Strain-dependent strength profiles
Implication of planetary tectonics

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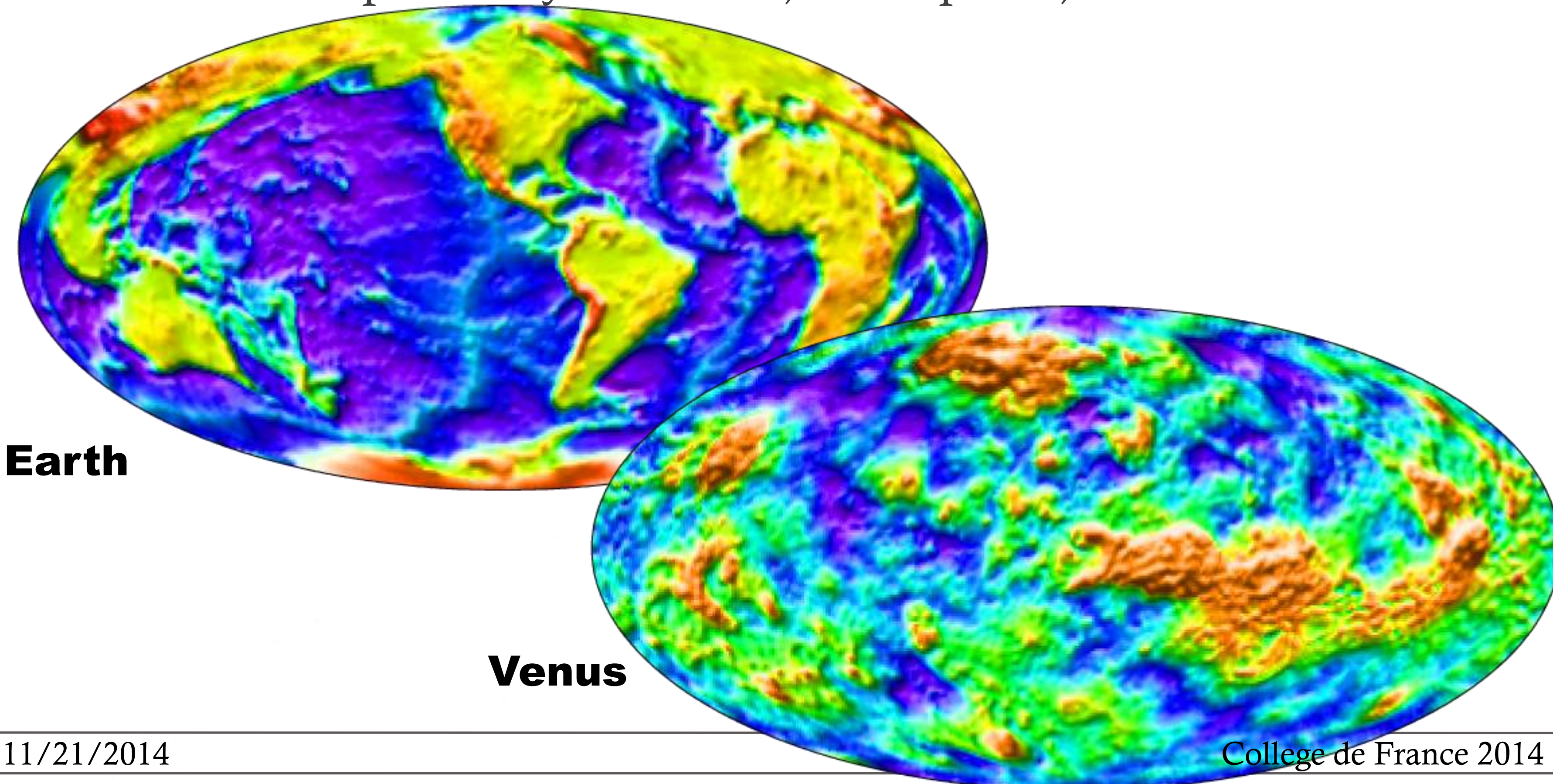
Plate Tectonics: Only on Earth!

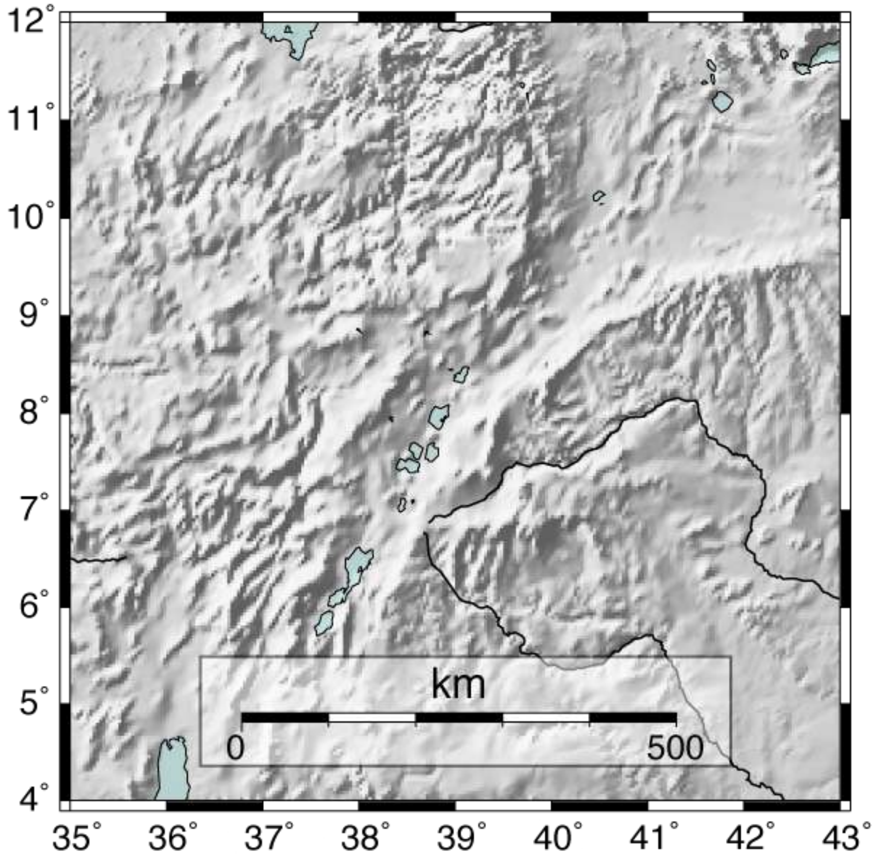
- Grand challenge problem in Solid Earth Sciences (NAS report, 2008)
- Affects planetary evolution, atmosphere, life?



Extension on Earth and Venus

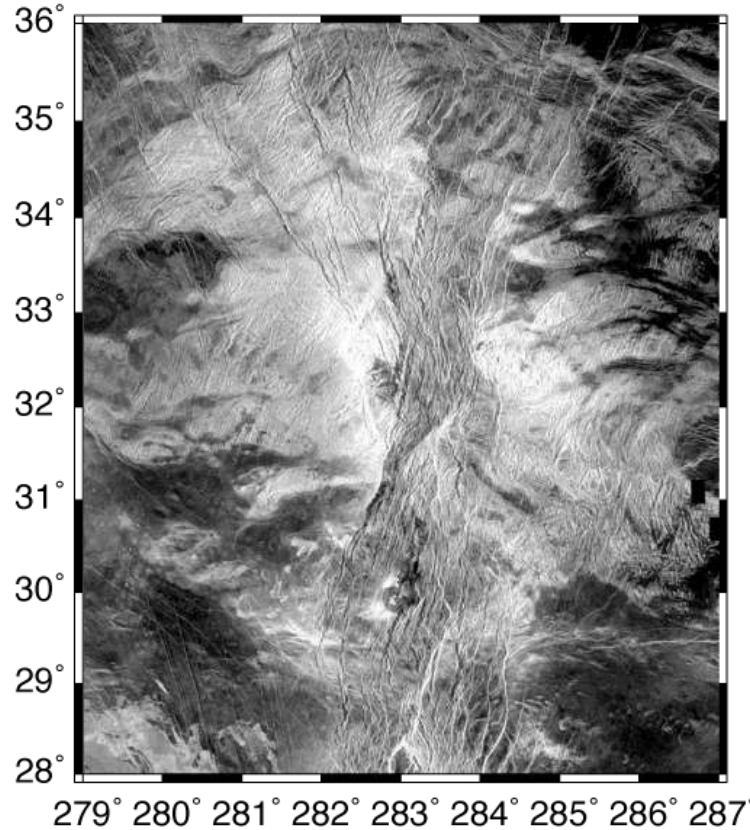
Extension

Earth



Main Ethiopian Rift

Venus

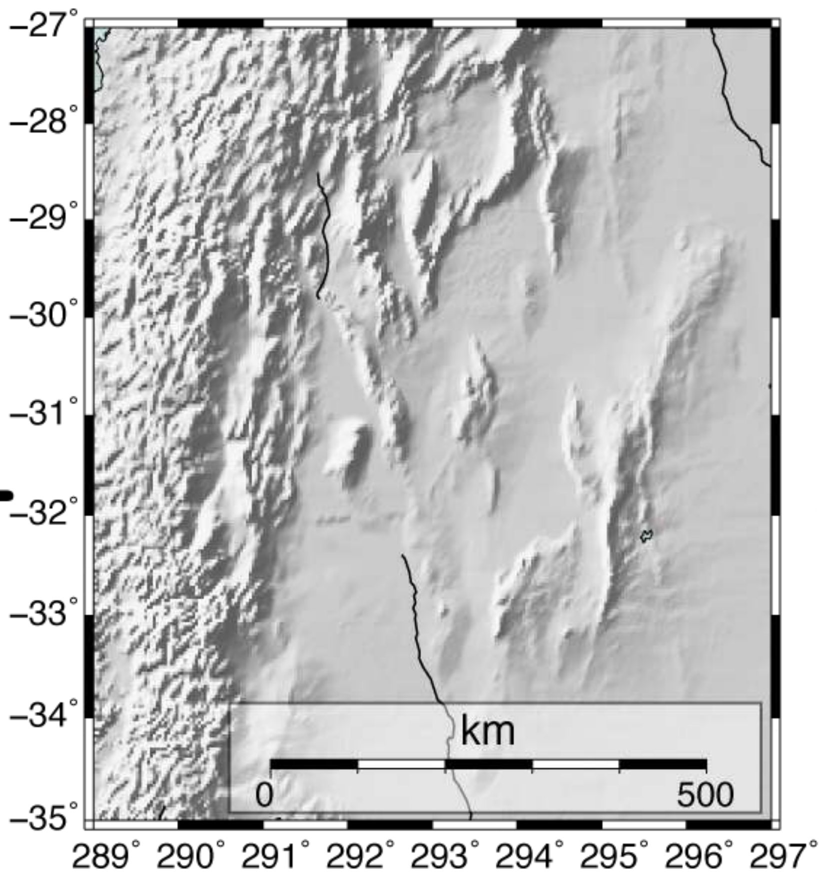


Devana Chasma

Shortening on Earth and Venus

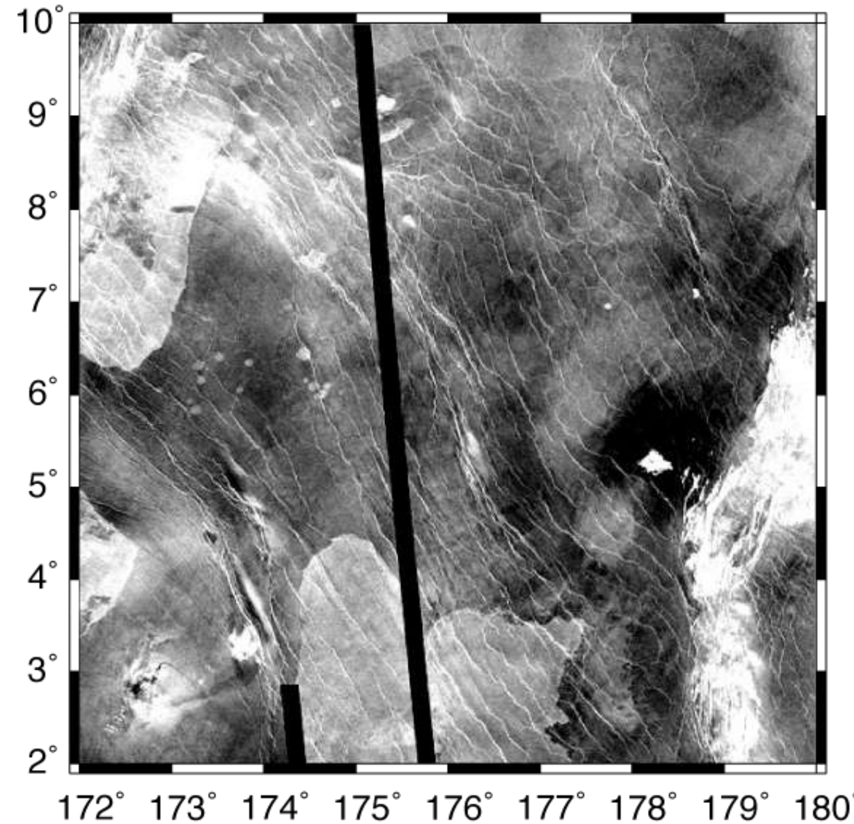
Earth

Compression



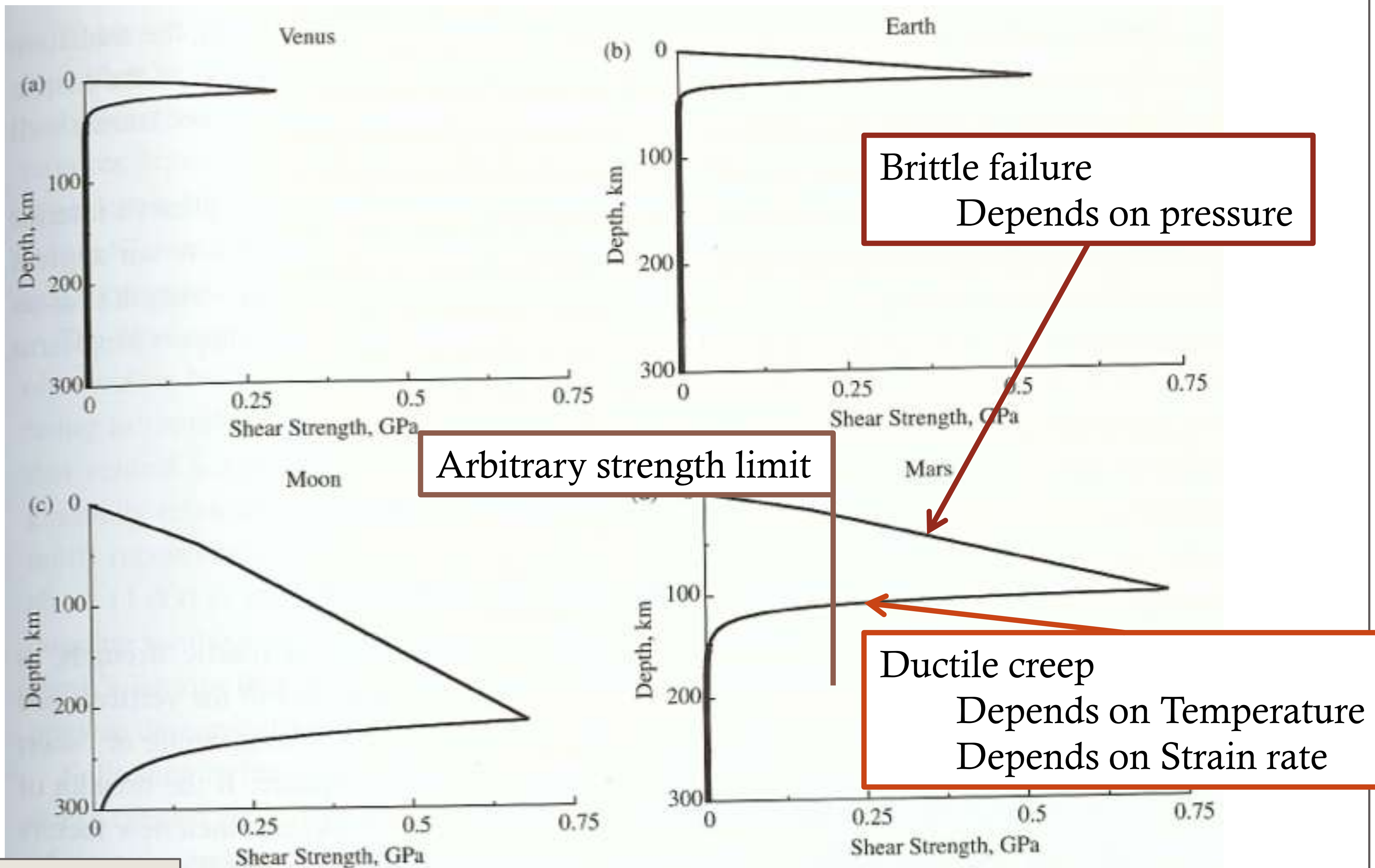
Sierra Pampaneas

Venus



Yalyane Dorsa

Strength envelopes (classical)

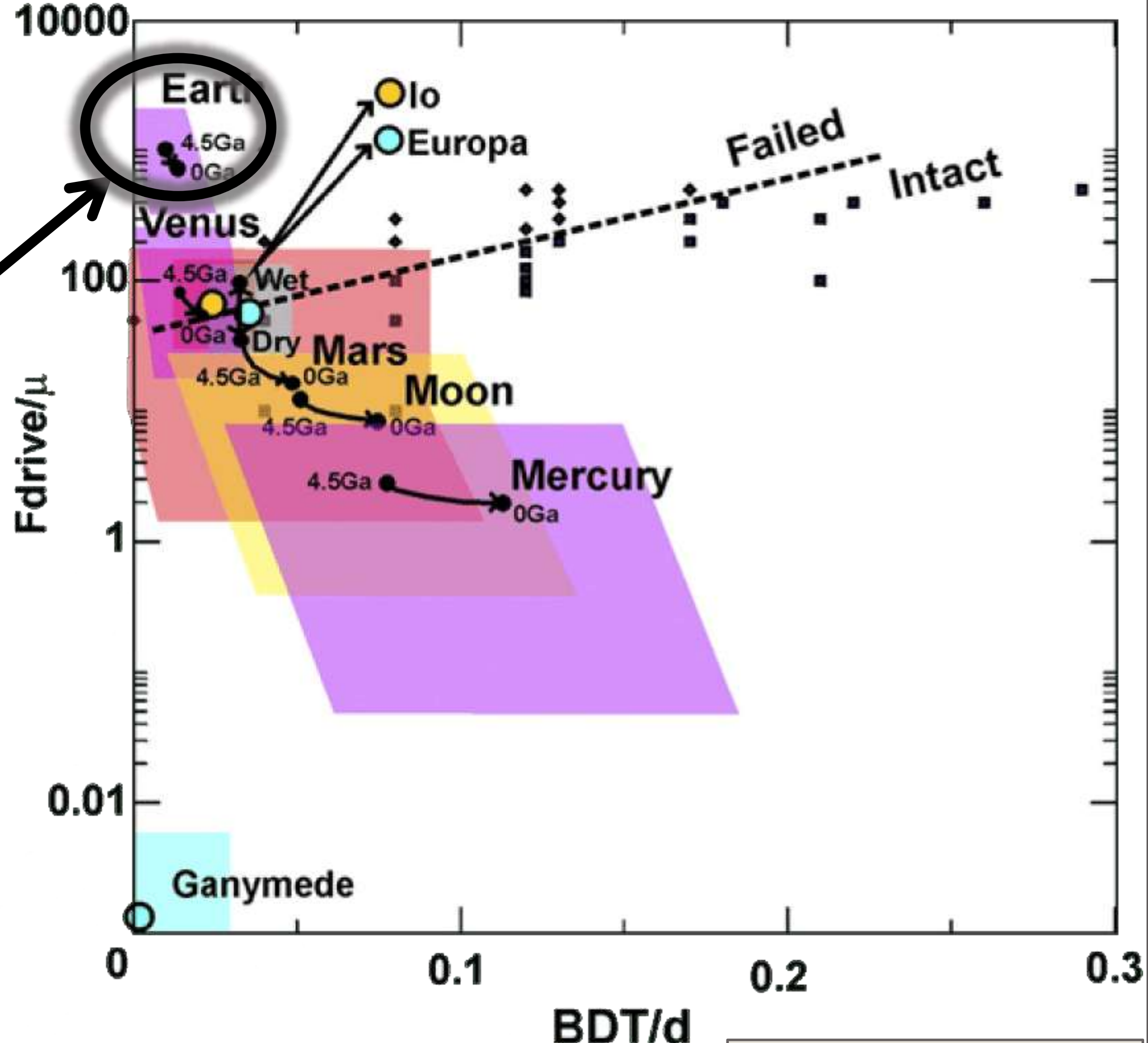


Melosh, 2011

A plate tectonic recipe

- Vigorous convection
- Weak deformation zones

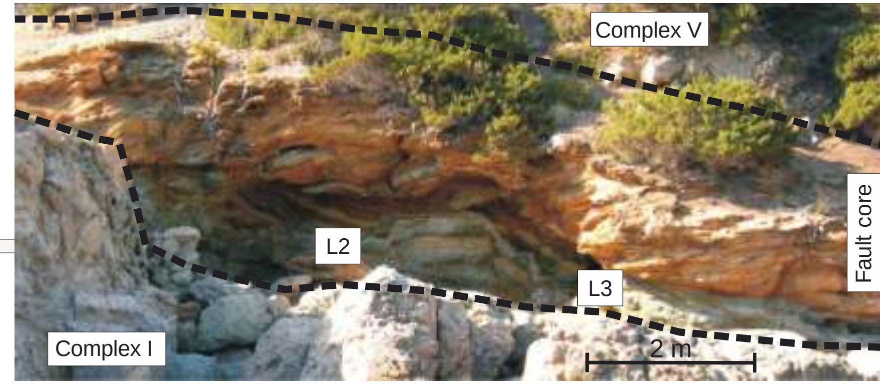
Weakened arbitrarily



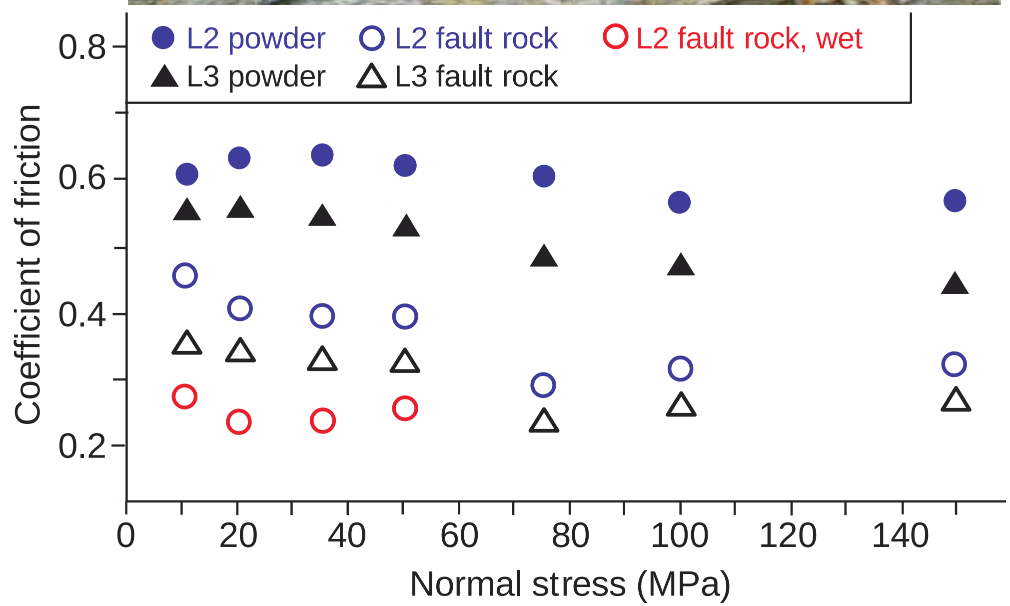
- *What mechanism weakens plate boundaries?*
- *Which mechanisms are active only on Earth*
- *Is the "strength" all that is needed?*

O'Neill et al., 2007

Weakness of brittle faults



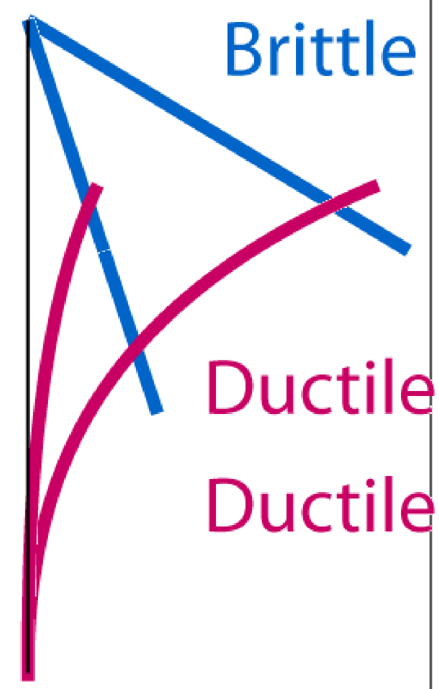
- Fault rocks contain weak minerals (smectite, talc and minor chlorite).
- Low friction results from slip on a network of weak phyllosilicate-rich surfaces that define the rock fabric



Collettini et al., 2009

Which level is weak?

- Low yield strength of the lithosphere
  - Solomatov (2004): <~3MPa
- Low brittle strength
  - Friction coefficient of 0.15 (O'Neill et al. 2007)
    - Serpentine? (Moore et al., 2007)
  - High pore fluid pressure
- Low ductile strength
  - Necessary to reconcile low coefficient of friction and depth to brittle-ductile transition
  - Ductile shear zones



The San Andreas Fault at depth?

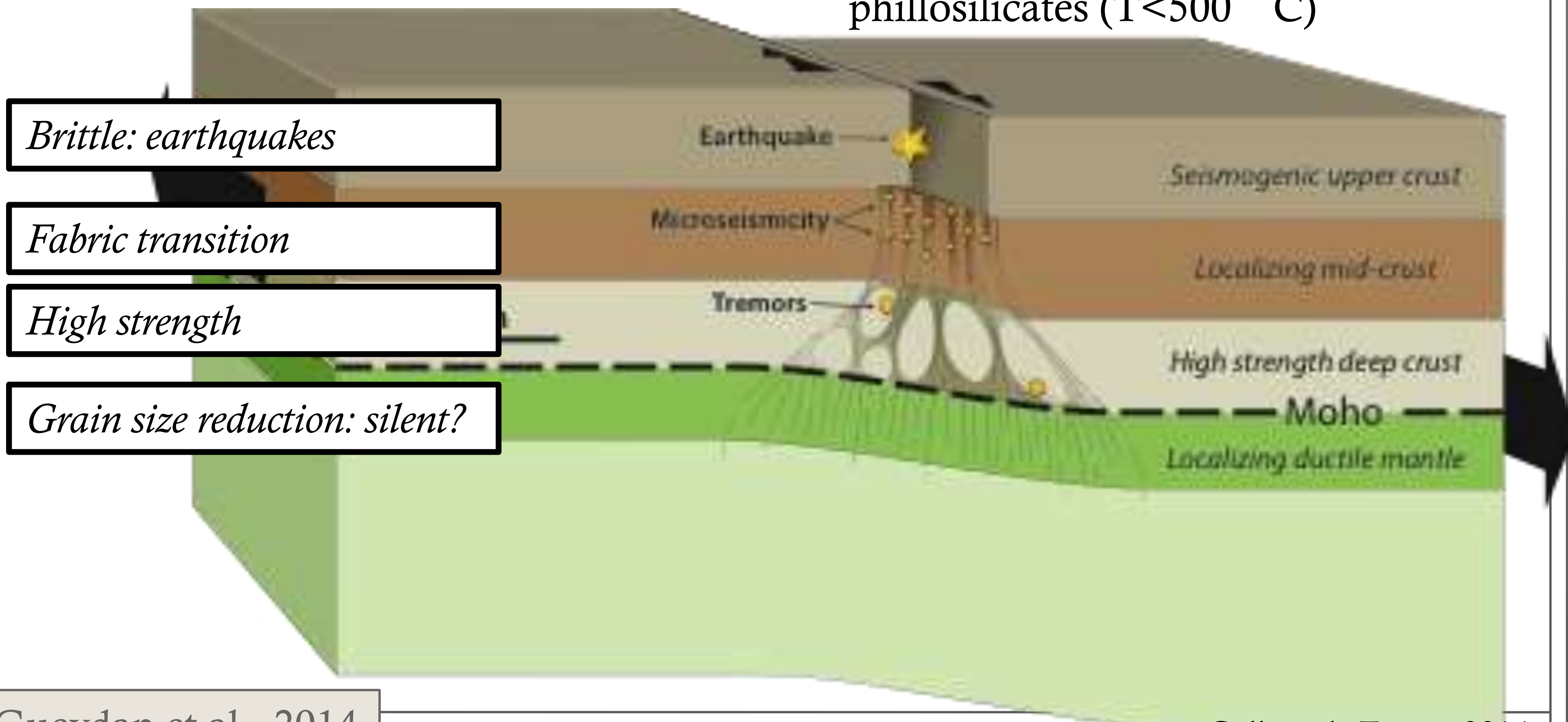
Brittle failure

Need fluids and/or serpentine

Ductile failure

In the mantle when dis-GBS is possible (T<700° C)

In the crust in presence of phillosilicates (T<500° C)



Gueydan et al., 2014

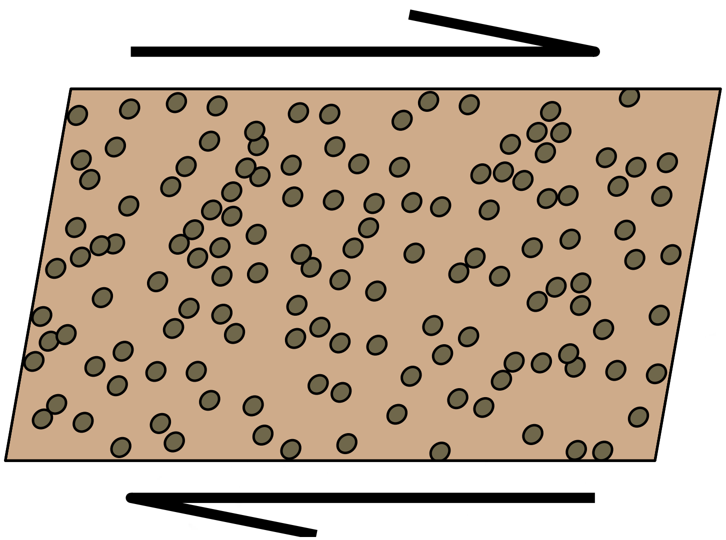
Ductile shear zone structure

- Requires change in state or environment
  - Temperature
  - Grain size
  - Interconnection of weak phase
  - Abundance of weak phase
  - Composition (metamorphism, melt)

L-S tectonites, South Armorican Shear Zone
F. Gueydan, personal communication, 2006

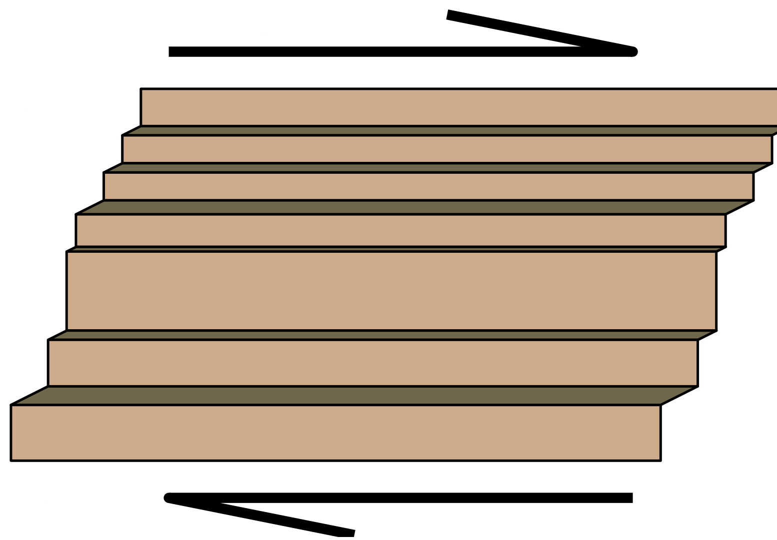
Fabric and rheology

Protolith (uniform strain)



Strength controlled by strong phase

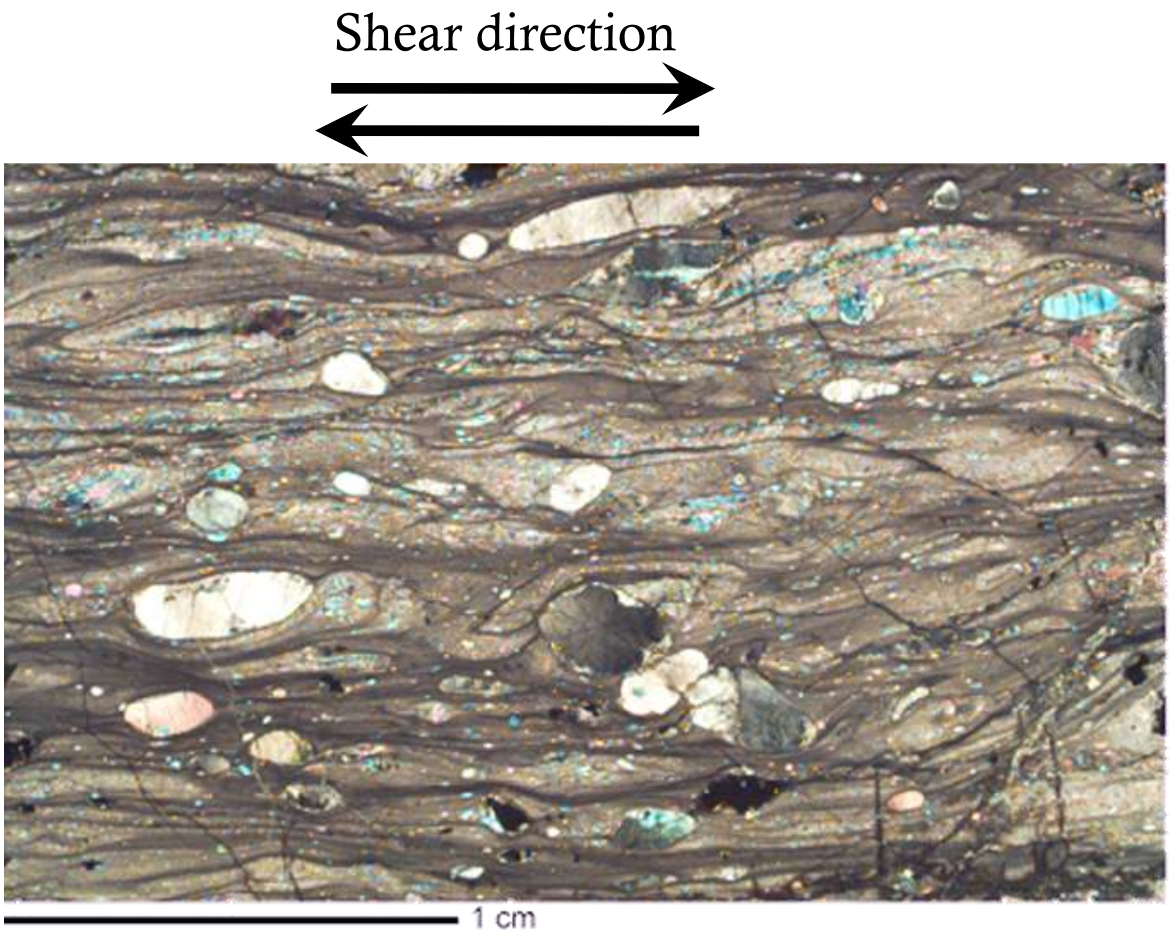
Shear zone (uniform stress)

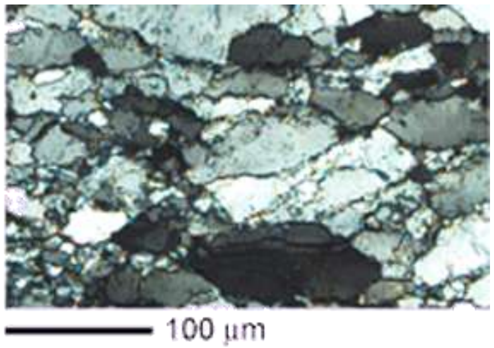


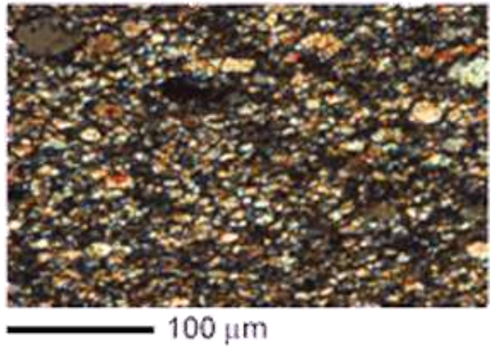
Strength controlled by weak phase

Grain Size Reduction

- Mylonite in oceanic peridotite, Shaka Fracture zone



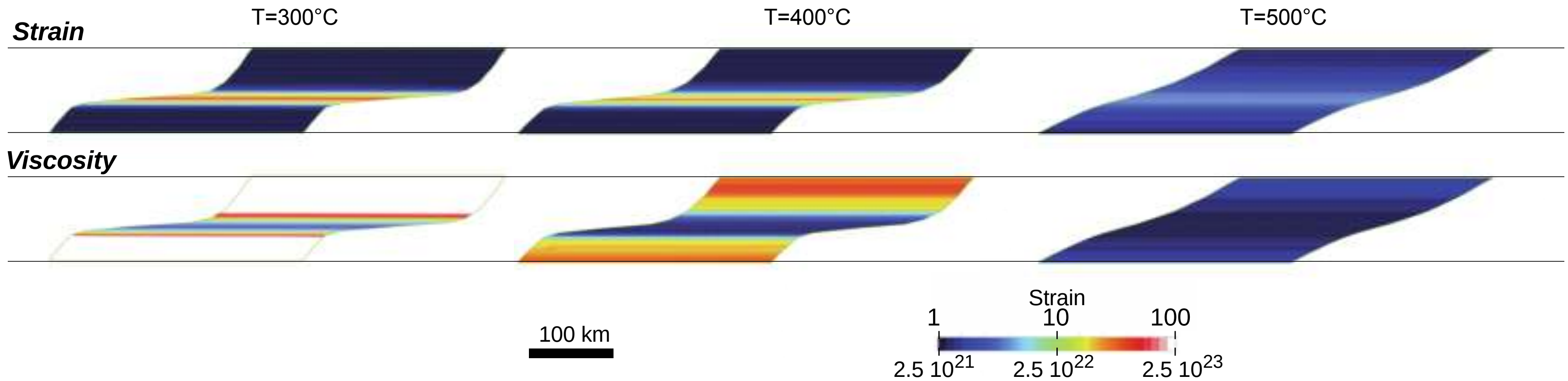




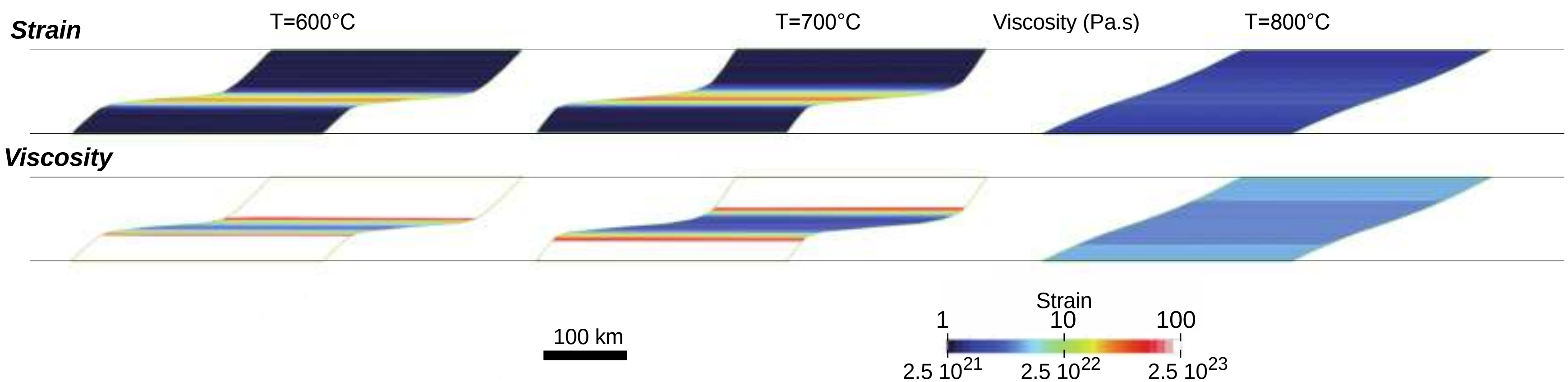
Warren and Hirth, 2006

Shear zone development

In the crust: Weak phase interconnection if phyllosilicates

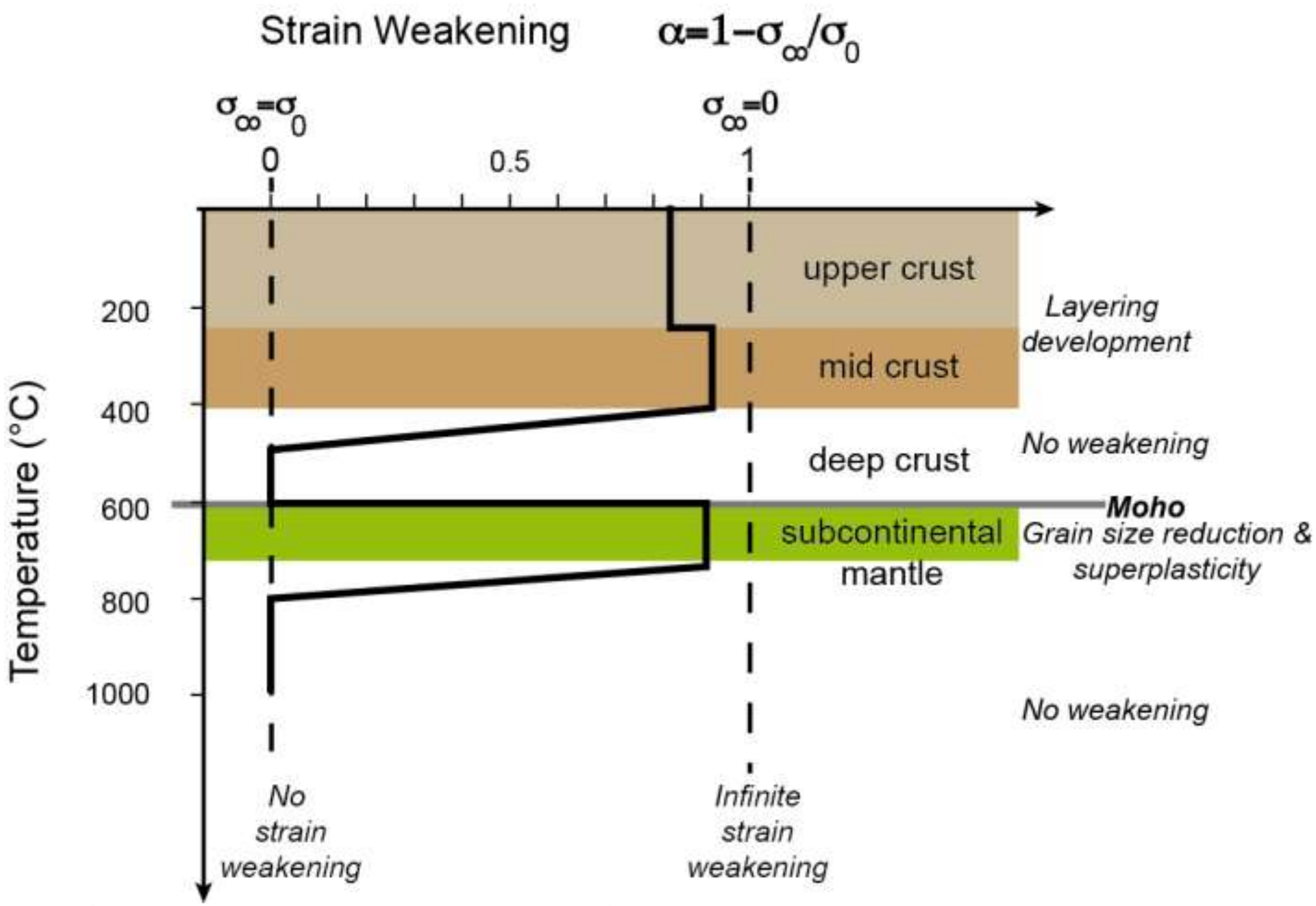


In the mantle: grain size reduction if dis-GBS



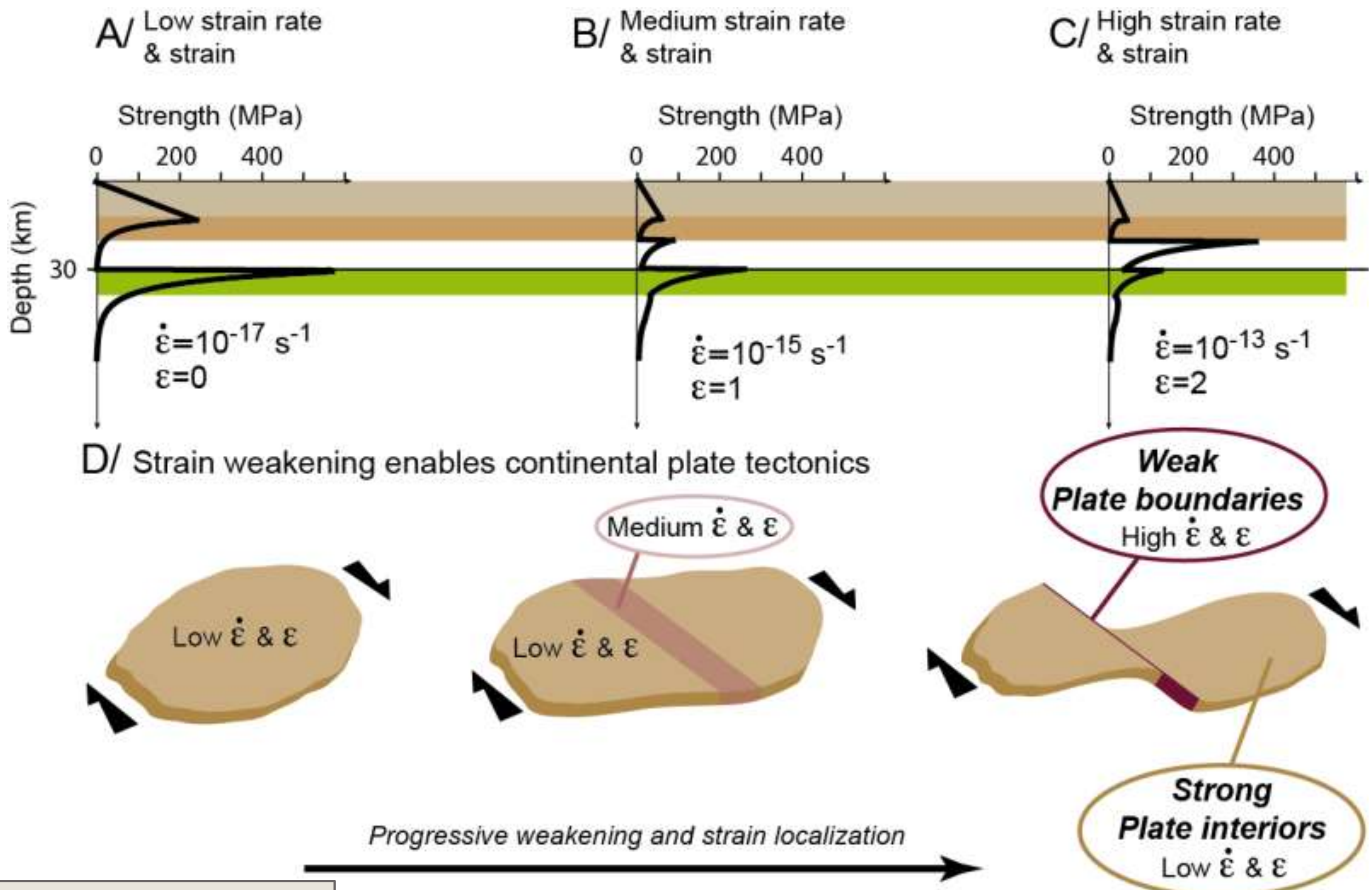
Gueydan et al., 2014

Final weakening



Gueydan et al., 2014

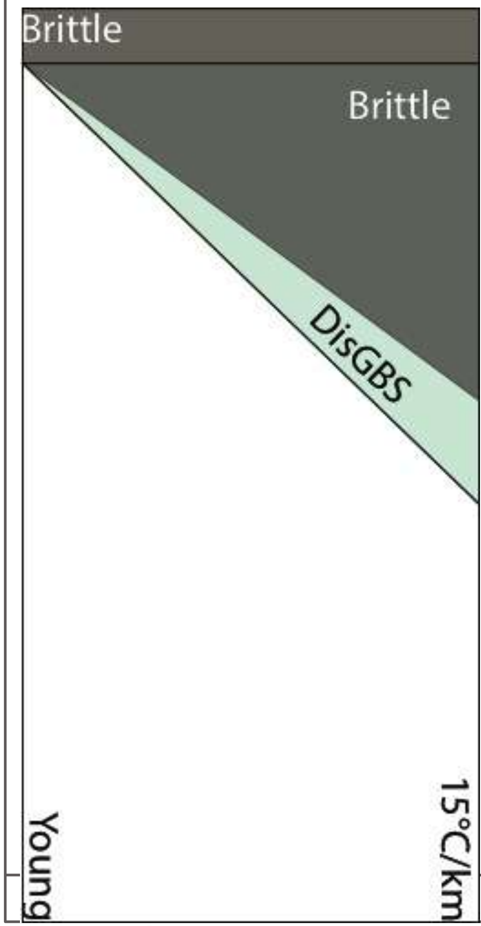
Strain-dependent strength envelopes

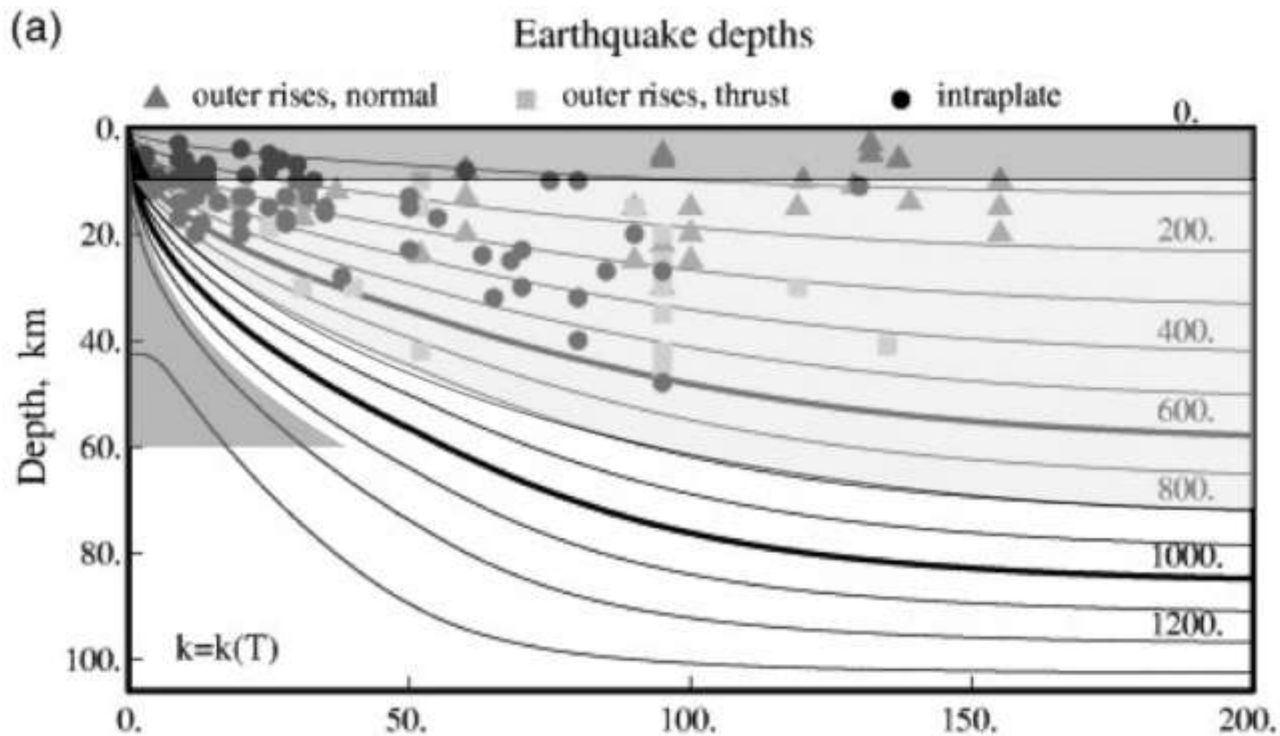


Gueydan et al., 2014

Oceanic lithosphere

- Crust: mostly brittle
  - Hydrated minerals and high pore fluid pressure
- In the mantle
  - Dis-GBS starts essentially at zero age
  - Older lithosphere has a thicker localizing mantle
- Melt embrittlement?

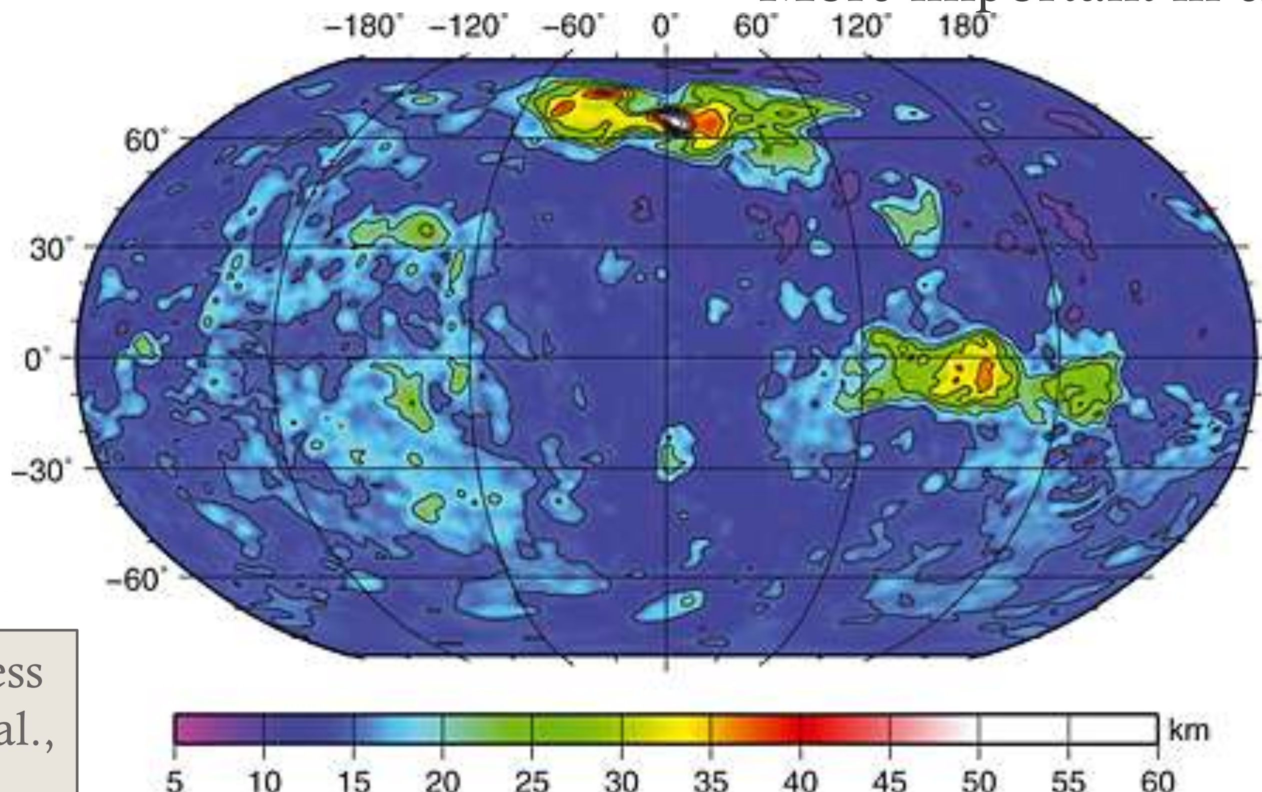




Thermal structure from McKenzie et al., EPSL 2005

Venus

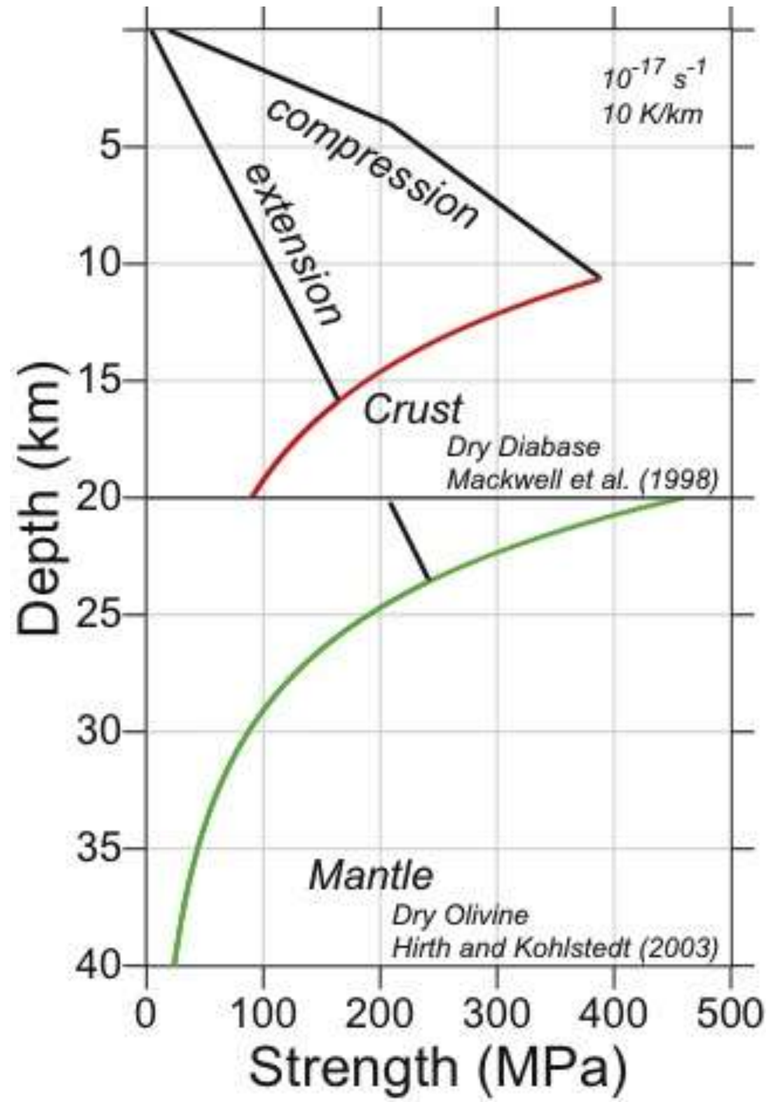
- Mantle
  - Dis-GBS possible if low enough geotherm / thin crust
    - 15 K/km: 22km
    - 10 K/km: 34 km thick
- Crust
  - High surface temperature, no water: no phyllosilicates
  - Shallow brittle failure
  - More important in extension



Crustal thickness from James et al., 2013

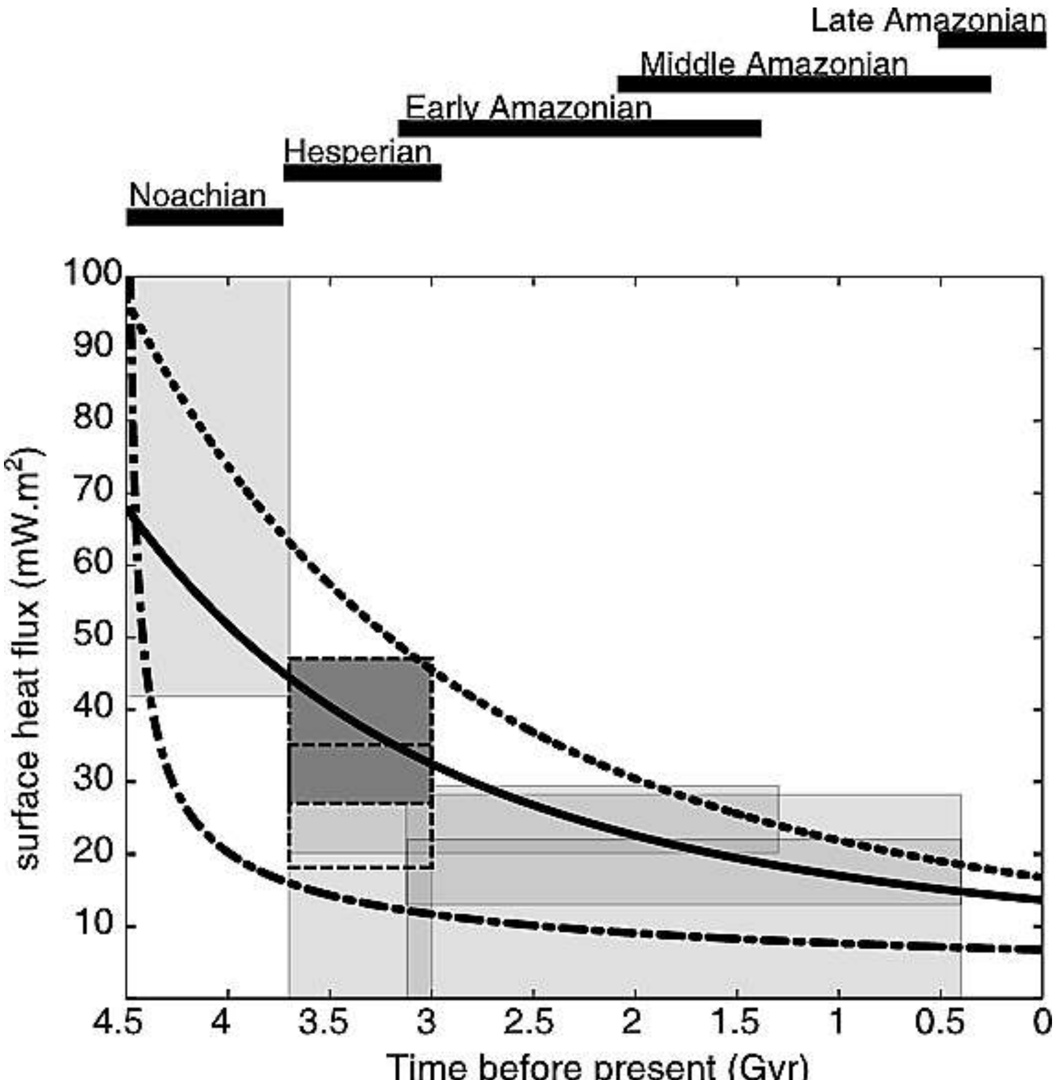
Localization easier in extension

- Deeper brittle layer => larger fault offsets
- Possibility of melting => melt weakening and melt embrittlement
- Geometrical effects (stress focusing)



Mars

- Mantle:
  - Dis-GBS if low enough heat flux/ thin crust
    - 30km crust (lowlands): 100 mW/m^2
    - 60km crust (highlands): 50 mW/m^2
- Crust:
  - Water likely: brittle weakening
  - Mafic composition does not favor phyllosilicates at depth: no layering effect



Montési and Zuber, 2003

Localization in planetary lithospheres

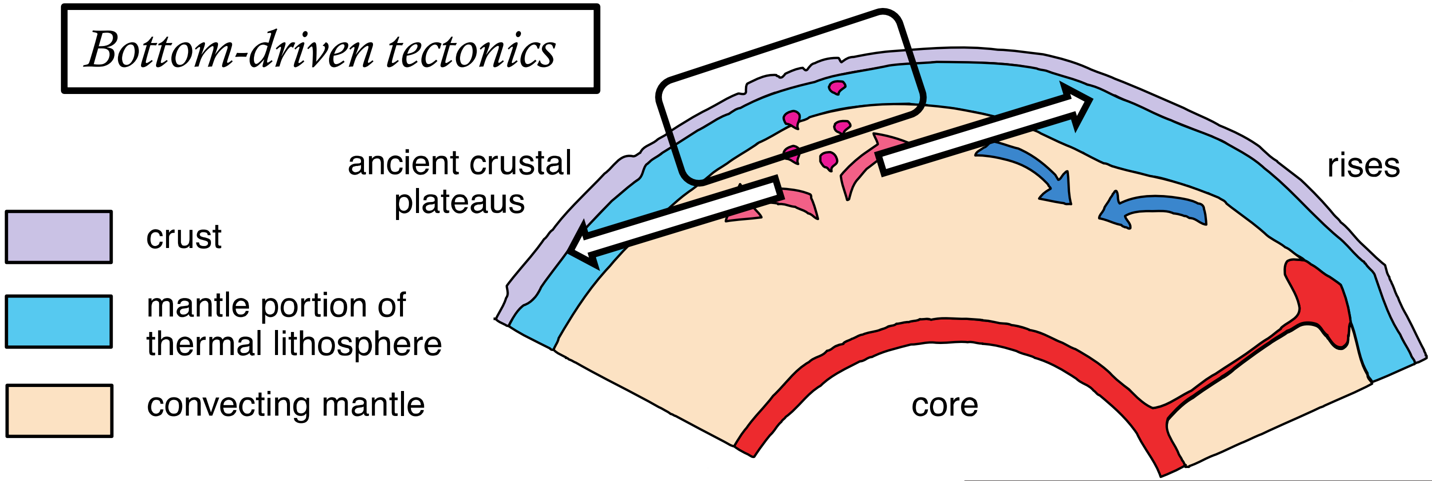
Earth continents

Earth Oceans

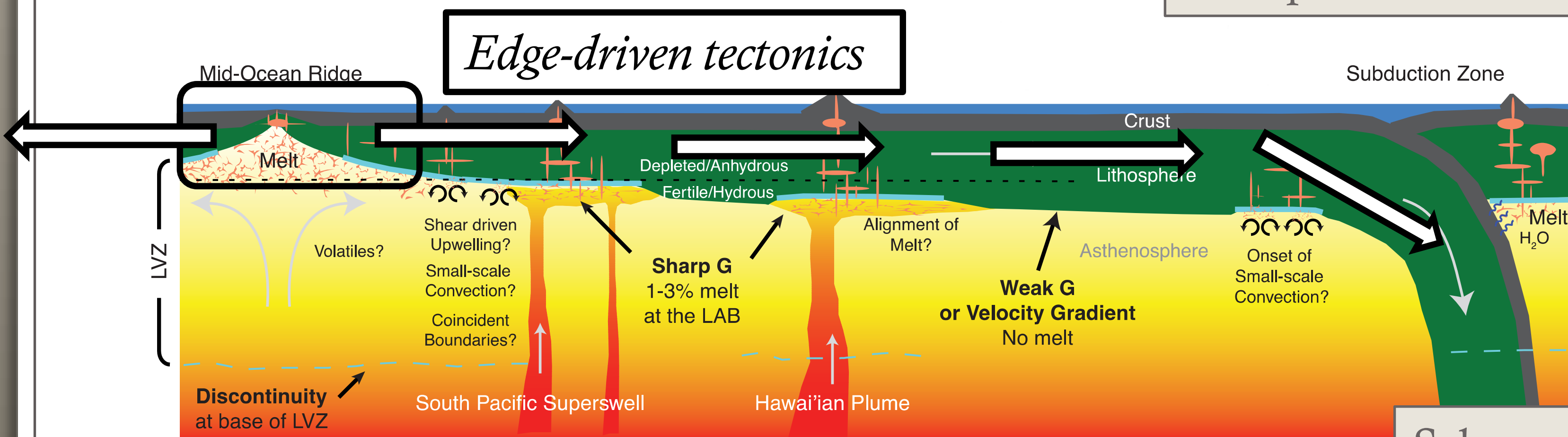
Mars

Venus

Convection and tectonics

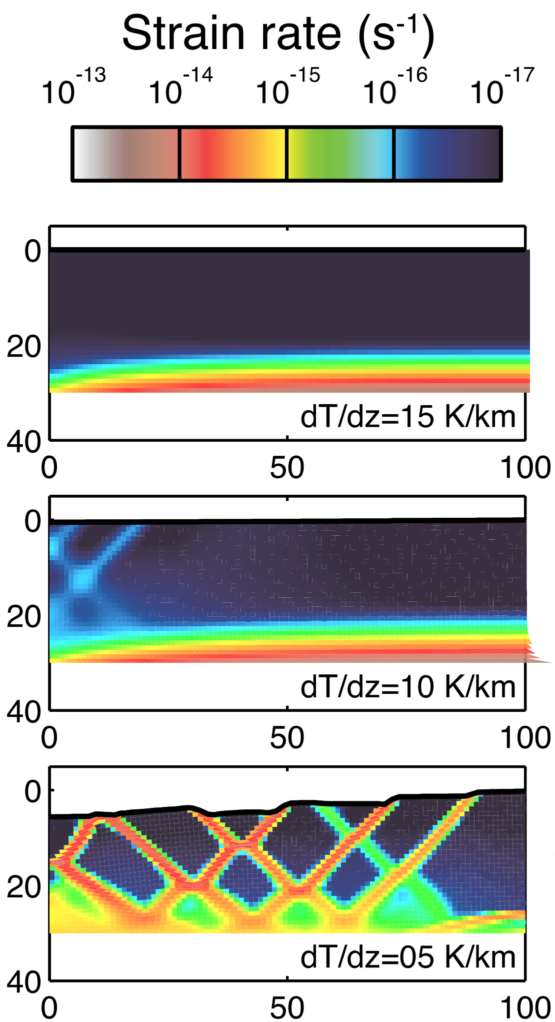


Phillips and Hansen, 1998

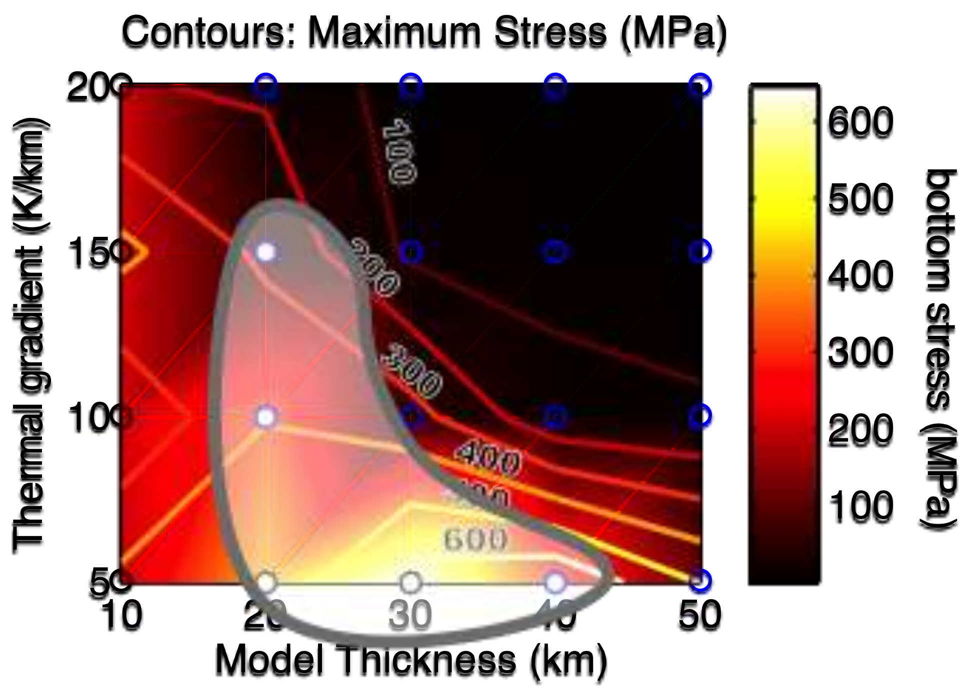


Schmerr, 2012

Bottom-driven tectonics



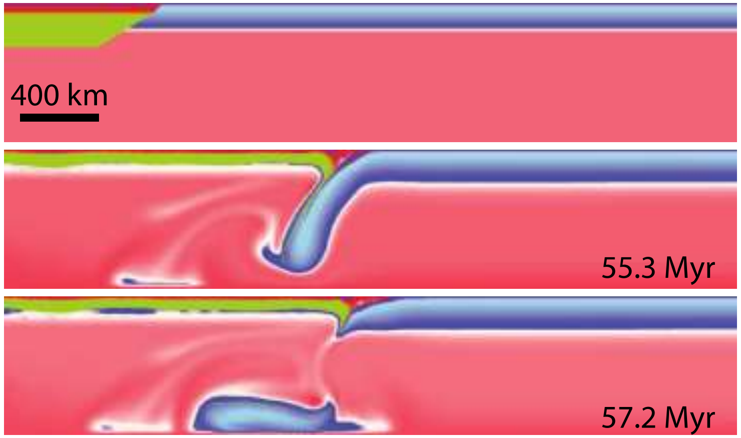
- Need high basal stress: convection reaches the brittle-ductile transition
- Need ductile layer for accommodation of shear zones



Montési, LPSC 2013

Buoyancy-driven tectonics

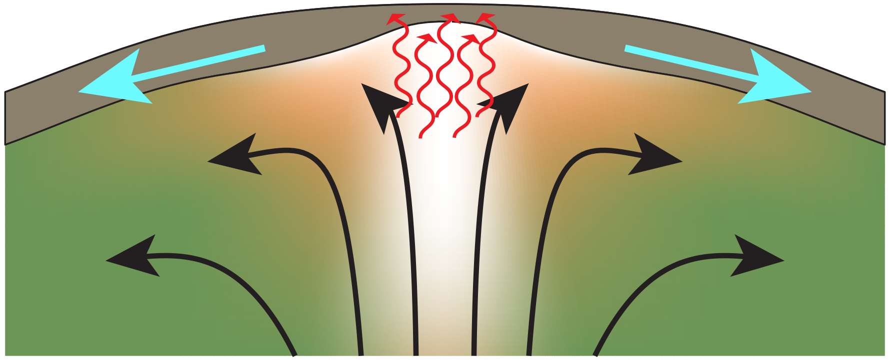
- Continent spreading (Earth's Archean)



Less efficient on Mars

Rey et al., 2014

- Upwellings (Beta Regio, East African Rift?)



Montési, LPSC 2013

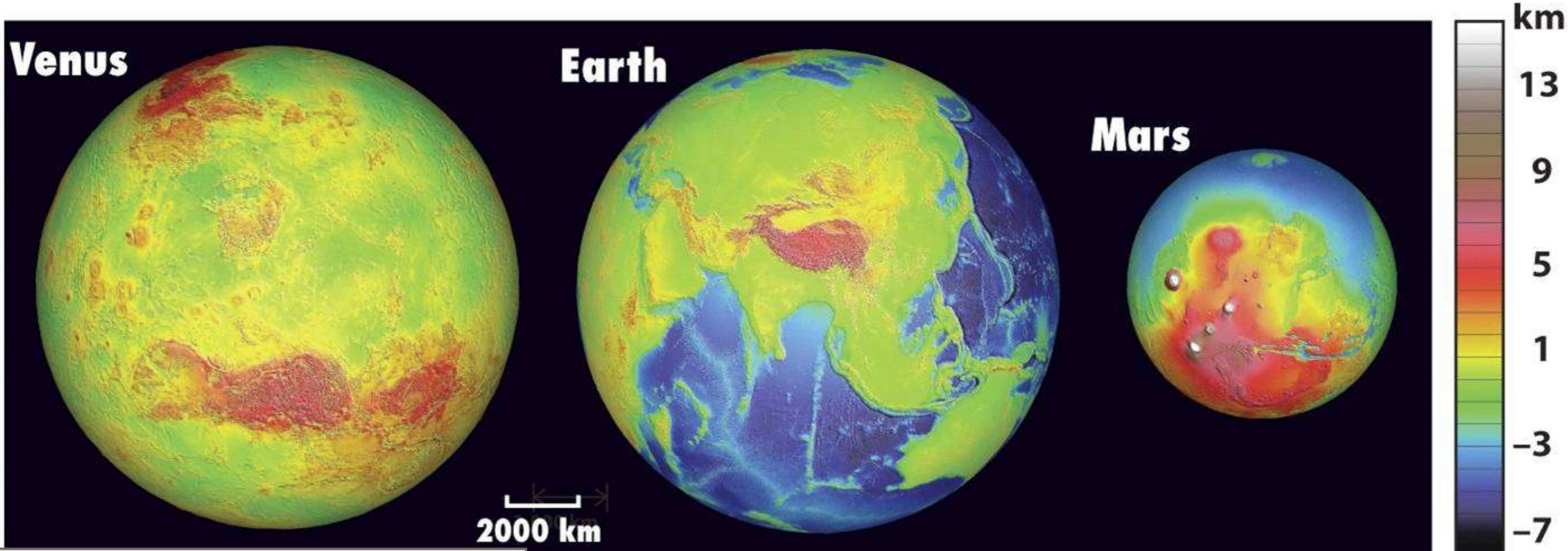
Summary

- The strength of the lithosphere changes with strain
  - Layering in brittle regime or in presence of micas
  - Grain size reduction in presence of dis-GBS creep

compared to the Earth
  - Mars is similar to Earth's continents
  - Venus is dominated by brittle localization unless low heat flux

- Issue of driving forces

inefficient to drive tectonics
  - Continents dominated by buoyancy-driven flows?
  - Buoyancy less efficient on Mars



Understanding Earth textbook