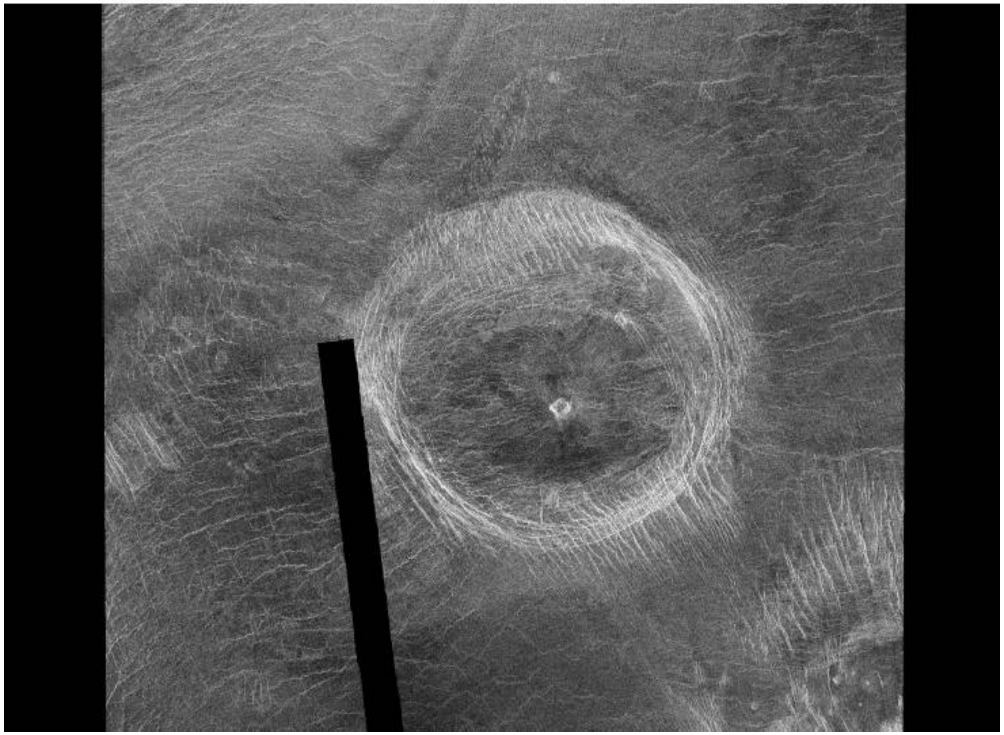
Arachnoids



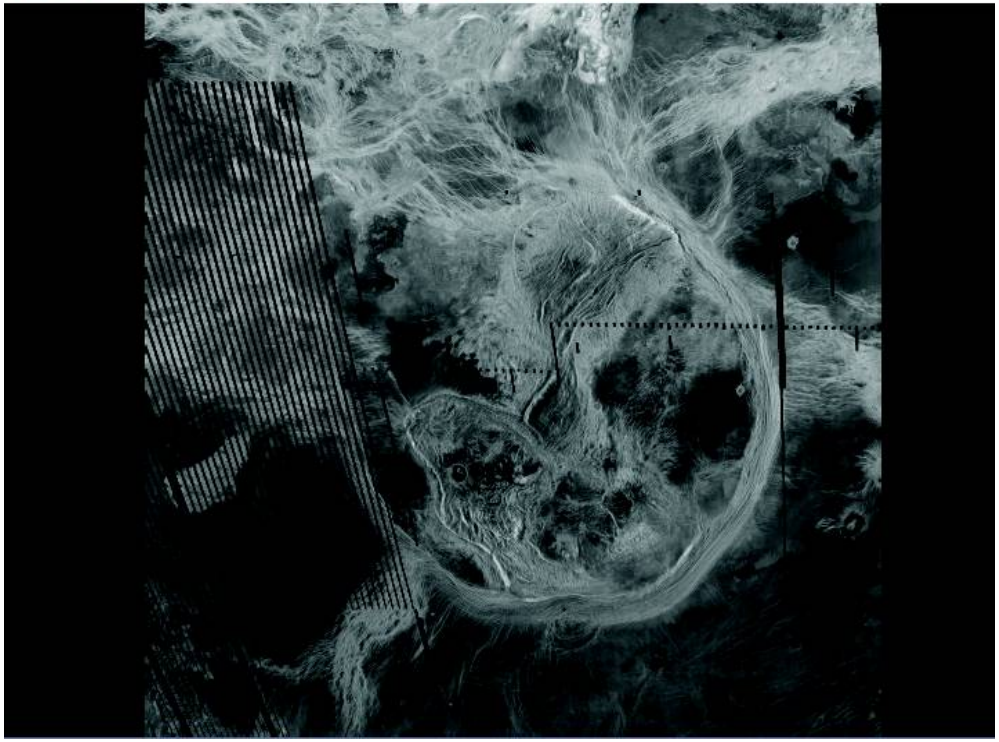
Farra *(Pancake domes)*

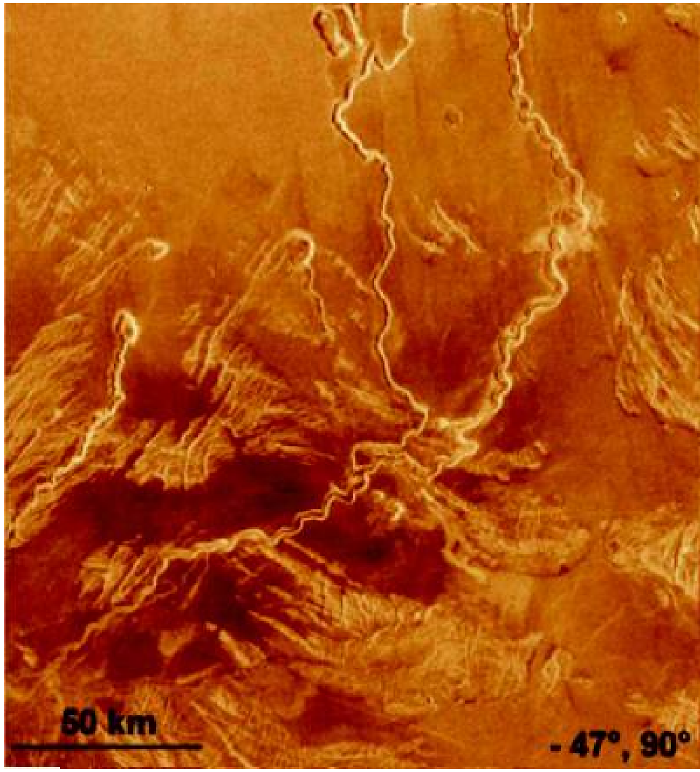


Thourus corona *(190 km diameter)*

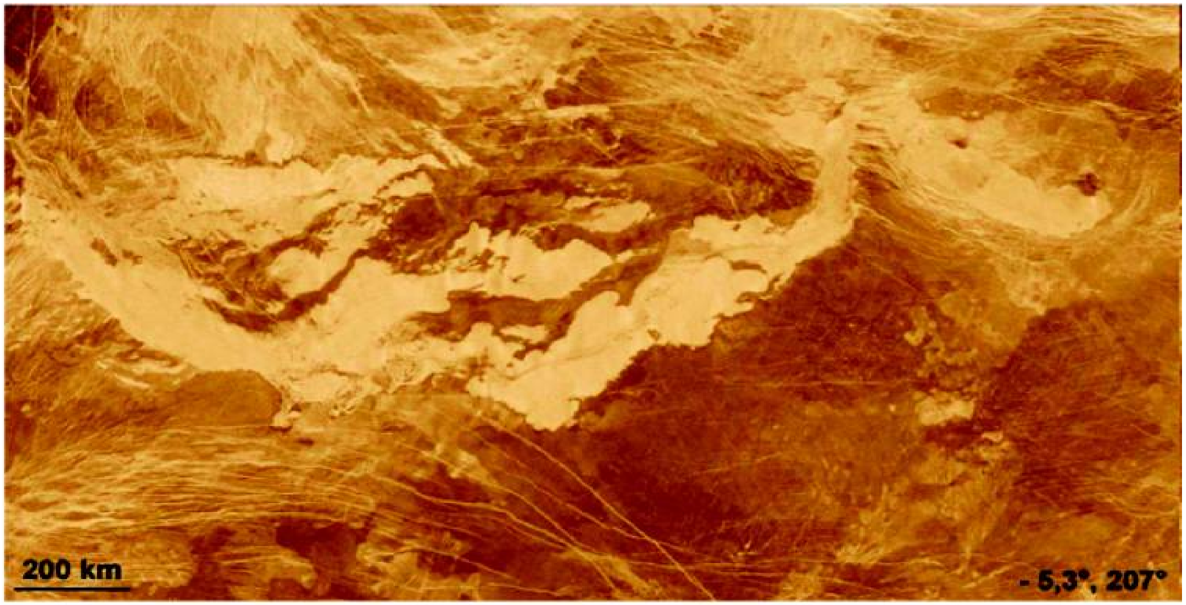


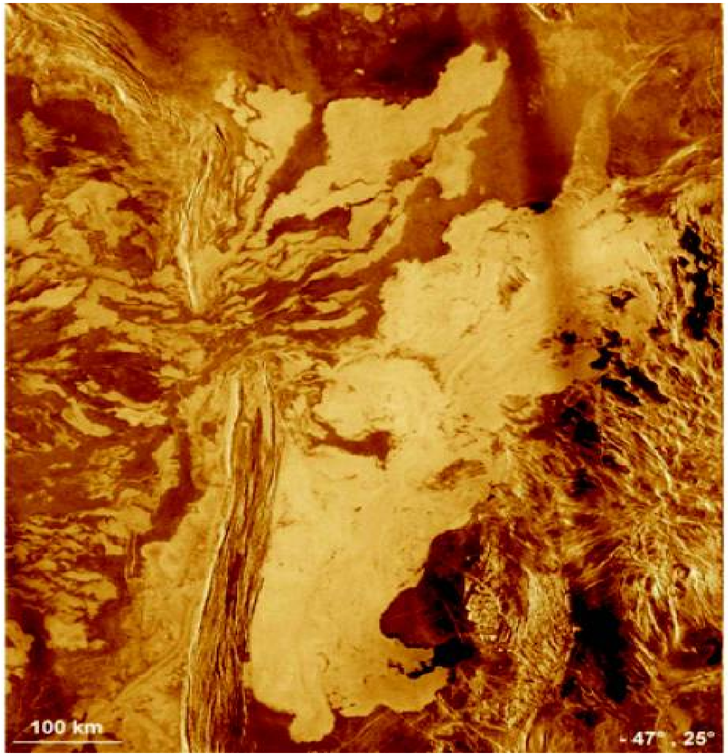
Artemis corona *(2600 km diameter)*





Coulées de lave très fluide = tunnels de lave effondrés.

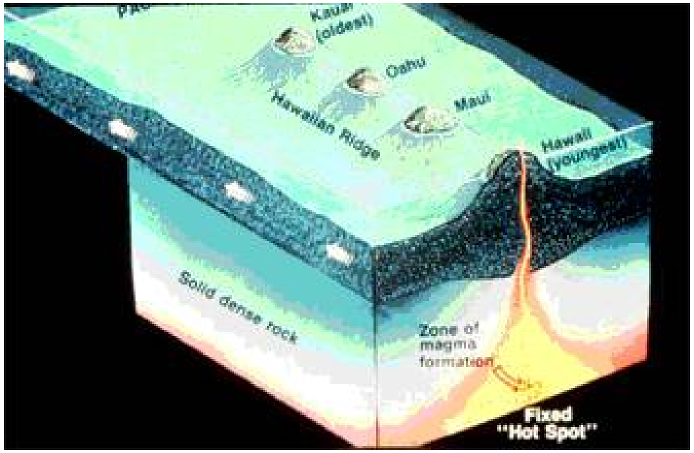


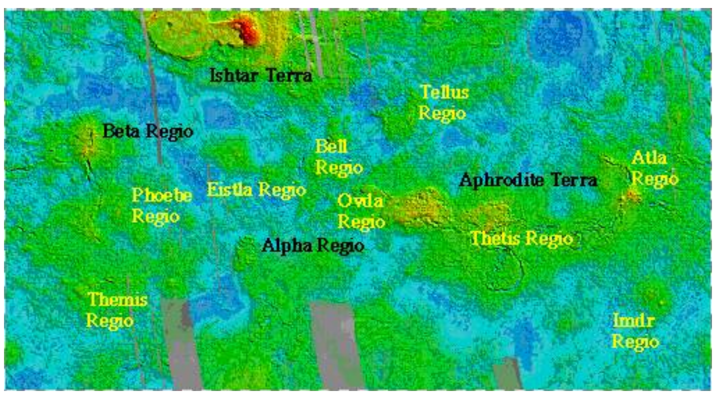


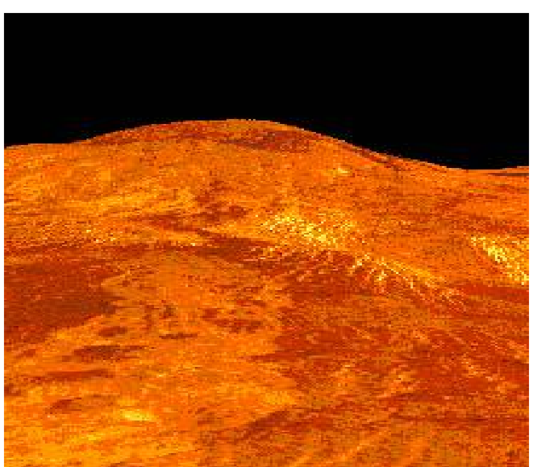
Des coulées de lave de plus de 1000 km de long

Des coulées de lave qui passent par dessus une chaîne de montagne.

Mountains on Venus



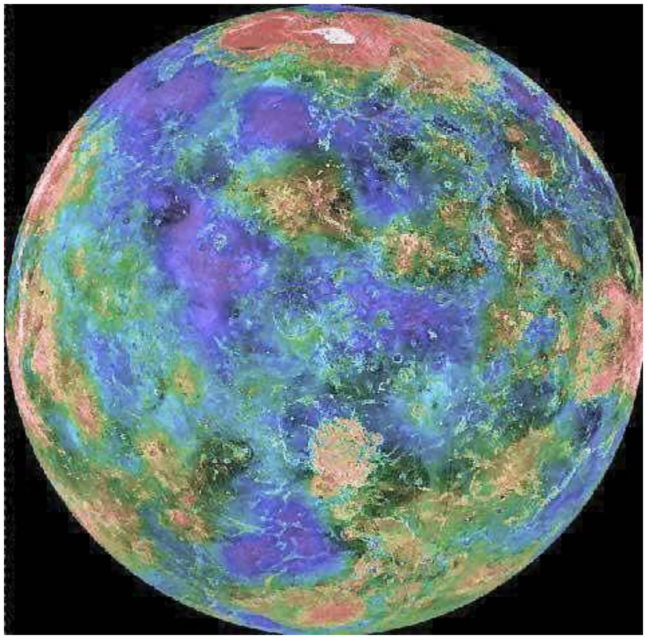


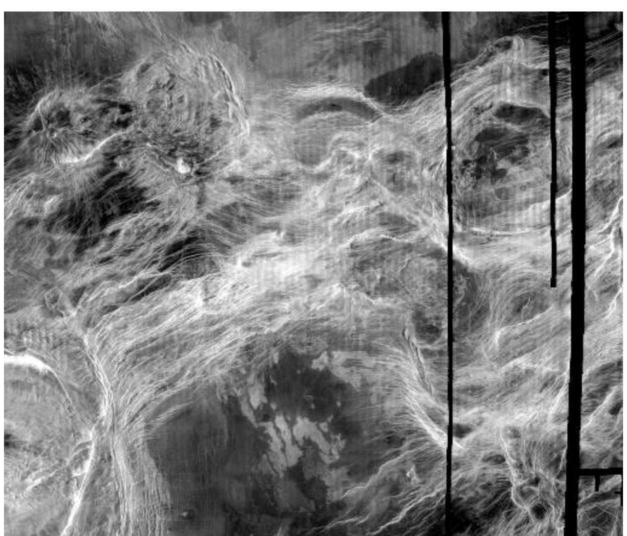


- **On Earth**, because of plate tectonics, the "island" created by hotspot volcanism moves away, and a new island forms.
- **On Venus**, because of no plate motion, volcanic islands keep growing, called Volcanic Rises.

- Mountains of Venus are of big (Mount Maxwell is 11 km high).
- The crust may be very thick in order to support the weight.
- Other data suggest the opposite, that the crust may be thin.
- The uncertainties imply that the surface of Venus may ***turn over*** in a manner which is completely unlike that of the Earth.

Cratering History
& theories of catastrophic turn-over of the surface





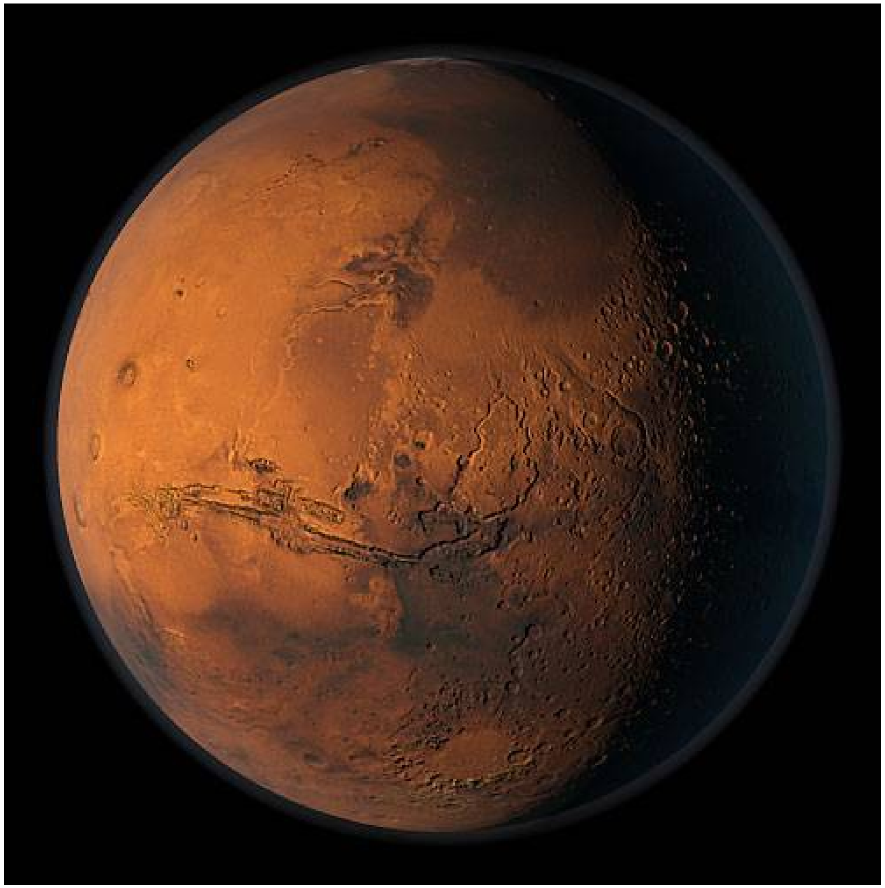
No present-day plate tectonics

- continents, volcanic rises, coronae
- thick lithosphere (maybe)
- lithosphere = frozen (maybe)
- plate tectonics is not understood

there is some evidence of rifting & faulting

- The surface of **Venus** has just as few craters as does the Earth. This means that the surface is just as young as Earth's surface!
- Suggests a cataclysmic ***turn-over*** process may be at work.
- The inside heats up until, POW! The whole surface melts.

Mars



A thin atmosphere,

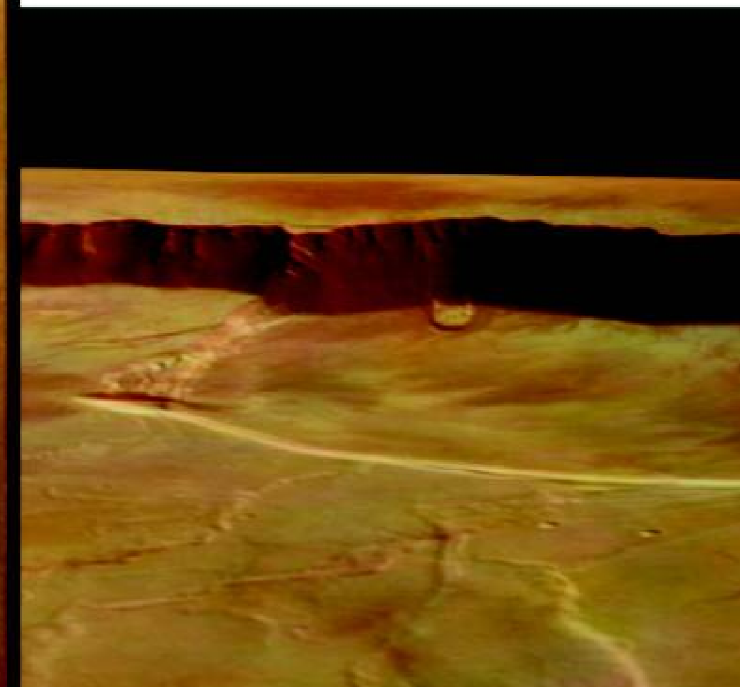
no present-day plate tectonics

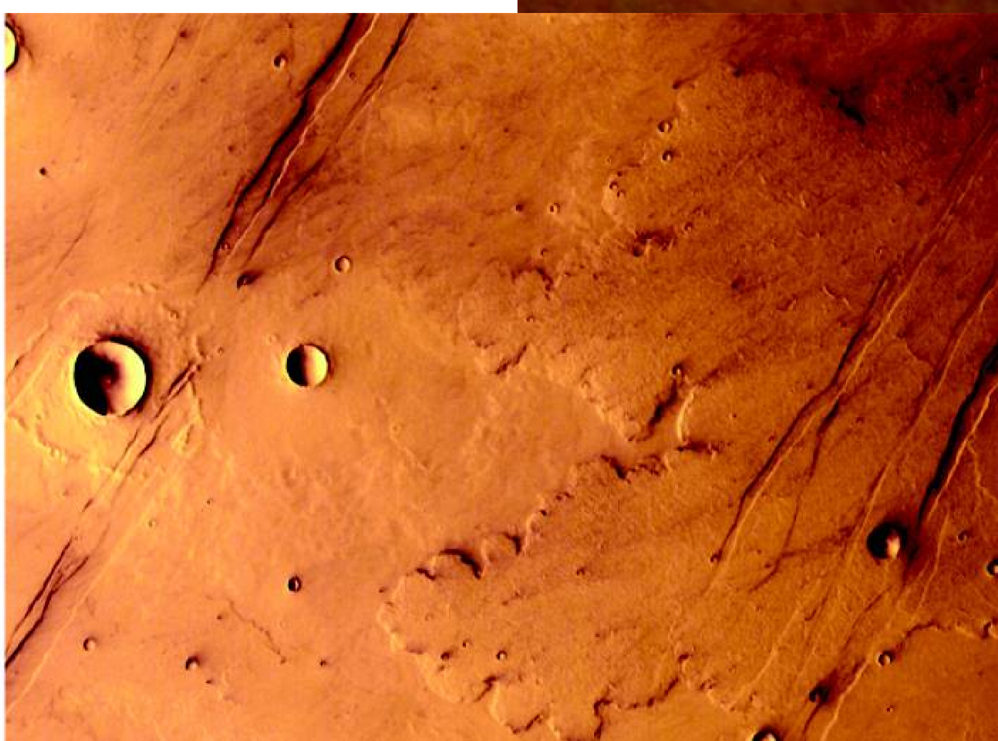
- continents, volcanic rises, magnetic stripes
- thick lithosphere (maybe)
- lithosphere = frozen in place

Plate tectonics must have taken place in the past

there is some evidence of rifting & faulting

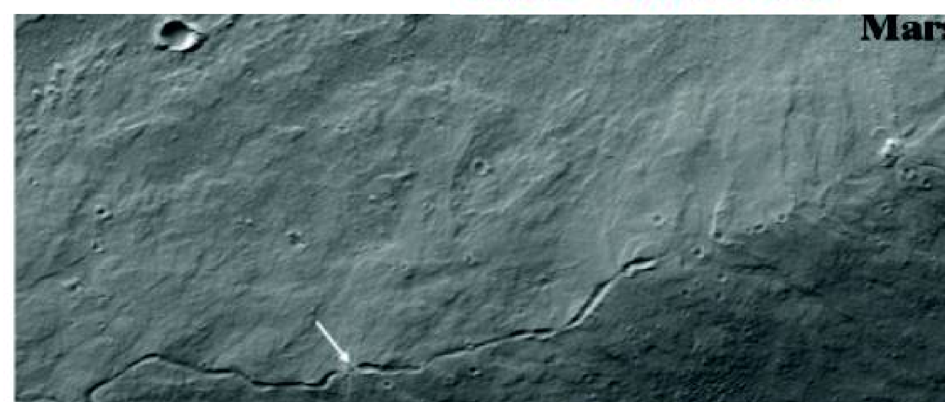
De très belles caldeiras sommitales emboîtées

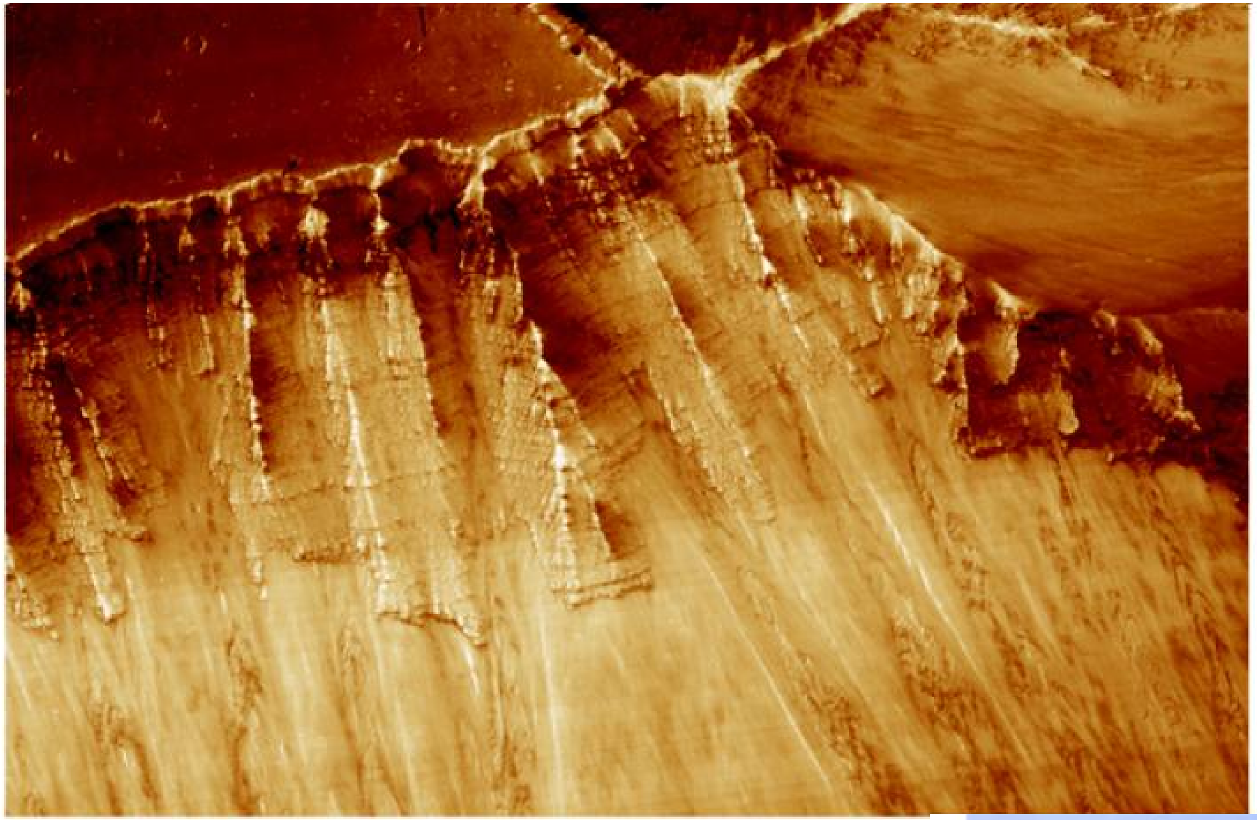




Des coulées de laves formant de vastes plateaux

… avec tunnel de lave effondré

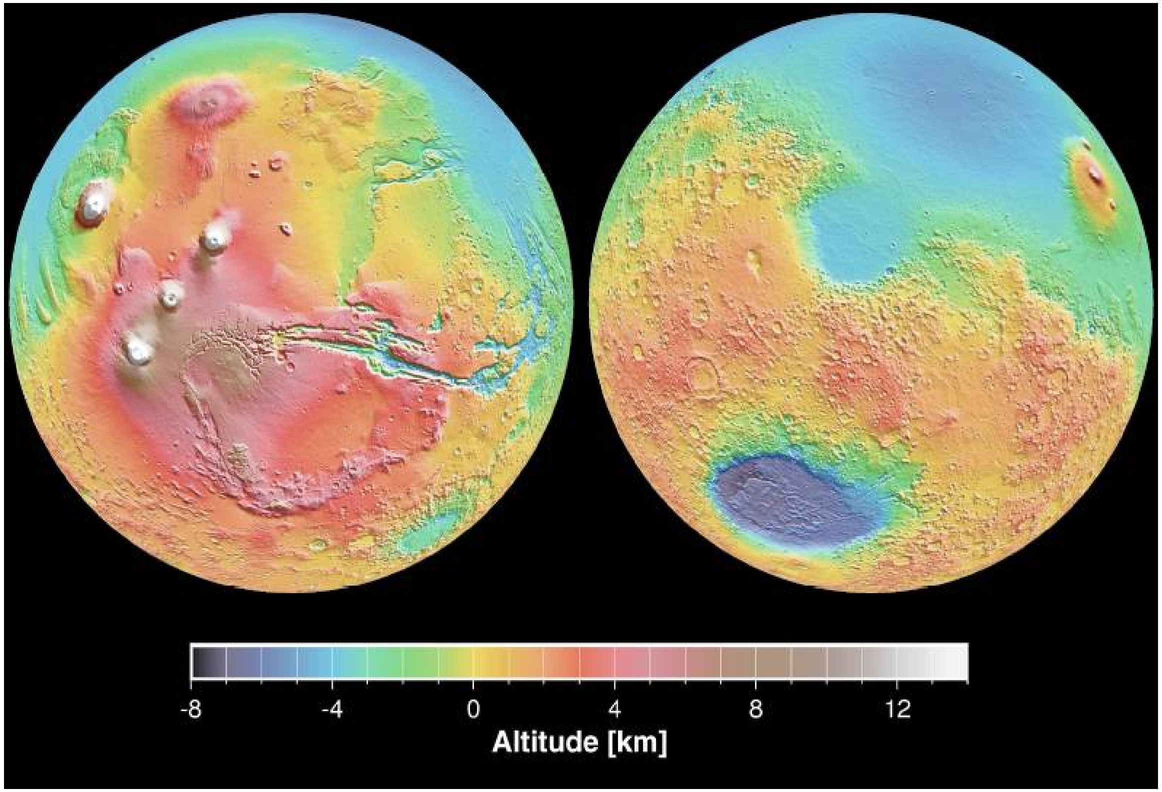




On voit parfois des empilements de couches de coulées de lave, comme en ….

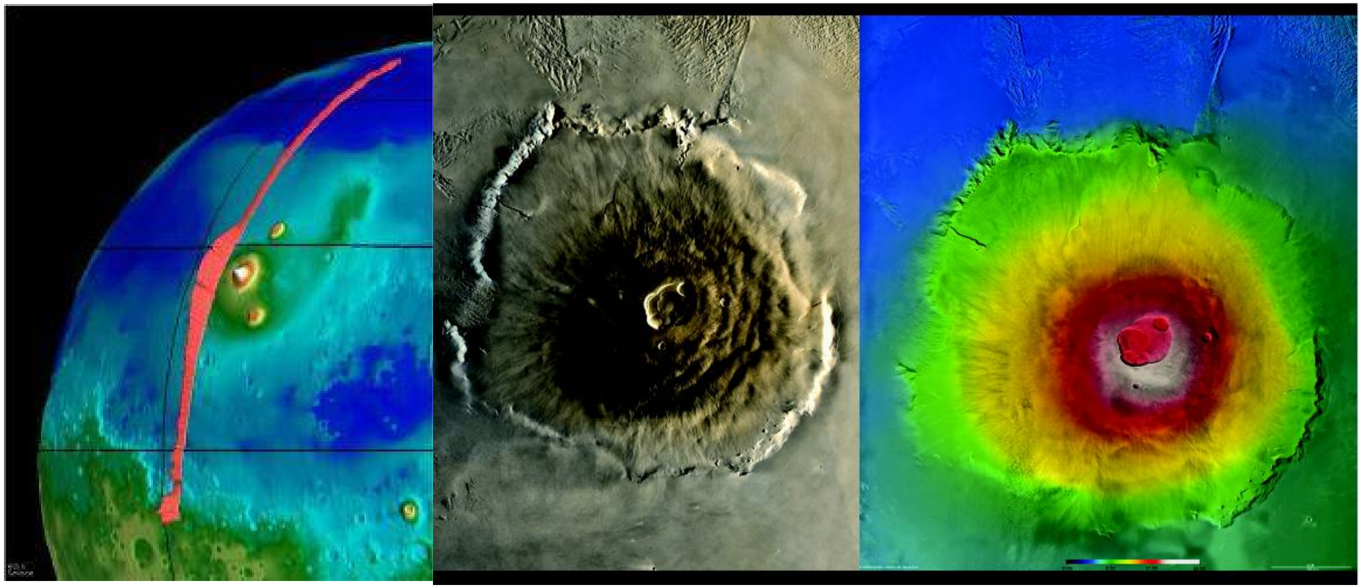
… en Islande, au climat plus « neigeux » que Mars.

Crustal dichotomy



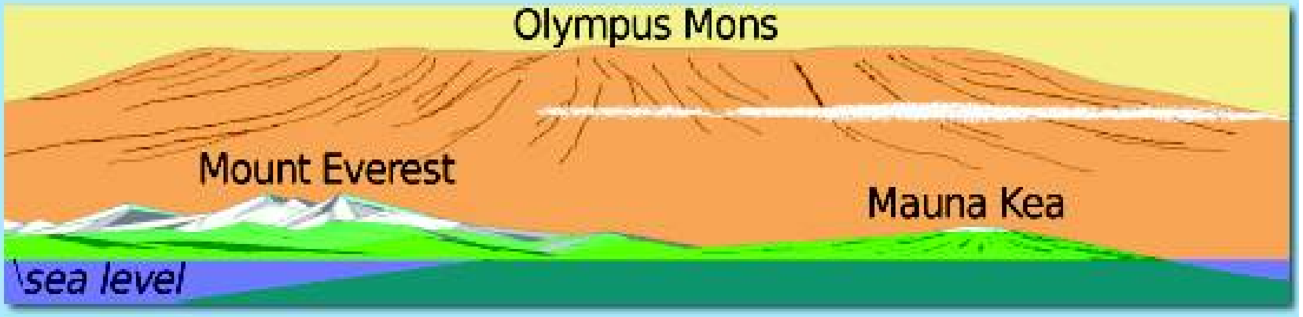
Mars has severe topographic differences between north and south.

Olympus Mons



The presence of a volcanic rise suggests a thick, and immobile lithosphere.

Why are martian mountains so tall?



Newton's 3rd law:

$$F = G\frac{M_P \rho A dx}{(R_P + x)^2}$$

Use $x \ll R_P$:

$$F = G\frac{M_P \rho A dx}{R_P^2}$$

Reformulate for pressure gradient:

$$\frac{dP}{dx} = \frac{F}{A dx} = G\frac{M_P \rho}{R_P^2}$$

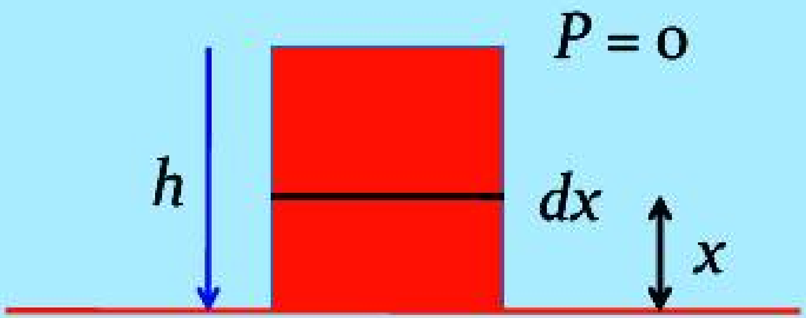
Integrate:

$$P = G\frac{M_P \rho h}{R_P^2}$$

Use $P = P_{crit}$ and $M_P = 4\pi\rho R_P^3/3$:

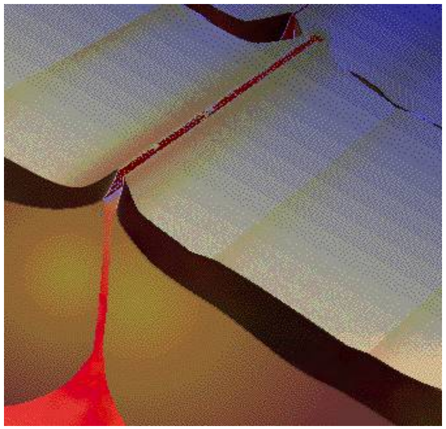
$$h_{max} = \frac{3P_{crit}}{4\pi G \rho^2 R_P}$$

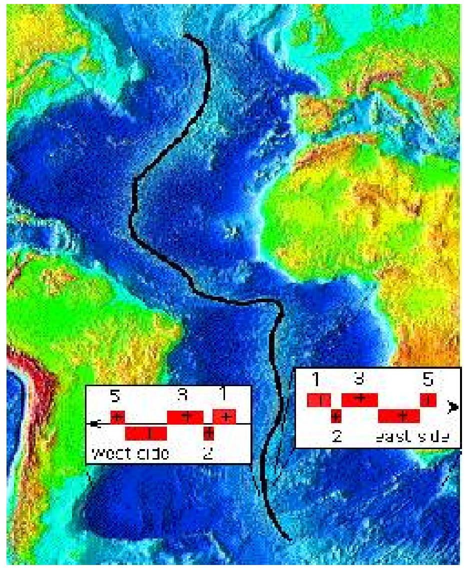
$$h_{max} \sim \frac{1}{R_P}$$

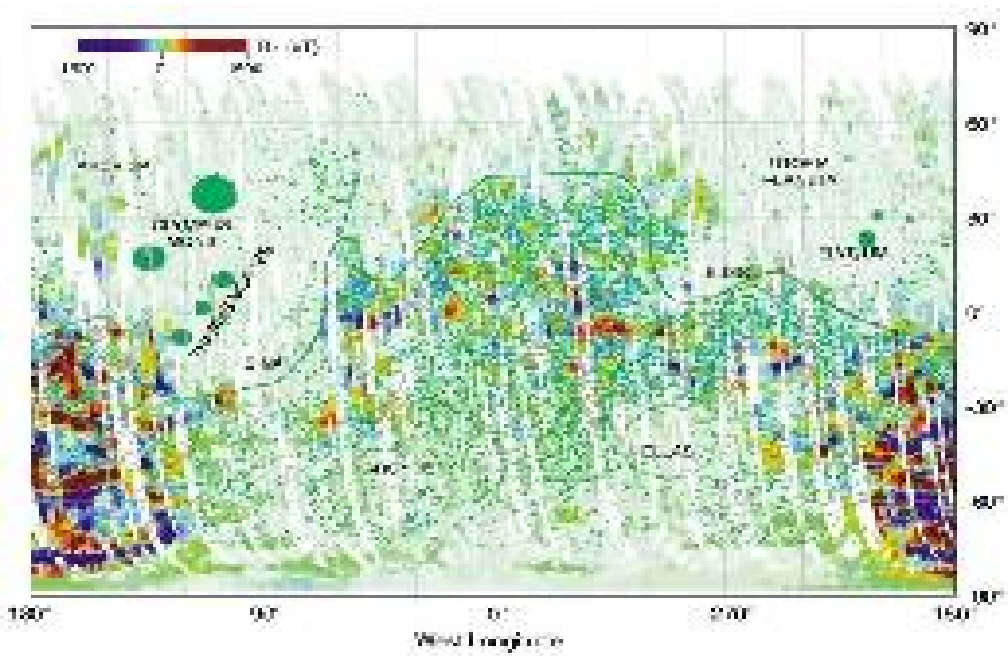


Planet	Tallest mountain
Earth	10 km
Venus	11 km
Mars	22 km

Magnetic Stripes: Earth and Mars







- **On Earth**, the biggest proof of the mechanism of plate tectonics, sea-floor spreading, is in the striped ocean floor.
- **Mars** has been found to have similar stripes, indicating plate tectonics in the past.
- Martian geological epocs:

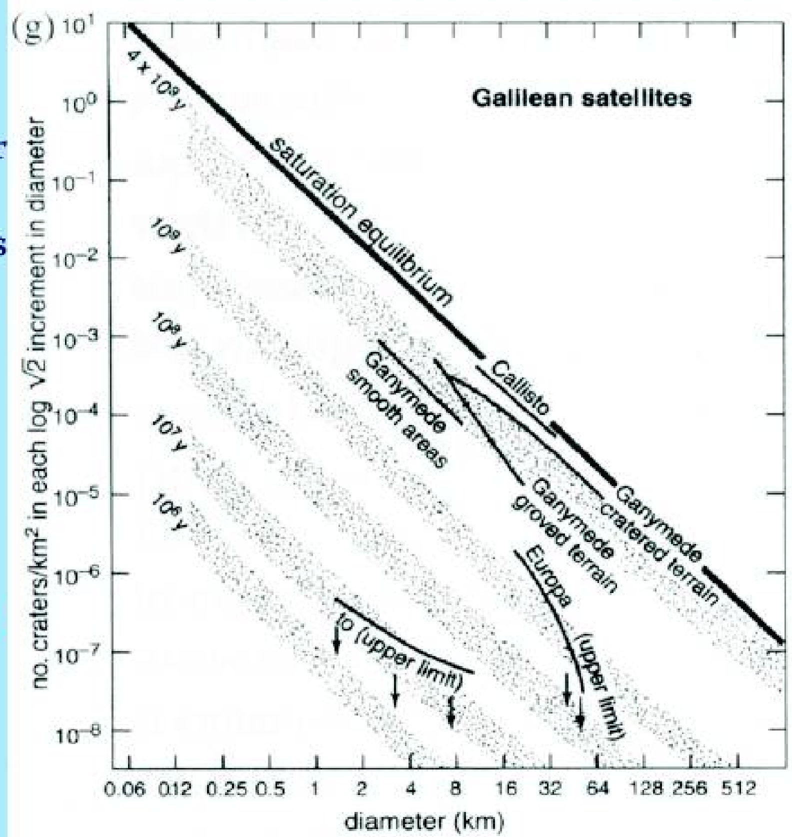
- Hesperian : When the super continent at the southern hemisphere formed

- Something: 90% of the rest of martian history, when the cratering eased off

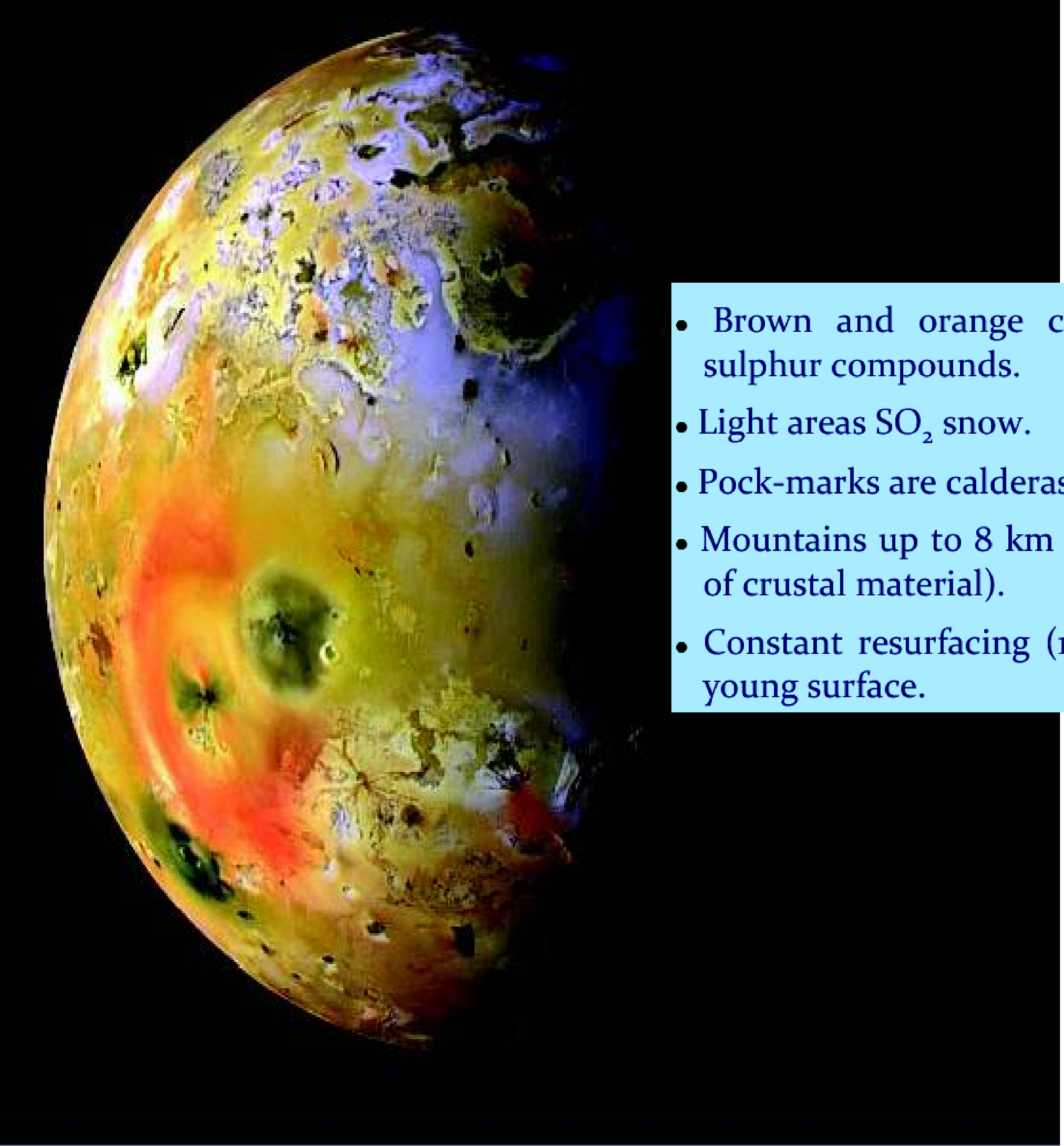
Les lunes de Jupiter

Io	*Europa*	*Ganymede*	*Callisto*
D = 3642 km	*D = 3122 km*	*D = 5262 km*	*D = 4821 km*

- ***Cratering:***
  - Jupiter attracts impactors
    => inner bodies higher crater density
  - Leading edge more impacts than trailing edge
- **Io**:
  very young
- **Europa**:
  quite young
- **Ganymede** & **Callisto**:
  old



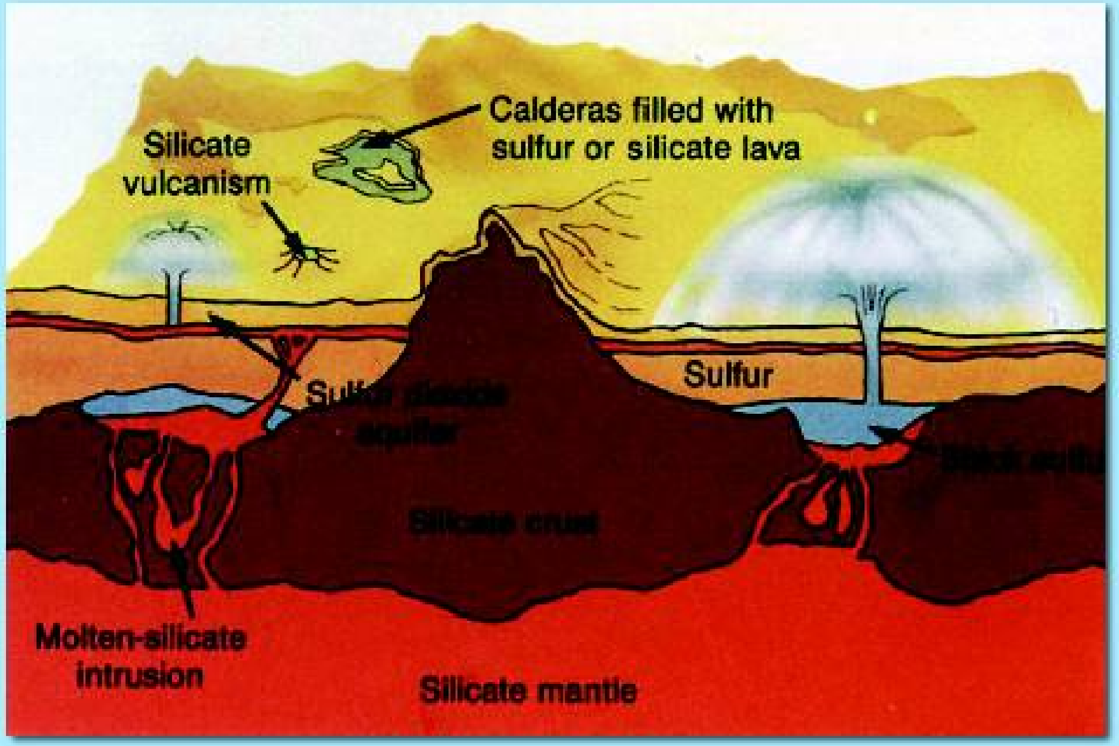
Io



- Brown and orange colors probably sulphur or sulphur compounds.
- Light areas SO_2 snow.
- Pock-marks are calderas up to 200 km across
- Mountains up to 8 km high (look like tilted blocks of crustal material).
- Constant resurfacing (100 m/million years), hence young surface.

Io's volcanism: two types

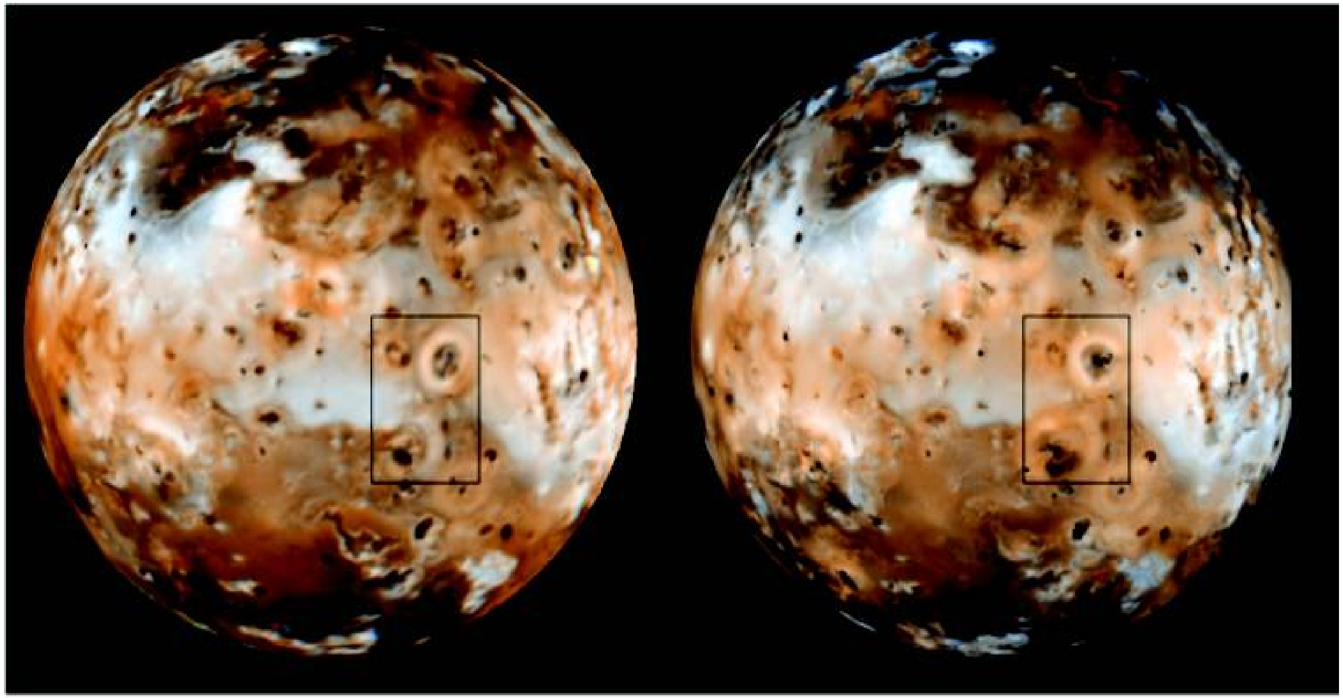
- **Geyser-like eruptions** *(Prometheus)*: 'cold' (~ 650 K) plumes of SO_2, 1 km/s, to heights of 100s of km.
  - 8 plumes observed by Voyagers.
  - Cover surface by ~100 m every million years.
- **Lava eruptions** *(Pele, Loki)*: 'hot' (~ 900-1200 K) lava flows of liquid sulfur (+ silicates ?) with different colors.



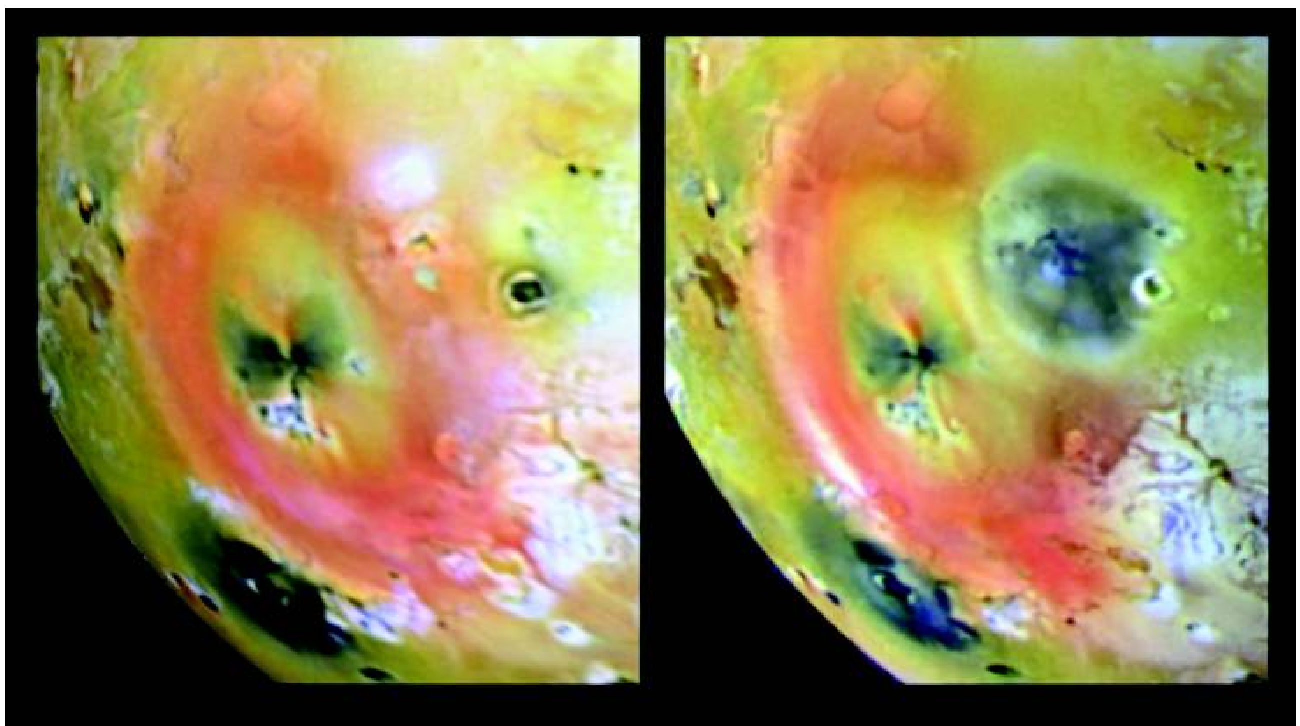
Geysers on Io

- Liquid sulfur dioxide comes into contact with hot material below the surface
- The superheated, boiling liquid rises quickly through fractures in the surface and produces a high-velocity column of gas.
- Because of the extremely cold conditions, the gas immediately starts condensing into sulfurous snowflakes.

Lava Eruptions on Io

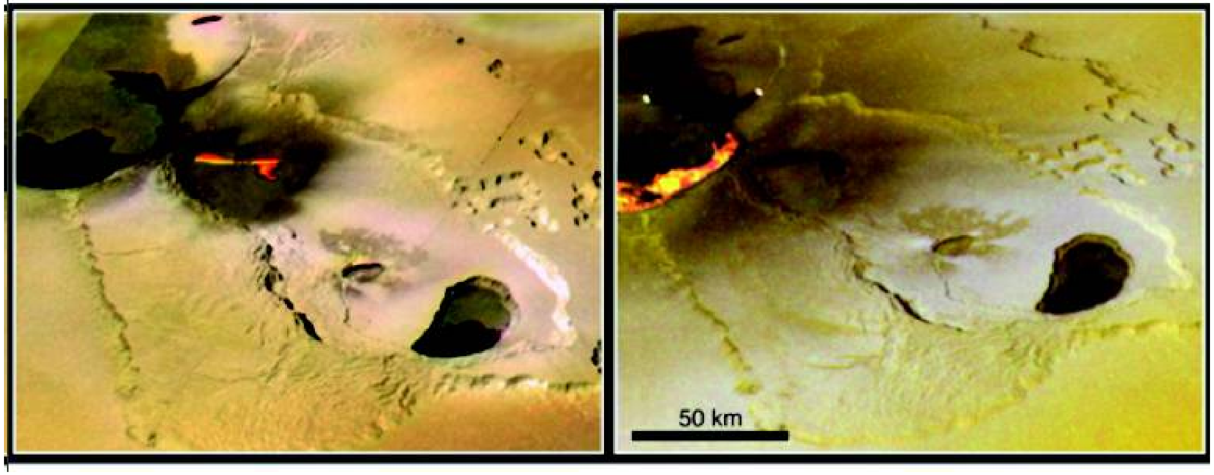


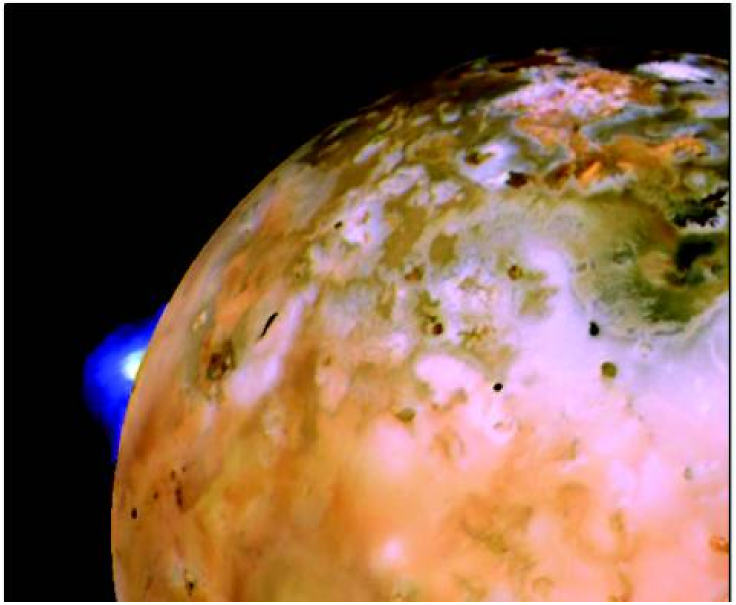
1979 (Voyager) 1996 (Galileo)



Avril 1997 Septembre 1997

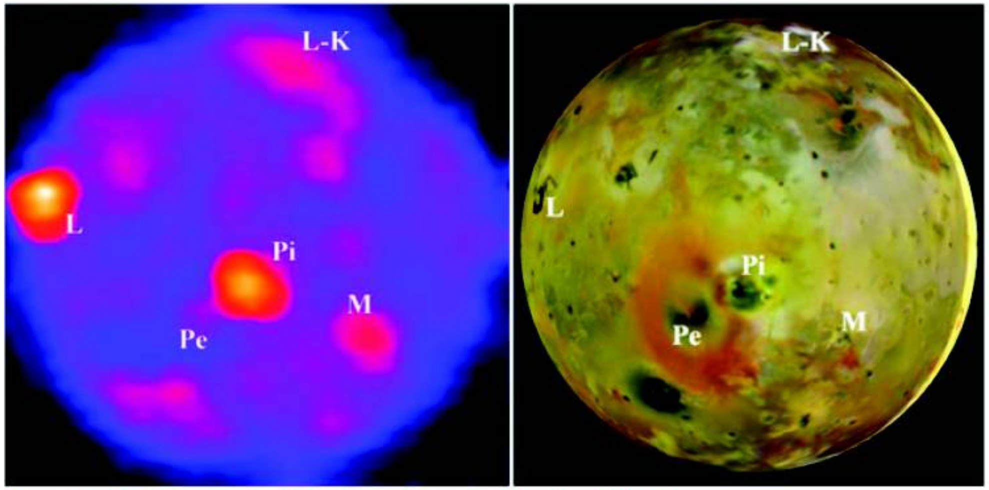
L'évolution de l'éruption de Tvashtar , entre novembre 1999 (à gauche) et février 2000 (à droite)





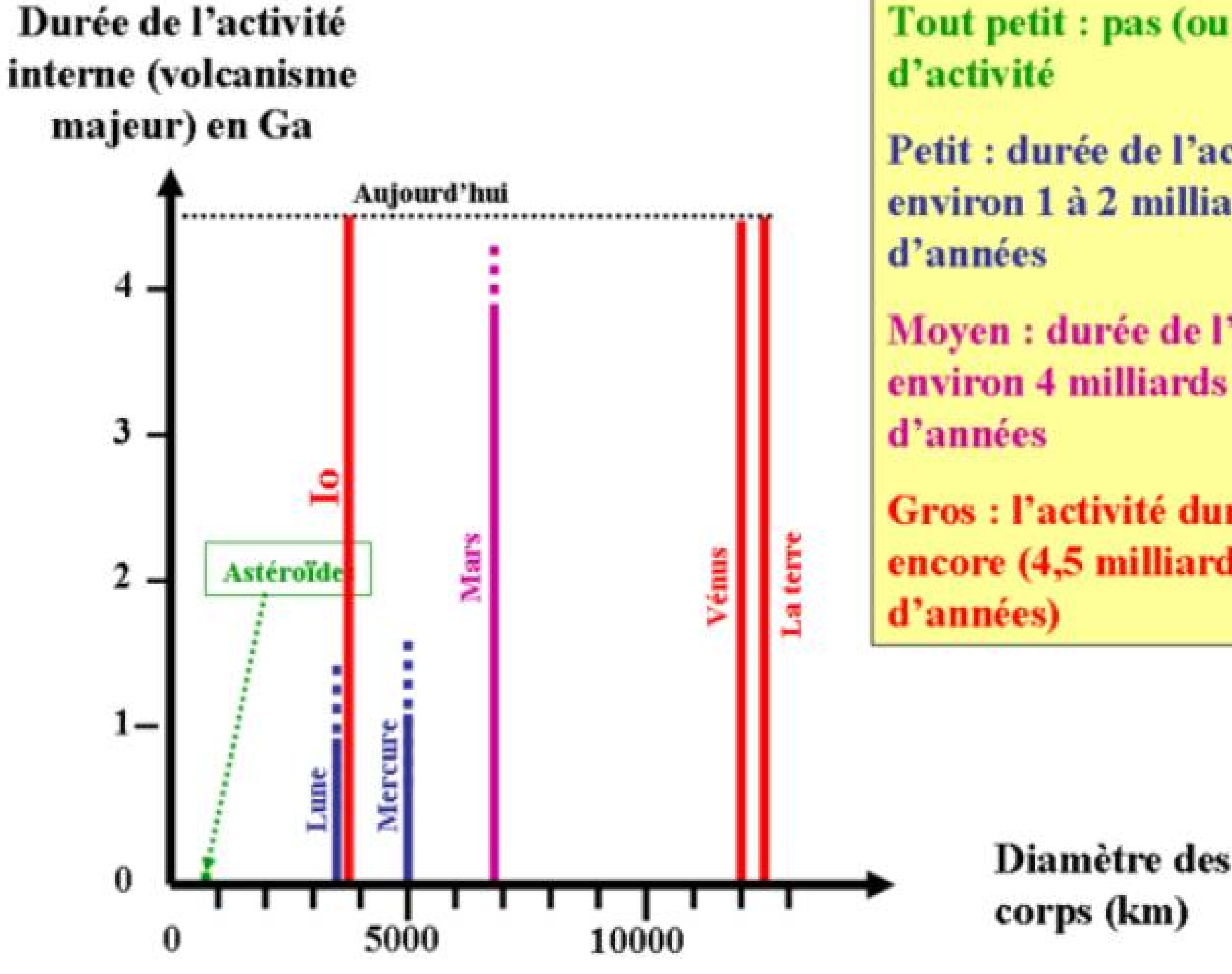
Non seulement c'est chaud, mais ça crache !

Io, dont la T superficielle est « normalement » de 90 K (- 180°C) possède des zones à T > 1500 K (+1230°C). Il y a des volcans hyper-chauds.



De –180° (bleu) à +1200° (blanc), février 2000

Conclusion pour le volcanisme : des durées différentes



Tout petit : pas (ou peu) d'activité

Petit : durée de l'activité environ 1 à 2 milliards d'années

Moyen : durée de l'activité environ 4 milliards d'années

Gros : l'activité dure encore (4,5 milliards d'années)

4- Conditions for plate tectonics

- 1- Thermal conditions and role of water for active or stagnant lid tectonics *(a,b)*
- 2- Presence of moderate temperatures – Venus is too hot so lithosphere never cool enough to subduct (b)
- 3- Importance of composition and presence of water *(c,d)*

  needed for the formation of granite and fractional melting.
- 4- Heat removal from mantle through subduction of cool oceanic lithosphere and upwelling of new crust *(d,e)*
  - Drives convection cells
  - Allows basalt eclogite transition to be shallow
  - Subduction leads to fractional melting of oceanic crust and segregation to form continental crust

BIBLIO:
a) O'Neill et al., 2007: the role of water in plate tectonics and convection for different planets
b) Summeren et al., 2011: Mantle convection, plate tectonics and volcanism on exo-earths.
c) Albarede, 2009, 2010: how water came on Earth.
d) Karato, 2011: water distribution in planets' mantle.
e) VanHeek & Tackley 2011: plate tectonics on super Earths.

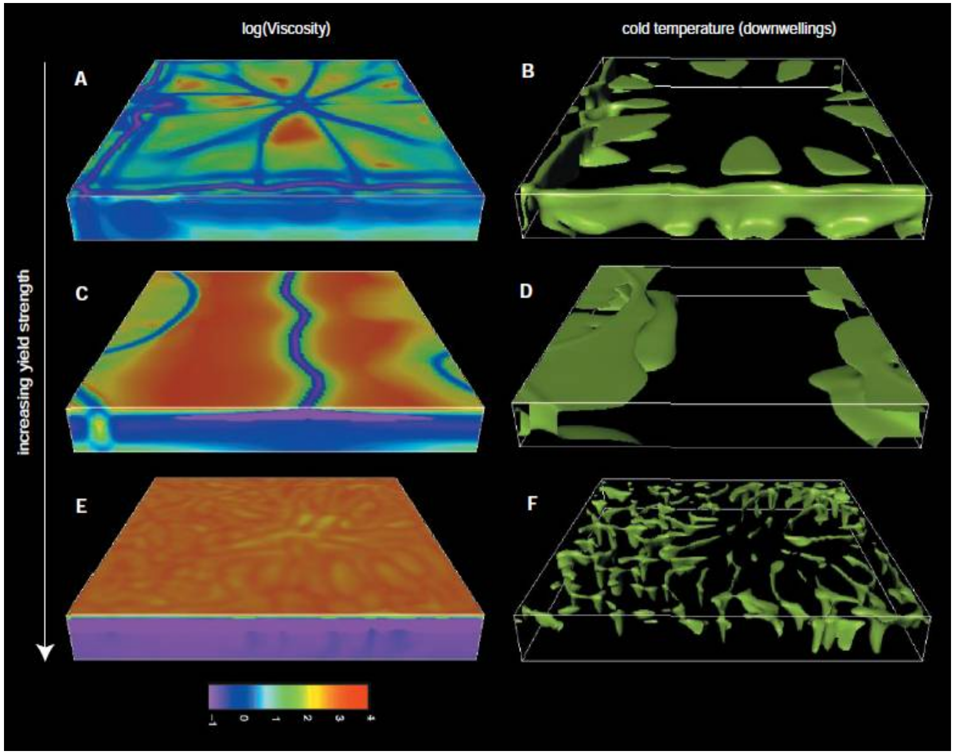
3- Composition (including water) as a condition for plate tectonics

REVIEW

Mantle Convection and Plate Tectonics: Toward an Integrated Physical and Chemical Theory

Paul J. Tackley

Plate tectonics and convection of the solid, rocky mantle are responsible for transporting heat out of Earth. However, the physics of plate tectonics is poorly understood; other planets do not exhibit it. Recent seismic evidence for convection and mixing throughout the mantle seems at odds with the chemical composition of erupted magmas requiring the presence of several chemically distinct reservoirs within the mantle. There has been rapid progress on these two problems, with the emergence of the first self-consistent models of plate tectonics and mantle convection, along with new geochemical models that may be consistent with seismic and dynamical constraints on mantle structure.



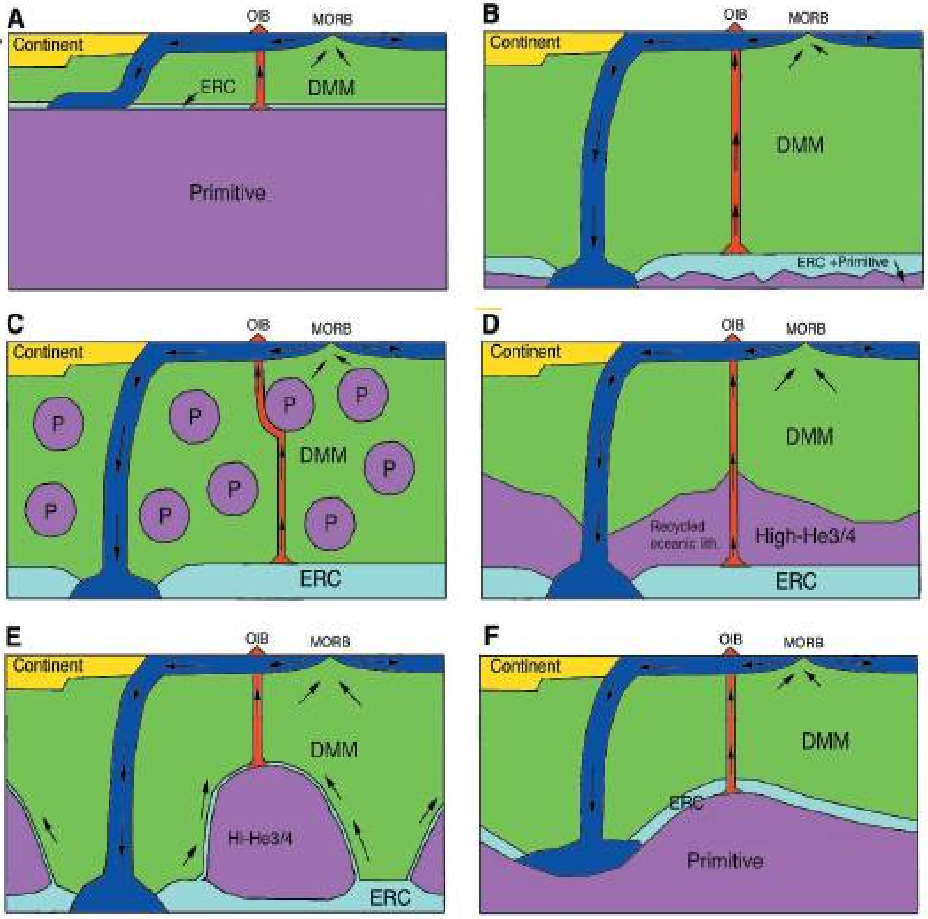


Fig. 2. Some possible locations of mantle reservoirs and relationship to mantle dynamics. Convective features: blue, oceanic plates/slabs; red, hot plumes. Geochemical reservoirs: dark green, DMM; purple, high $^3He/^4He$ ("primitive"); light green, enriched recycled crust (ERC). (A) Typical geochemical model layered at 660 km depth (7). (B) Typical geodynamical model: homogeneous except for some mixture of ERC and primitive material at the base. (C) Primitive blob model (71) with added ERC layer. (D) Complete recycling model (83, 84). (E) Primitive piles model [developed from (85)]. (F) Deep primitive layer (86).

Science 2000

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Earth and Planetary Science Letters
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Conditions for the onset of plate tectonics on terrestrial planets and moons

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http://dx.doi.org/10.1016/j.epsl.2007.05.038, How to Cite or Link Using DOI

For plate tectonics driven by convecting mantle to exist on any planet like on Earth, stresses associated with mantle convection must exceed the strength of the lithosphere. This condition is sufficiently restrictive that mantle convection in most terrestrial bodies remain in a stagnant lid regime.

Convective stresses on the lithosphere depend on the viscosity and velocity of underlying cold downwellings. The lithospheric yield stress is controlled by its friction coefficient and elastic thickness (the depth to the brittle–ductile transition or BDT). Both convective stresses and the plate's yield strength depend critically on the size, thermal state and cooling history of a planet.

Numerical simulations and scaling theory help to identify conditions in which mantle convection leads to lithospheric failure for a range of conditions relevant to the terrestrial planets.

- Whereas Earth is expected to be in a plate-tectonic regime over its full thermal evolution, the Moon and Mercury are expected to have always remained in a stagnant lid regime.

- Venus, Io and Europa fall on the transition between the two regimes : an episodic style of mantle convection for Venus, a tectonic component of deformation on Io, and the resurfacing lithospheric evolution of Europa. While stagnant now, it is plausible that Mars has also been in an active-lid regime, depending on the early presence of liquid water on the surface.

Definitions: active vs. stagnant lid

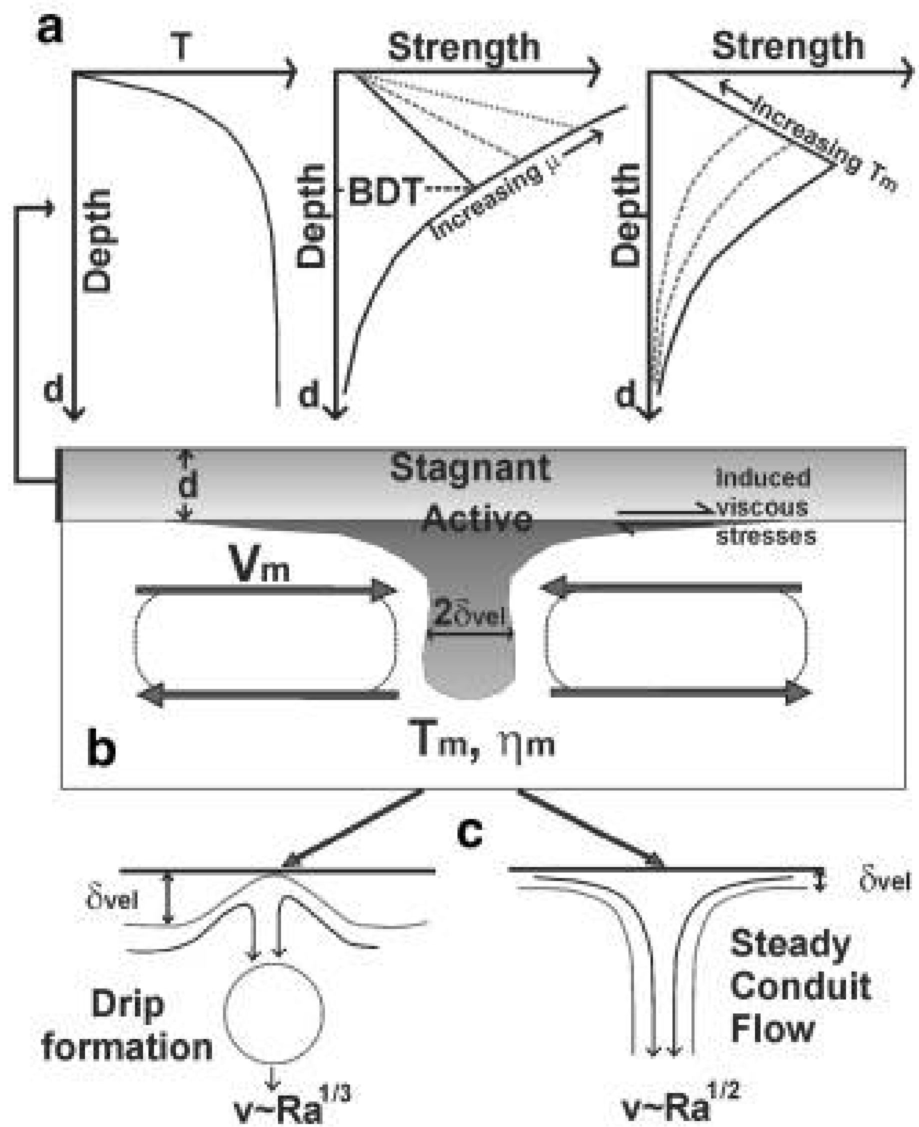
The lid behaves elastically at low stress and temperature (T) above the BDT, and viscously below the BDT. The lid fails and behaves in a brittle manner once lithospheric stresses exceed the yield stress (Y).

A strong lid of thickness d over a mantle at constant T_m, with a viscosity η_m.

The mantle is stirred by two convergent cells (shown by horizontal arrows) turning at a velocity V_m, which can vary.

The stress applied onto the lid is a function of the active downwelling velocity V_m.

Sub-lithospheric velocities due to cold-downwellings, either in the form of a sinking drip (left) or steady flow into a conduit (right).

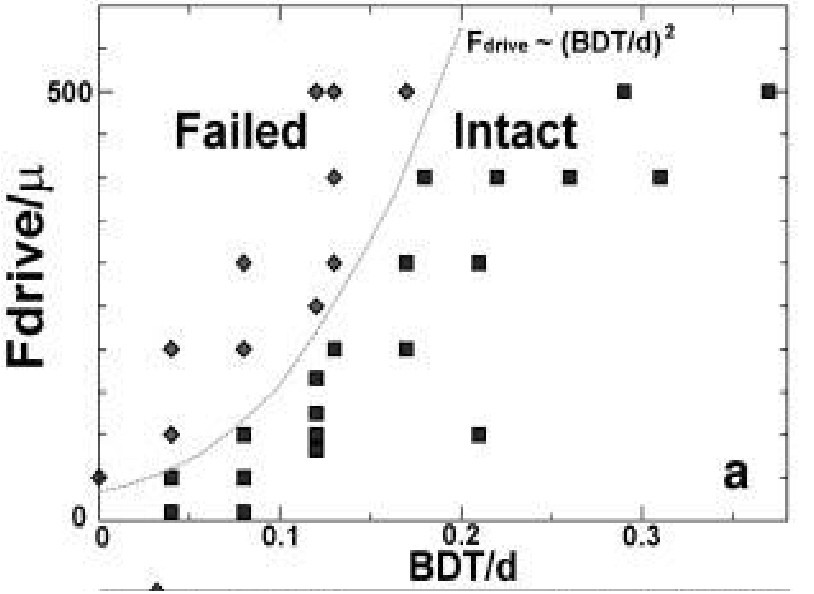


Numerical modelling :of driving forces vs. strength

$$\nabla \cdot \sigma = g\rho_0\alpha T$$
$$\sigma_{ij} = 2\eta D_{ij} - p\delta_{ij}$$

$$\frac{DT}{Dt} = \kappa\nabla^2 T + Q$$

$$\nabla \cdot v = 0$$



Linear plot of Fdrive/µ vs BDT/d (for n=1). The transition between failed and intact lithosphere follows the relationship : Fdrive ∼ 33.7 + 1.4 × 10^4(BDT/d)^2.

Mantle viscosities are temperature dependent.

$$\eta_{lid} = \frac{b}{\tau^{n-1}} e^{-\gamma T}$$

Viscosity depends on internal heating H.

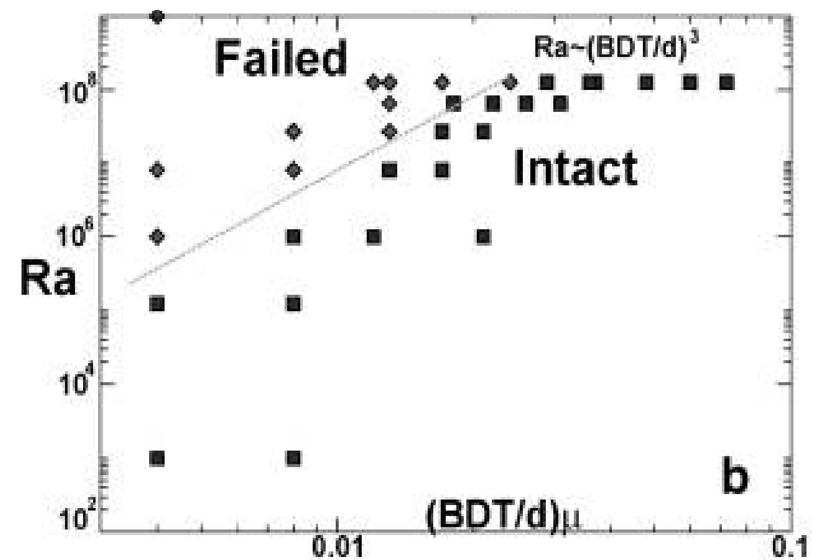
$$\ln(\Delta\eta)(=\theta) = \frac{\rho H d^2}{k\gamma^{-1}}$$

Lithospheric Rayleigh number

$$Ra_{rh} = \frac{g\rho\alpha\Delta T_{rh} d^3}{\kappa\eta_{rh}}$$

Convective stress depends on

$$Ra_{rh} = \frac{g\rho\alpha\Delta T_{rh} d^3}{\kappa\eta_{rh}}$$



Log–log plot of Ra vs. (BDT/d)µ (for n=1). The transition between failed and intact lithosphere behaves as Ra ∼ 4.4 × 10^{13}(µBDT/d)^3 .

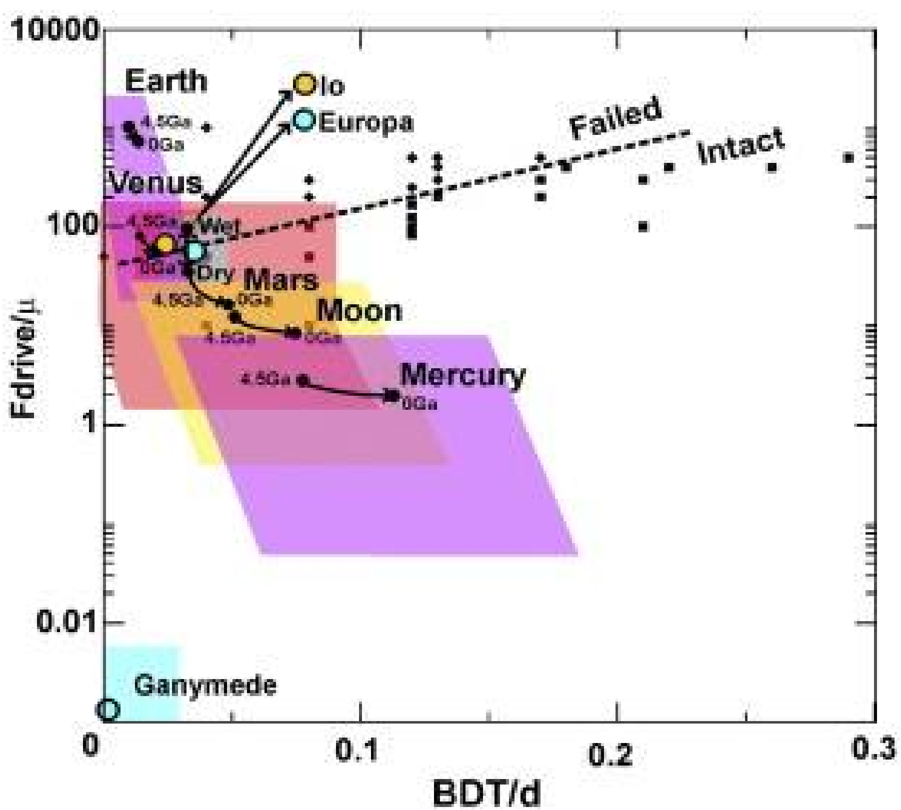
Physical properties and determined parameters for a number of terrestrial planets and icy moons

Planet/satellite	Depth of mantle (km)[a]	g (m/s^2)[b]	Ra[c]	Velocity (cm/yr)[d]	BDT (km)	Reference
Mercury	618	3.78	4.70E+04	0.130	70+/−40	(Siegfried and Solomon, 1974; Melosh, 1977)
Venus	2745	8.9271	1.92E+08	0.468	60+20/−40	(Smrekar and Stofan, 2003)[e]
Earth	2890	9.81	2.73E+08	1.000	40+/−20	(Schubert et al., 2001; Watts and Burov, 2003)
Moon	1340	1.62	9.66E+05	0.164	100+/−50	(Konopliv et al., 1998; Aoshima and Namiki, 2001)
Mars	1698	3.7278	7.26E+06	0.254	80+80/−60	(Folkner et al., 1997; McGovern et al., 2002)
Io	835	1.80	–	0.151	20+/−5	(Segatz et al., 1988; McKinnon et al., 2000)
Europa	170	1.32	–	0.631	6+5/−2	(Anderson et al., 1998; Nimmo et al., 2003)[f]
Ganymede	800	1.44	–	3.15E−6	1.3+/−0.4	(Anderson et al., 1996; Nimmo et al., 2002)[f]

[a] Determined by moment of inertia measurements on most planets to be the thickness of the convecting rocky mantle (for terrestrial bodies) or the thickness of the water ice/mush layer (for the Galilean icy satellites).

[b] From Table 14.1 of Schubert et al. (2001).

[c] Rayleigh number for a rheologically active "sublayer", $Ra = \frac{\rho \alpha g \Delta T_{rh} d^3}{\kappa \eta_{rh}}$, where ρ is the density (3400 kg/m^3), α is the thermal expansivity (3×10^{-5}),



Log-linear plot of the variation in tectonic style with increasing driving force (F) and depth to the brittle–ductile transition (BDT).

Planets and satellites for which estimates of mantle depth, elastic lithospheric thickness and mantle velocity exist (non-dimensionalized).

Driving forces at 4.5 Ga are determined assuming higher internal heat production and Rayleigh numbers .

Coloured regions indicate uncertainties.

The Astrophysical Journal Letters **736** (2011) L15
doi:10.1088/2041-8205/736/1/L15

1- Thermal condition

MANTLE CONVECTION, PLATE TECTONICS, AND VOLCANISM ON HOT EXO-EARTHS

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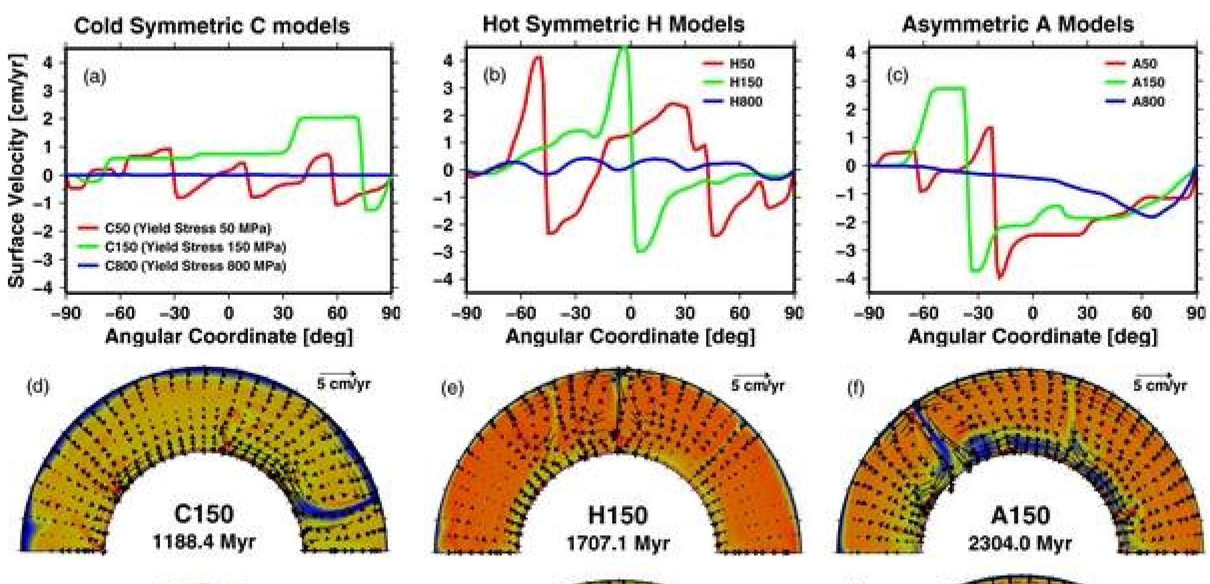
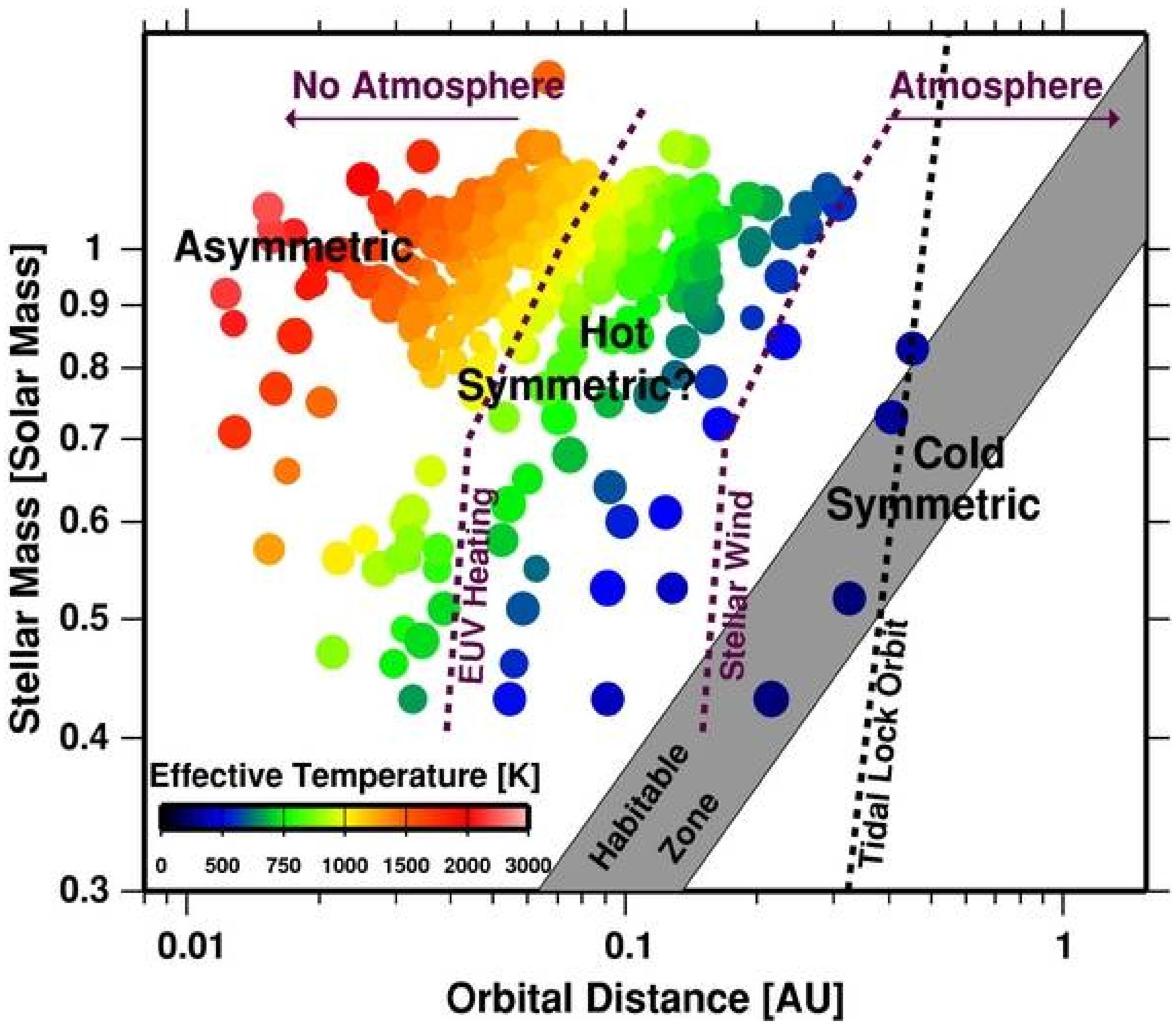
ABSTRACT

Recently discovered exoplanets on close-in orbits should have surface temperatures of hundreds to thousands of Kelvin. They are likely tidally locked and synchronously rotating around their parent stars and, if an atmosphere is absent, have surface temperature contrasts of many hundreds to thousands of Kelvin between permanent day and night sides. We investigated the effect of elevated surface temperature and strong surface temperature contrasts for Earth-mass planets on the (1) pattern of mantle convection, (2) tectonic regime, and (3) rate and distribution of partial melting, using numerical simulations of mantle convection with a composite viscous/pseudo-plastic rheology. Our simulations indicate that if a close-in rocky exoplanet lacks an atmosphere to redistribute heat, a ≳400 K surface temperature contrast can maintain an asymmetric degree 1 pattern of mantle convection in which the surface of the planet moves preferentially toward subduction zones on the cold night side. The planetary surface features a hemispheric dichotomy, with plate-like tectonics on the night side and a continuously evolving mobile lid on the day side with diffuse surface deformation and vigorous volcanism. If volcanic outgassing establishes an atmosphere and redistributes heat, plate tectonics is globally replaced by diffuse surface deformation and volcanism accelerates and becomes distributed more uniformly across the planetary surface.



Possible occupation of planets in orbital distance-stellar-mass domain space.



Purple lines show atmospheric escape estimates for EUV heating for a 6 ME, and stellar wind erosion for 1ME.

Tidal locking (black dots line) is likely at distances < tidal lock orbit.

Colored dots show effective temperatures, for Kepler candidate exoplanets with R < 2 RE.

Different dot size reflects planets size.

The theoretical habitable zone lies between the 273 and 373 K isotherms where liquid water can be maintained.

2- Where can the water come from ?

Comet : ~50 %
Carbonaceous chondrite : ~10 %
Ordinary chondrite : ~1 %
Enstatite chondrite:<0.1 %
(continuous range of compositions, Gounelle, 2011)

Albarède (2009)

Earth and chondrites are "depleted" (95% or more)

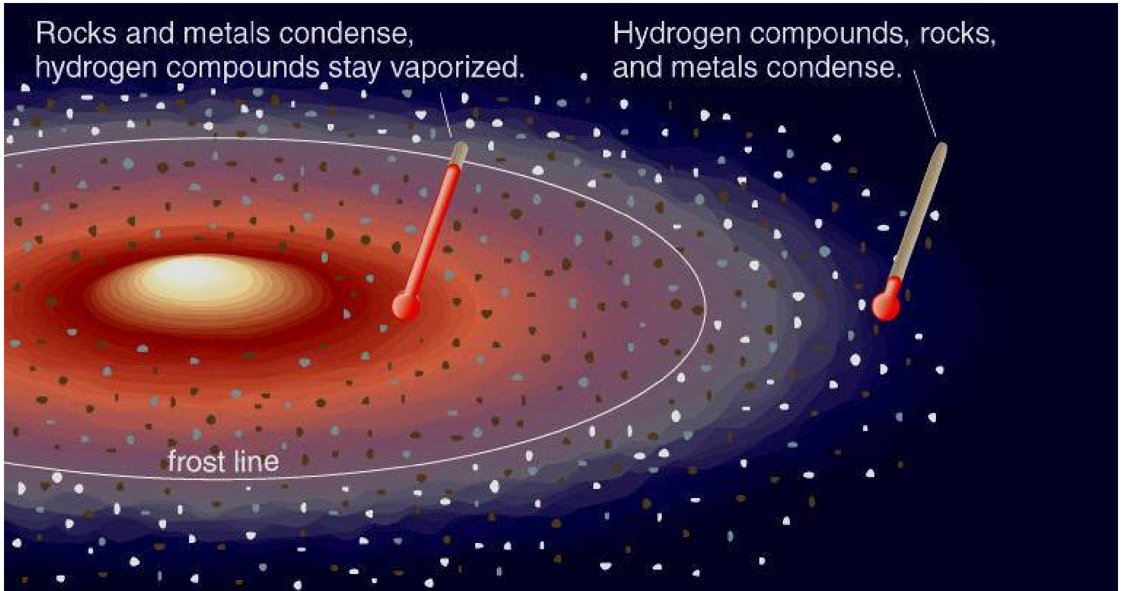
→ volatiles comes from material away from the "ice-line"

→ late stage volatile acquisition

Isotopic observations (not only D/H but also C, N isotopes)

→ The main source of water on Earth is not comets but some materials similar to common meteorites.

→ **Did most of water-rich materials come from regions beyond the ice-line in the later stage of planetary accretion?**



Vol 461|29 October 2009|doi:10.1038/nature08477 nature

PROGRESS

Volatile accretion history of the terrestrial planets and dynamic implications

Francis Albarède[1]

Accretion left the terrestrial planets depleted in volatile components. Here I examine evidence for the hypothesis that the Moon and the Earth were essentially dry immediately after the formation of the Moon—by a giant impact on the proto-Earth—and only much later gained volatiles through accretion of wet material delivered from beyond the asteroid belt. This view is supported by U–Pb and I–Xe chronologies, which show that water delivery peaked ~100 million years after the isolation of the Solar System. Introduction of water into the terrestrial mantle triggered plate tectonics, which may have been crucial for the emergence of life. This mechanism may also have worked for the young Venus, but seems to have failed for Mars.

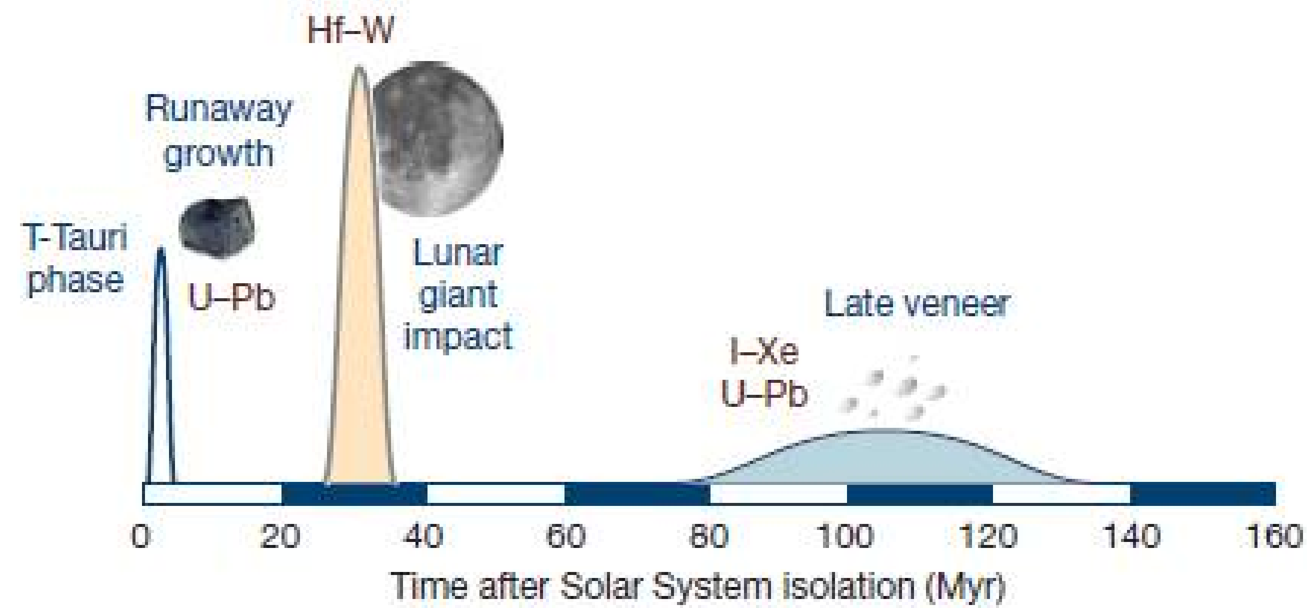
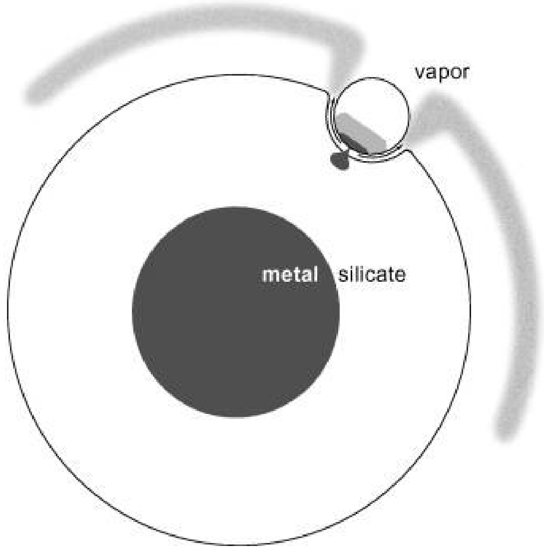


Figure 5 | A tentative chronology of the Earth's accretion. Chronometers shown in brown. Accretion of planetary material was interrupted by energetic electromagnetic radiation (T Tauri phase) sweeping across the disk within a few Myr of the isolation of the solar nebula. Runaway growth of

Icarus
Volume 222, Issue 1, January 2013, Pages 44–52

Asteroidal impacts and the origin of terrestrial and lunar volatiles

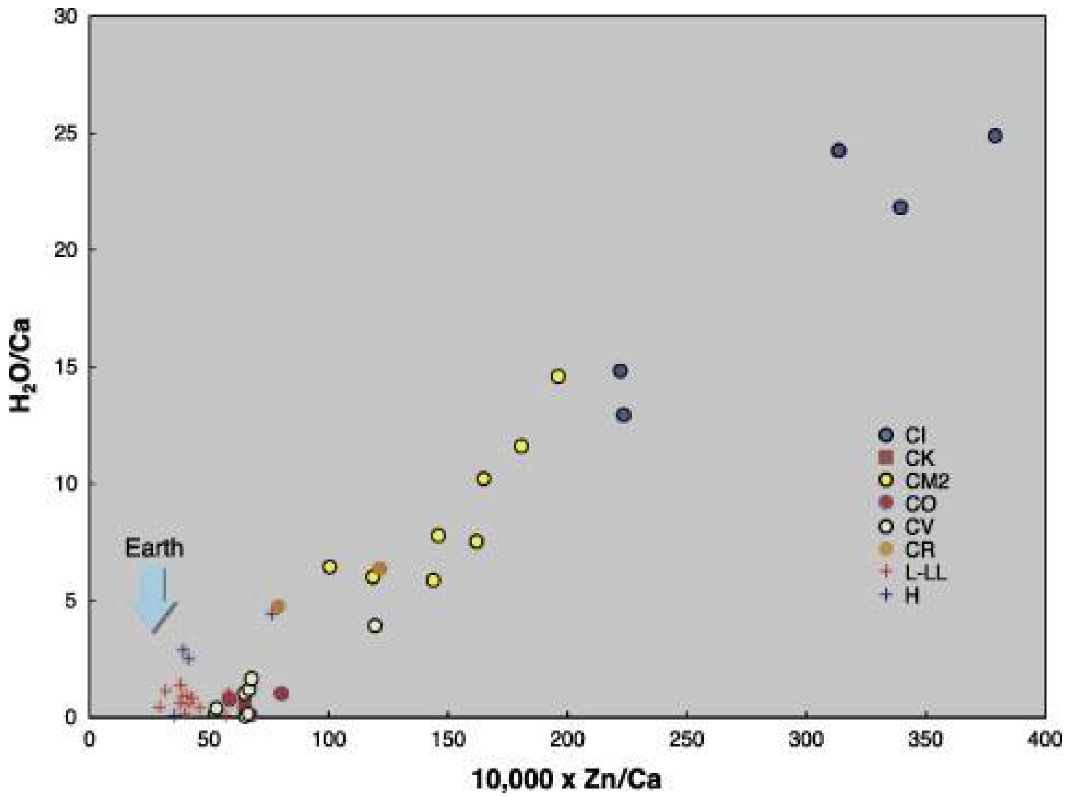
Francis Albarede[a, b], Chris Ballhaus[c], Janne Blichert-Toft[a, b], Cin-Ty Lee[b], Bernard Marty[d], Frédéric Moynier[e], Qing-Zhu Yin[f]



Asteroids impacting the Earth partly volatilize, partly melt. While metal rapidly segregates out of the melt and sinks into the core, the vaporized material orbits the Earth and eventually rains back onto its surface.

The siderophile and chondritic content of the mantle hence is accounted for, not by the impactors themselves, but by the vapor. The impactor’s hydrogen, is added to the mantle and hydrosphere.

The addition of late veneer may have lasted for 130 Ma after isolation of the Solar System. Constraints from the stable isotopes of oxygen and other elements suggest that **~4% of CI chondrites accreted to the Earth.** The amount of water added in this way and now dissolved(oxidized Fe in the mantle an core), may correspond to 10–25 times the mass of the present-day ocean.



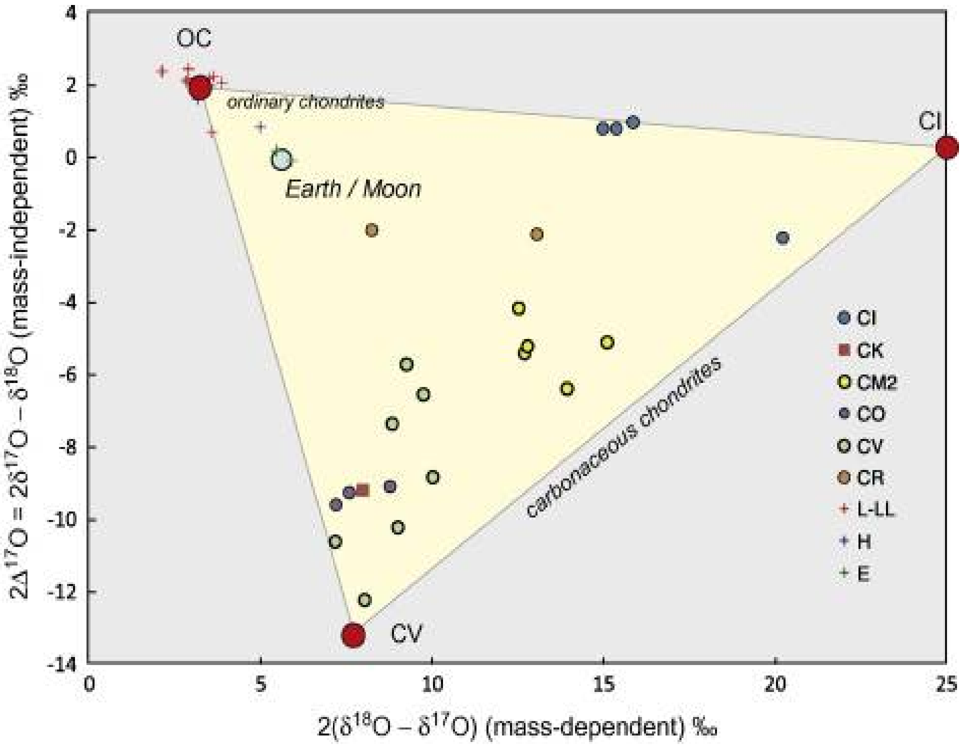
Water-bound hydrogen in the Solar System behaves coherently with respect to other volatile elements.

For example, once normalized to refractory calcium, Zn and water in chondrites are remarkably well correlated. Nitrogen(N2 and NH3), and carbon (CO2 and CH4), show similar trends.

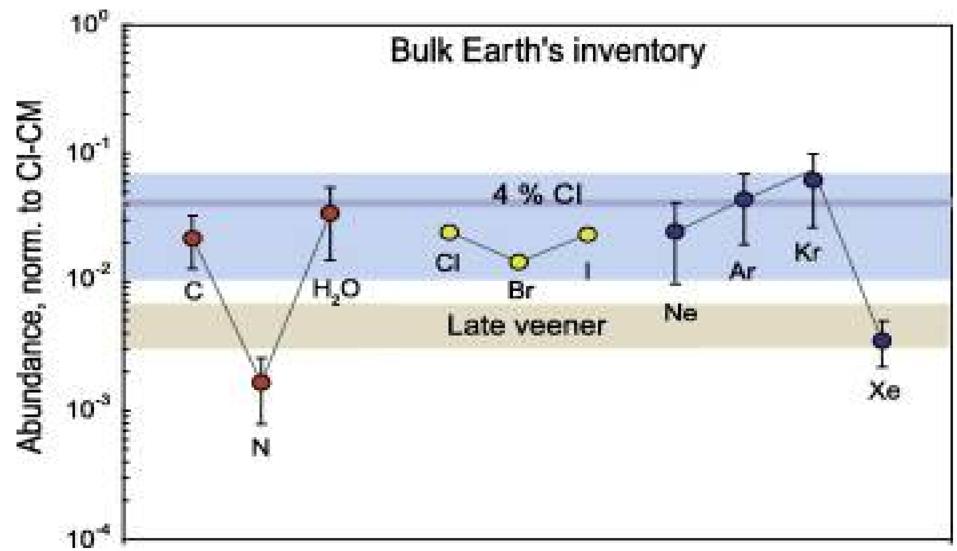
The choice of a refractory element reflects mixing between distinctive planetary components, one nearly volatile-free and the other remarkably rich in H, C, N, and Zn.

The volatile-free component is itself a binary mixture.

Oxygen isotope compositions of the Earth and different groups of chondrites.



CI-normalized concentrations of terrestrial volatile elements compared with predictions by the conventional late veneer assumption (brown) and by the addition of 4% CI chondrites.



The addition of small proportions of CI chondrites (15–20% water and 310 ppm Zn) to anhydrous chondrites is the only efficient way for a terrestrial planet to acquire significant amounts of water. Such a mixture should be detectable with oxygen isotopes.

In order to explain the heterogeneities of oxygen isotope abundances across the Solar System, it has been suggested that water ice scattered beyond the *frost line had* dynamics of its own, hence making its distribution with heliocentric distance a critical parameter of planetary water content.

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Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl

Plate tectonics on super-Earths: Equally or more likely than on Earth

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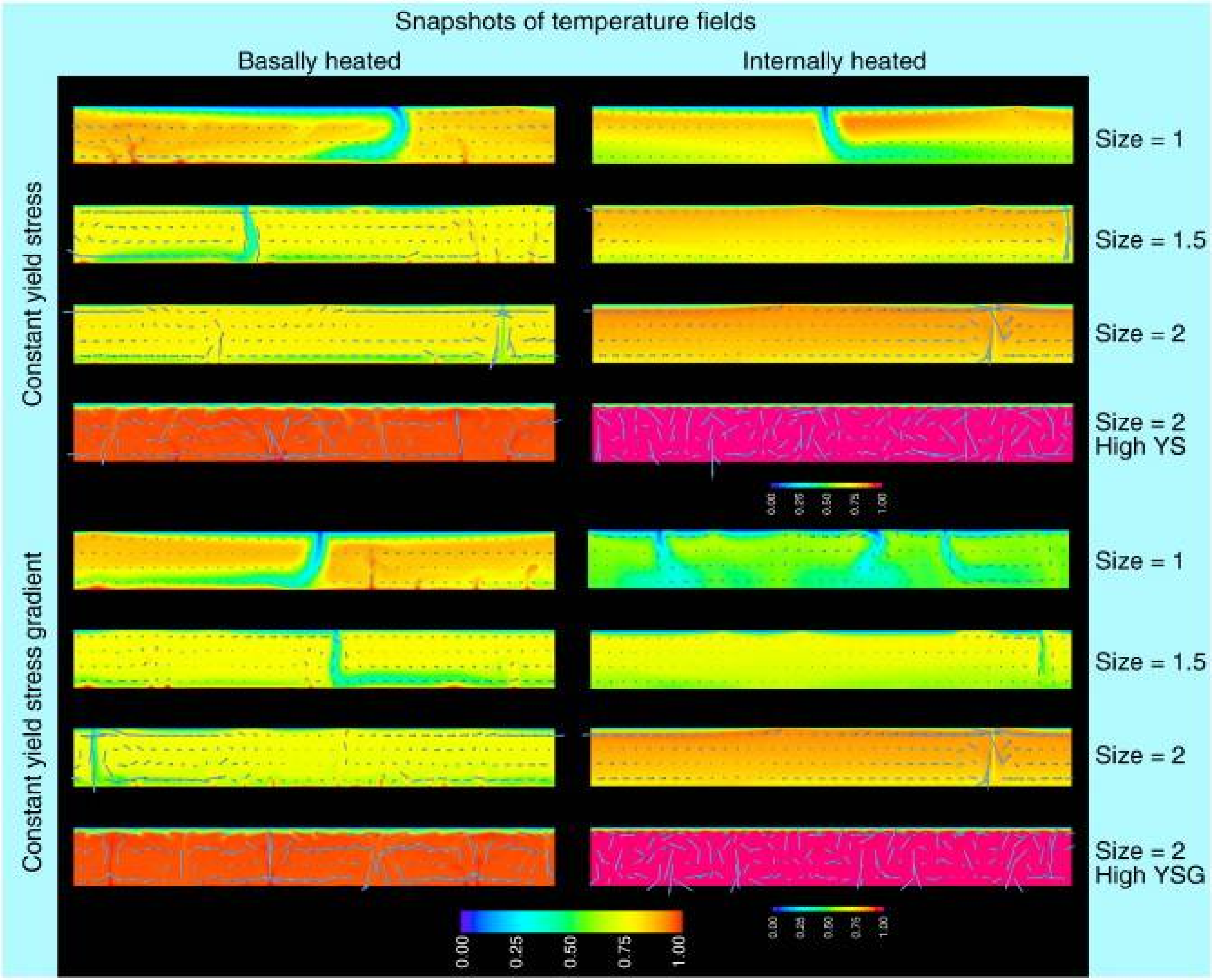
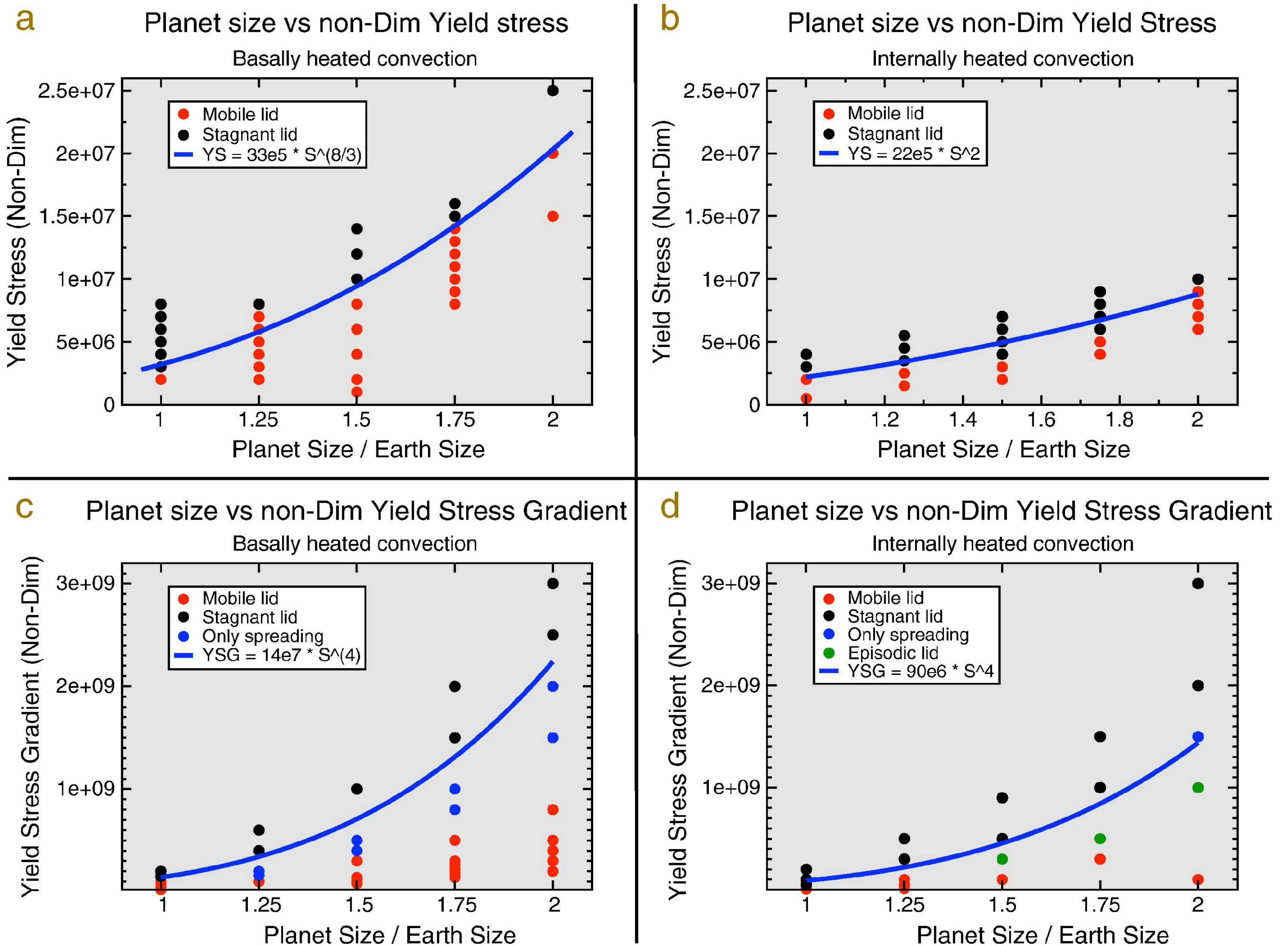
Extra-solar super-Earths are likely to be undergoing active plate tectonics or be stagnant lids like Mars and Venus. The origin of plate tectonics is poorly understood for Earth, involving a complex interplay of rheological, compositional, melting and thermal effects, and remains challenging to make predictions for other planets. One numerical study on super-Earths finds that plate tectonics is less likely on a larger planet (O'Neill and Lenardic, 2007), in contradiction with an analytical scaling study (Valencia et al., 2007). We here present new calculations of yielding-induced plate tectonics as a function of planet size, focusing on idealized end members of internal heating or basal heating, and strength.

We model super-Earths as simple scaled up versions of Earth, i.e., assuming constant physical properties, keeping the ratio of core/mantle radii constant and applying the same temperature difference between top/bottom boundaries and the same internal heating rate. Effects that originate outside of the planet, such as tidal forces, meteor impacts and intense surface heating from a nearby star are not considered. We find that for internally-heated convection plate tectonics is equally likely for terrestrial **planets of any size,** whereas for basally-heated convection plate tectonics becomes more likely **with increasing planet size.** This is indicated both by analytical scalings and numerical results. When scalings are adjusted to account for increasing mean density with increasing planet size, plate tectonics becomes more likely **with increasing planet size**. The influence of pressure dependant viscosity, thermal expansivity and conductivity may however, act in the opposite sense. In general, the presence of surface water is most important for determining the occurrence of plate tectonics.



For each scenario 4 snapshots: mobile lid convection for size 1, 1.5 and 2, plus stagnant lid convection (with a higher yield stress YS or yield stress gradient YSG) for size 2 (with pink color scale since internal non-dimensional temperatures exceed 1).



a
Planet size vs non-Dim Yield stress
Basally heated convection
Mobile lid
Stagnant lid
YS = 33e5 * S^(8/3)
Yield Stress (Non-Dim)
Planet Size / Earth Size
b
Planet size vs non-Dim Yield Stress
Internally heated convection
Mobile lid
Stagnant lid
YS = 22e5 * S^2
Yield Stress (Non-Dim)
Planet Size / Earth Size
c
Planet size vs non-Dim Yield Stress Gradient
Basally heated convection
Mobile lid
Stagnant lid
Only spreading
YSG = 14e7 * S^(4)
Yield Stress Gradient (Non-Dim)
Planet Size / Earth Size
d
Planet size vs non-Dim Yield Stress Gradient
Internally heated convection
Mobile lid
Stagnant lid
Only spreading
Episodic lid
YSG = 90e6 * S^4
Yield Stress Gradient (Non-Dim)
Planet Size / Earth Size

Earth and Planetary Science Letters

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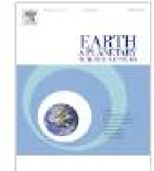


Frontiers

Water distribution across the mantle transition zone and its implications for global material circulation

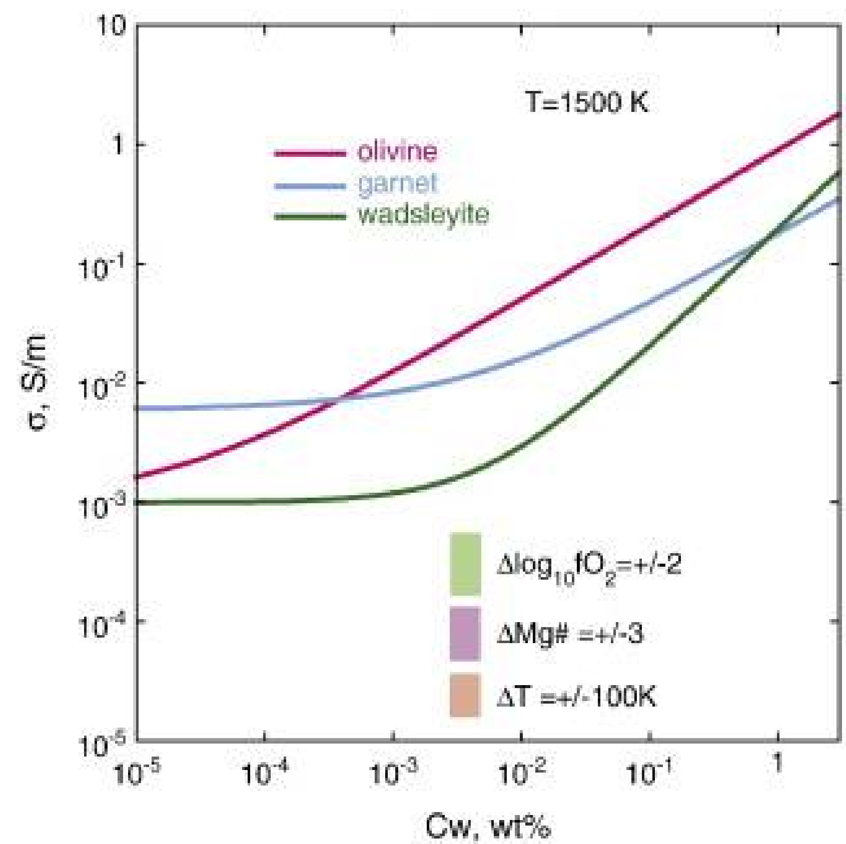
Shun-ichiro Karato

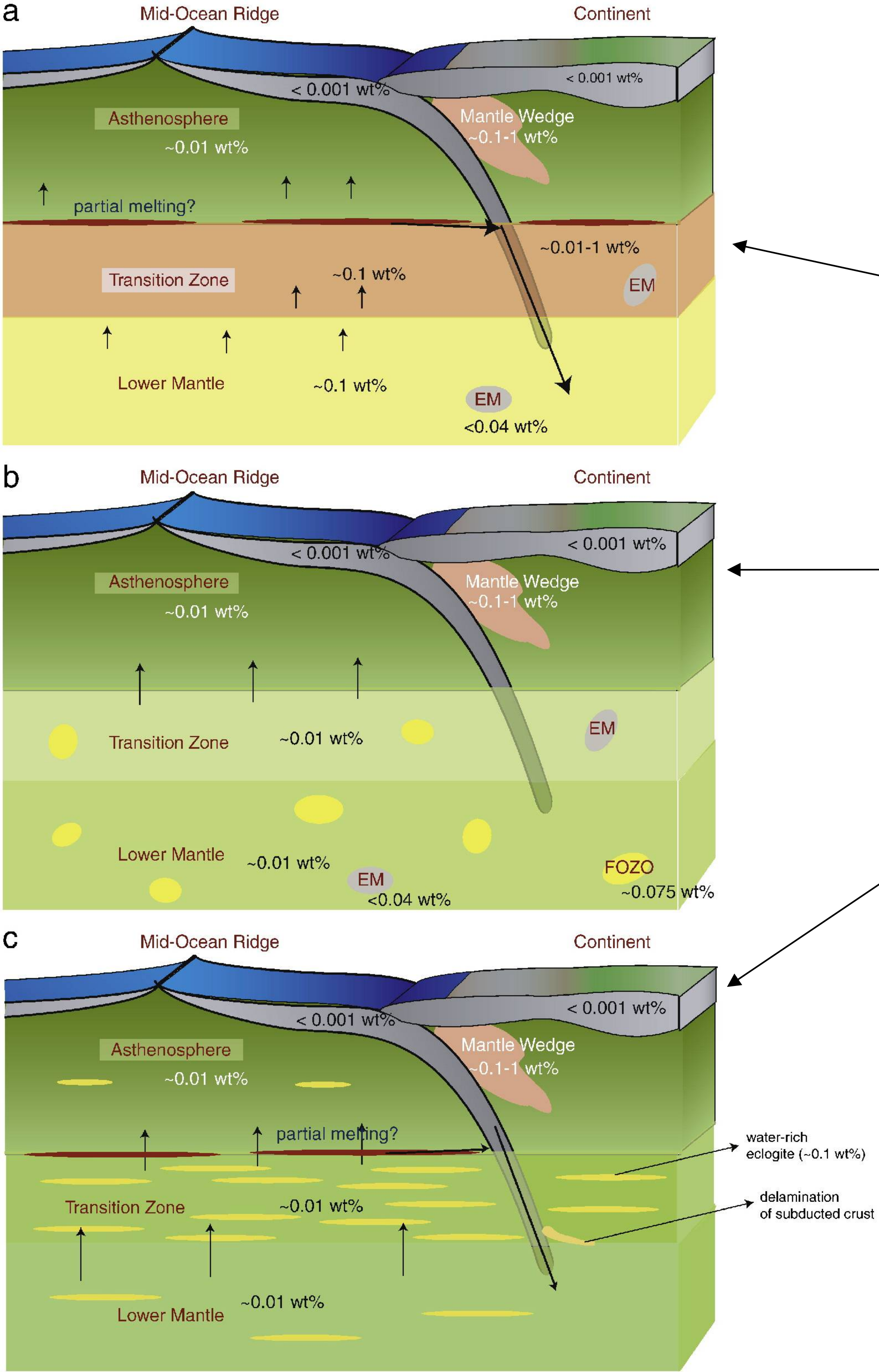
Yale University, Department of Geology and Geophysics, New Haven, CT 06520, USA

Influence of water content (CW) on electrical conductivity (σ) at 1500 K in olivin, garnet and wadsleyite (15 GPa) and fO2 (oxygen fugacity).

MORB : formed by melting eclogite-poor rock,
OIB : formed by melting of eclogite-rich rock.

If eclogites are connected or if they are distributed as fine lamellae
=> MTZ will have higher conductivity than the upper mantle : consistent with the electrical conductivity observations.



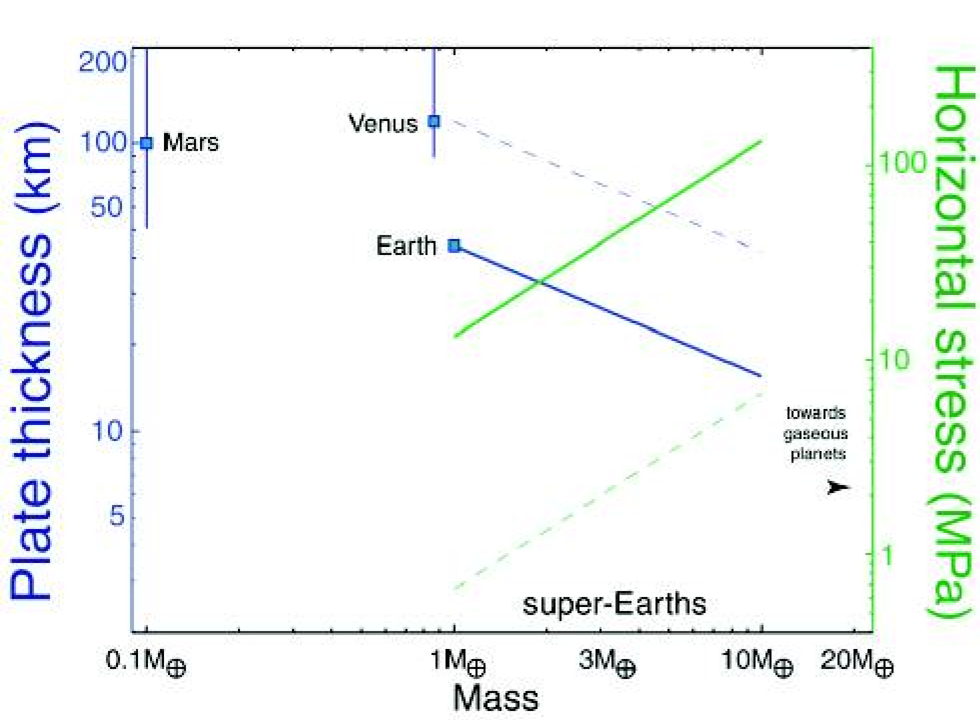


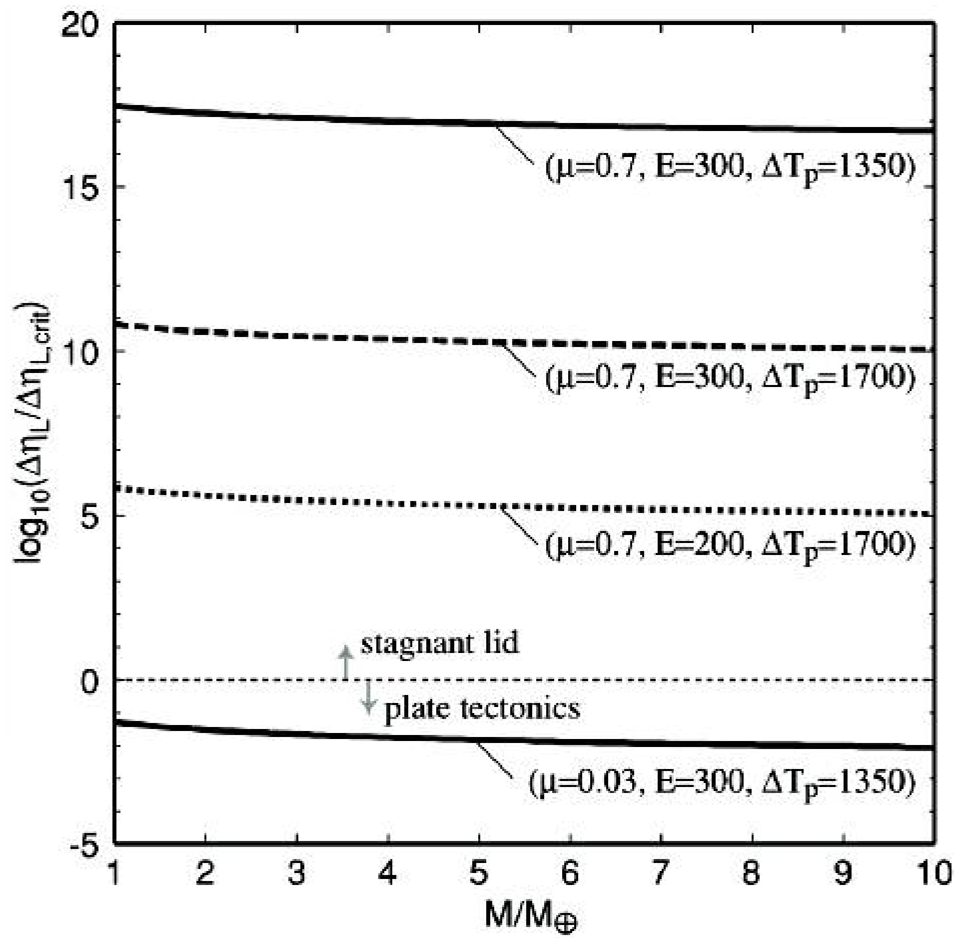
Models of water distribution based on the geochemical observations of water in basalts assuming that water-rich regions are in the lower mantle.

In model b) the source regions of OIB occur as patchy regions occupying ~7% of the mantle. If water-rich regions occur homogeneously or only in the lower mantle, then such a model is not supported by the observation of **electrical conductivity.**

In model c), the volume fraction of water-rich (eclogite material) is assumed higher in the MTZ than in the upper mantle.

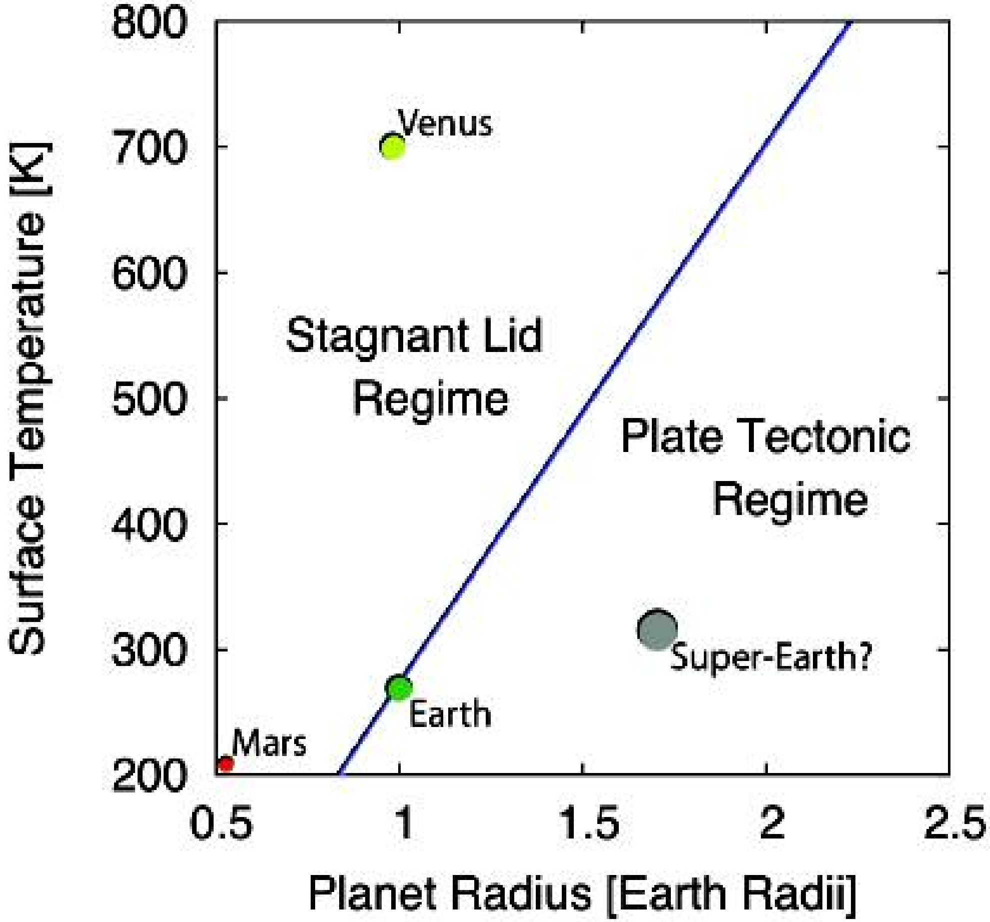
Still open debate on conditions for plate tectonics





Valencia-O'Connell (2007):
Planetary mass is most important
→ large mass → high Rayleigh number
→ large driving force + thin plate

Korenaga (2010) : **friction coefficient** (strength of lithosphere) is most important, the planetary mass is NOT important



Foley-Bercovici (2012):

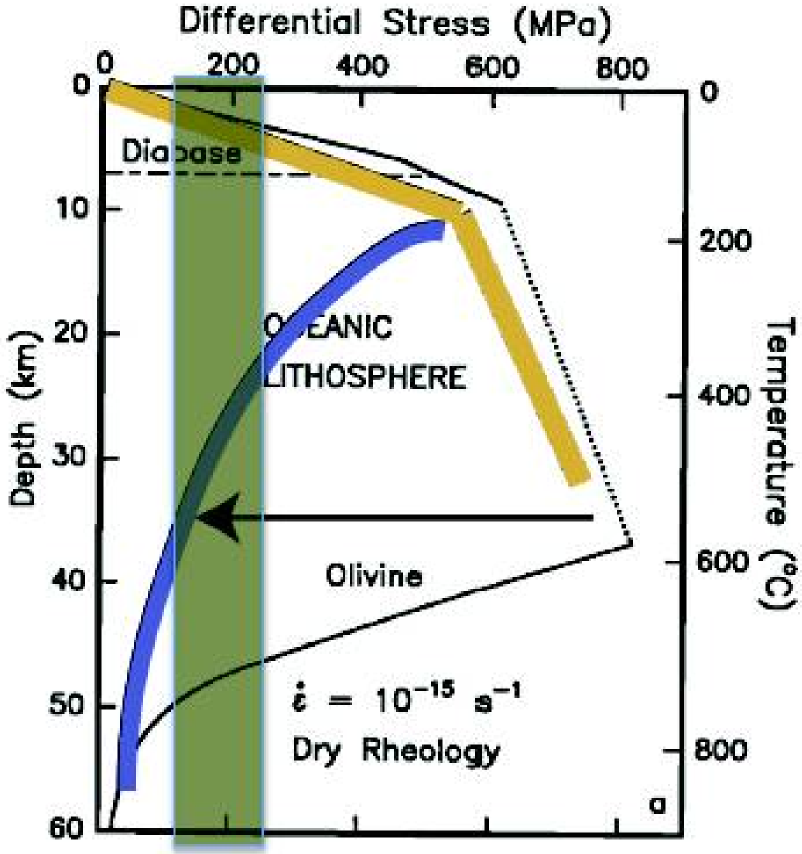
Plate strength is controlled by **grain-size reduction**. Driving force increases with planet size.

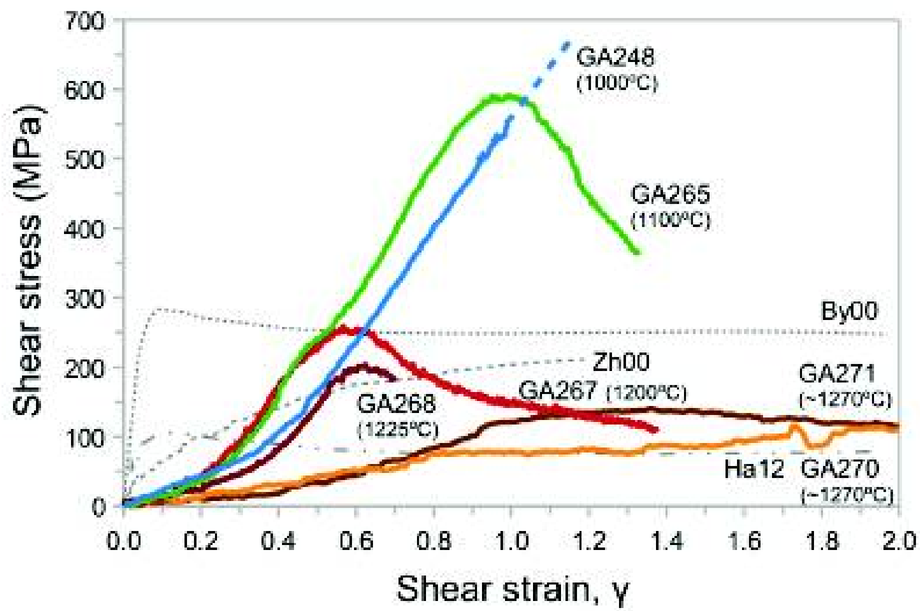
Grain-size reduction depends on (near surface) temperature through grain-growth.

Both planet size and surface temperature are important.

How to weaken the lithosphere?

Brittle ←→ Ductile



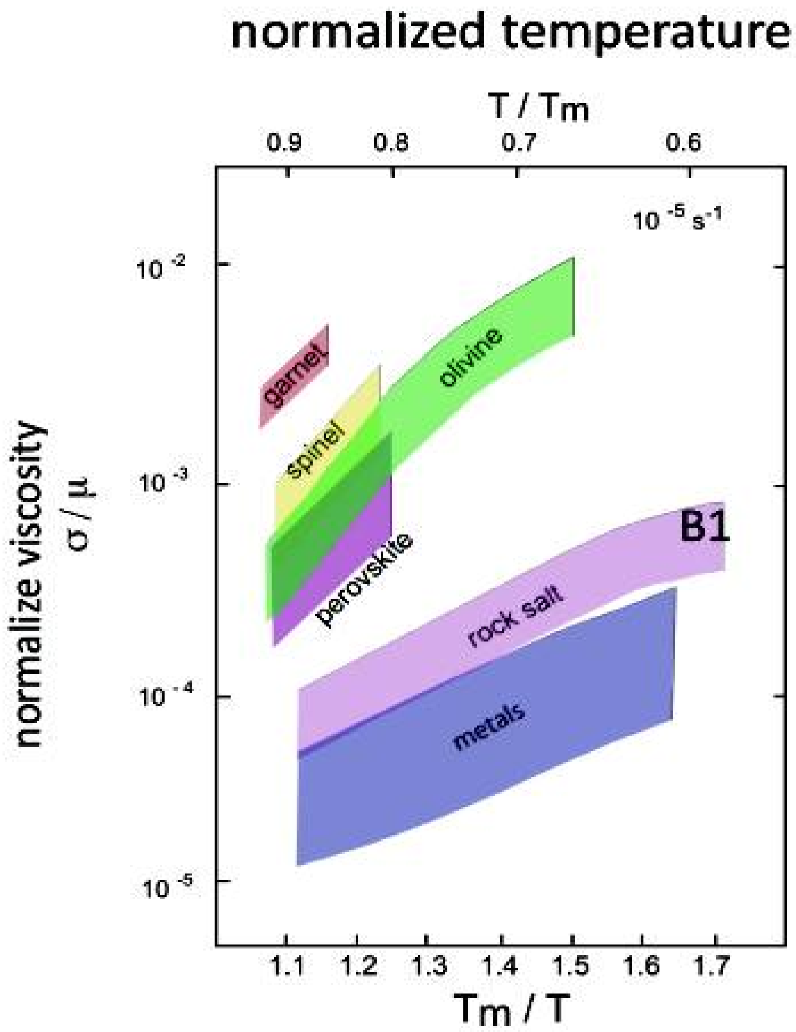


Farla et al. (2012, submitted)

V

Weakening in the ductile regime depends on T and water content.

Viscosity changes also with crystal structure/ chemical bonding.



In most of super-Earth's mantle, MgO is the softest phase.
MgO changes its structure from B1 to B2 at ~0.5 TPa. B2 structure is softer than B1 structure.

(modified from Karato (1989))

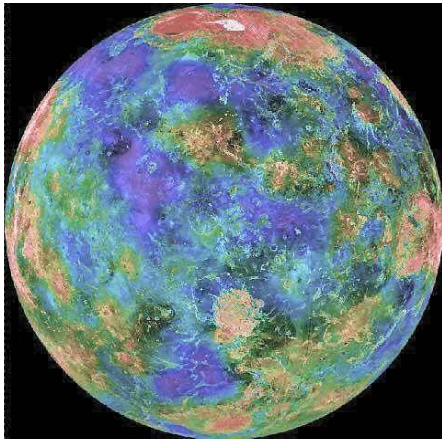
Conclusions

(According to Karato)

- In order to assess if **Plate Tectonics** occurs on other planets (e.g., super-Earths), we need to know what controls the magnitude of **driving force** and the **resistance for plate deformation.**

- **Major remaining issues**:
  Physical mechanisms of **localized deformation**
  Dependence of viscosity on **pressure** (phase transformations)

- **Volatile acquisition during planetary formation**
  - early or late acquisition? (→ H in the core?)
    - geochemical observations
  - liquid phases control volatile acquisition
    - volatility ←→ affinity to liquids (to Fe etc.)
- **Volatile circulation in a planet**
  (longevity of the surface ocean)
  - The role of deep (mid-) mantle melting
  - Plate tectonics on other planets?
    - "rheological properties"
      - shear localization, deep mantle viscosity

The primary difference between **Earth** and **Venus**, is free water at the surface.

This lowers the friction coefficient μ (0.6 to 0.15), and reduceslithospheric strength.

Free surface water results in the alteration of fault zones (chemical), and influences the pore pressure (pf), which reduces rock strength by on order of magnitude. The estimated maximum sustainable stress is 50–200 MPa for Earth.

If Venus had surface water at any time in its past, it could have been in an active-lid mode of convection. Even without water, it could have been in an active-lid regime, because higher temperatures increased convective velocities and lowered Te.

Its position on the transition of the stagnant-lid regime today is consistent with the recent (∼ 750 Ma) cessation of surface activity, and also permits the possibility of an episodic style of convection.

While **Mars** is probably in a *stagnant regime now*, at 4Ga there would have been higher convective velocities, thinner thermal boundary layers, and surface water. Therefore it would have bee in *active-lid regime*. Crustal magnetization in the Southern Highlands requires the existence of a dynamo on early Mars, suggesting *plate-tectonics*.

On the **Moon** and **Mercury** , there is no evidence of surface water, and both are predicted to have been *stagnant* for their entire history.

Io is the most volcanically active body in the solar system as a result of severe tidal heating from Jupiter. In fact, its predominant mode of heat loss is by volcanic resurfacing, and so it is clearly *NOT in a "classic" stagnant lid mode, a*nd in the *transition between active and stagnant lid regimes.* Mountain ranges over ∼ 2% of Io's surface show evidence of uplift and thrusting.

Similarly for **Europa**, the observed surface tectonic activity may be intrinsically endogenic, independantly from tidally-induced cracking.Evidence for *convergent features* strongly suggests internal convective motions. Based on the lack on cross-cut impact craters, Europa's surface is estimated to be *very young* (30–80 Myr), and since then the regime switched to a more cryovolcanic-dominated one. This is also consistent with the inferred thickening of the elastic lithosphere. Europa would thus be in *an episodic regime similar to Venus*.

In contrast, despite having a relatively small elastic lithosphere, the extremely small strain rates estimated for the icy shell of **Ganymede** preclude any surface deformation other than *tidally-induced tectonic features*.