Self-consistent plate tectonics in global convection models: Recent progress

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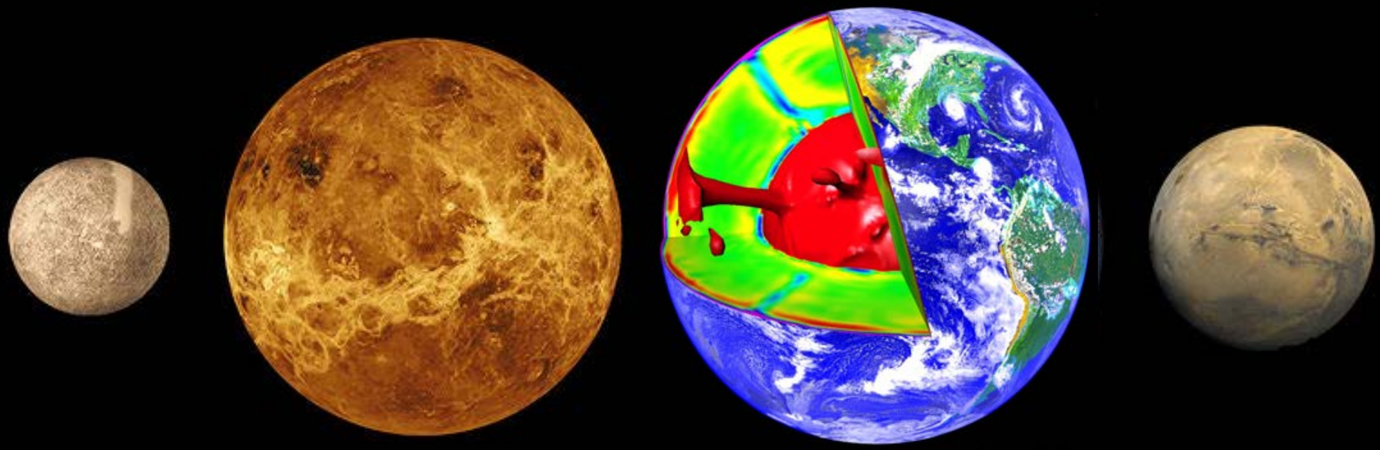


Overview

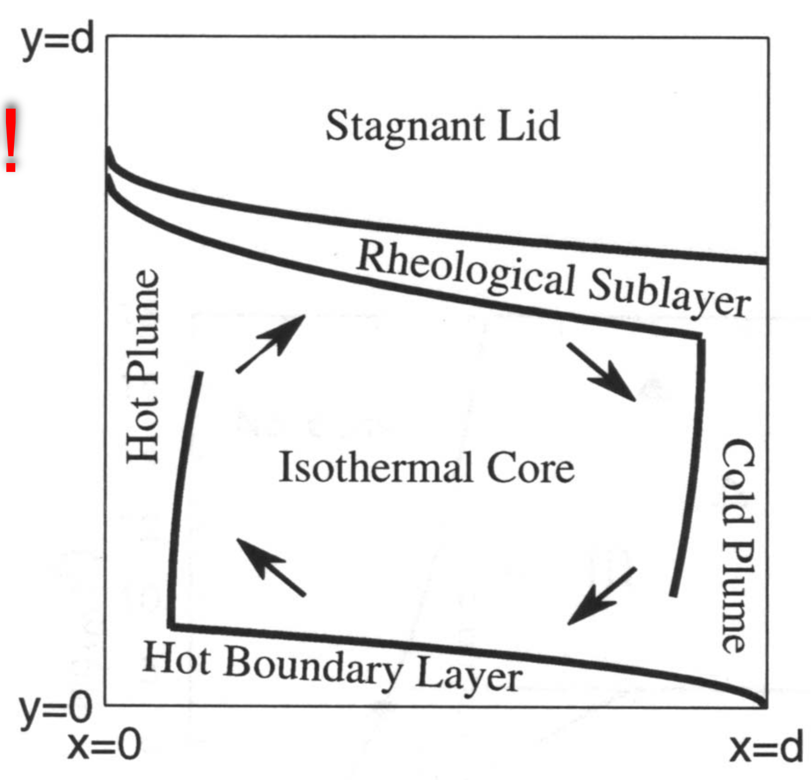
- Review of the problem
- Global statistics: easy to get correct?
- Magmatism->crust is important!

Why does Earth have plate tectonics?

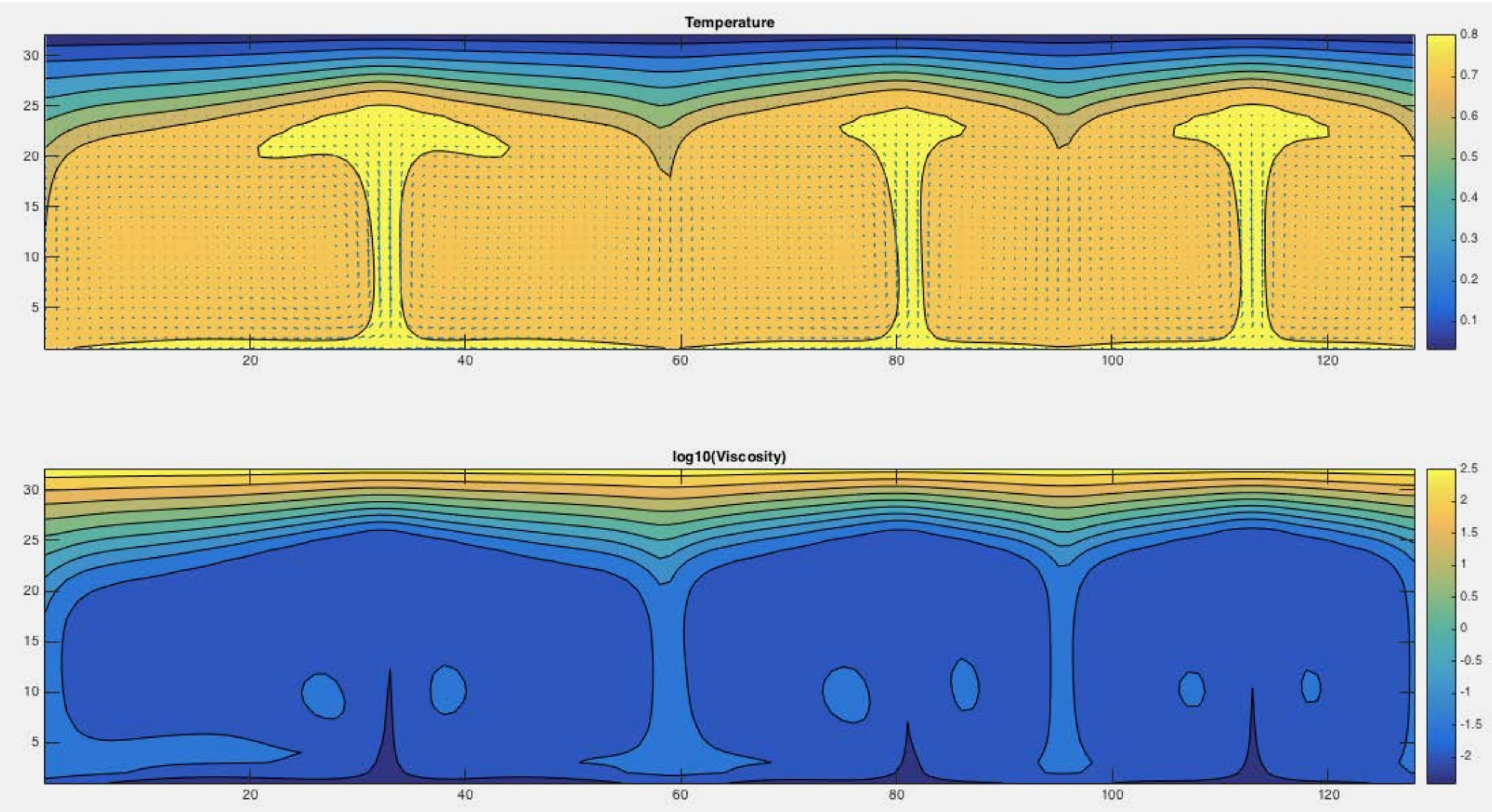
The plate problem

- Viscous, T-dependent rheology appropriate for the mantle leads to a stagnant lid
- exp(E/kT) where E~340 kJ/mol
- T from 1600 -> 300 K
- =>**1.3×10^{48}** variation
- => RIGID/STAGNANT LID!

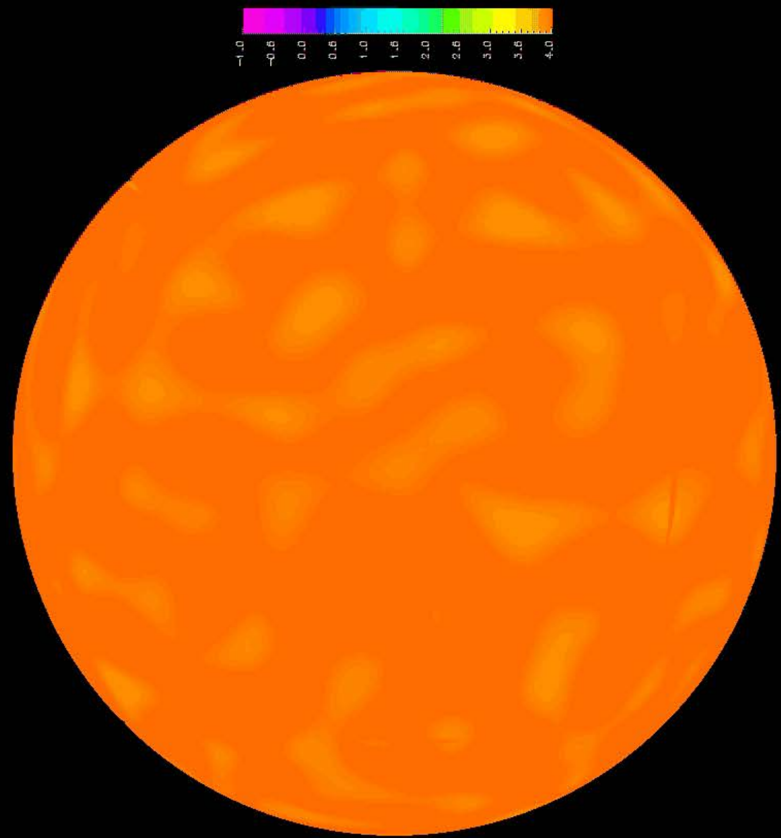
Only small ΔT participates in convection: enough to give Δη factor ~10

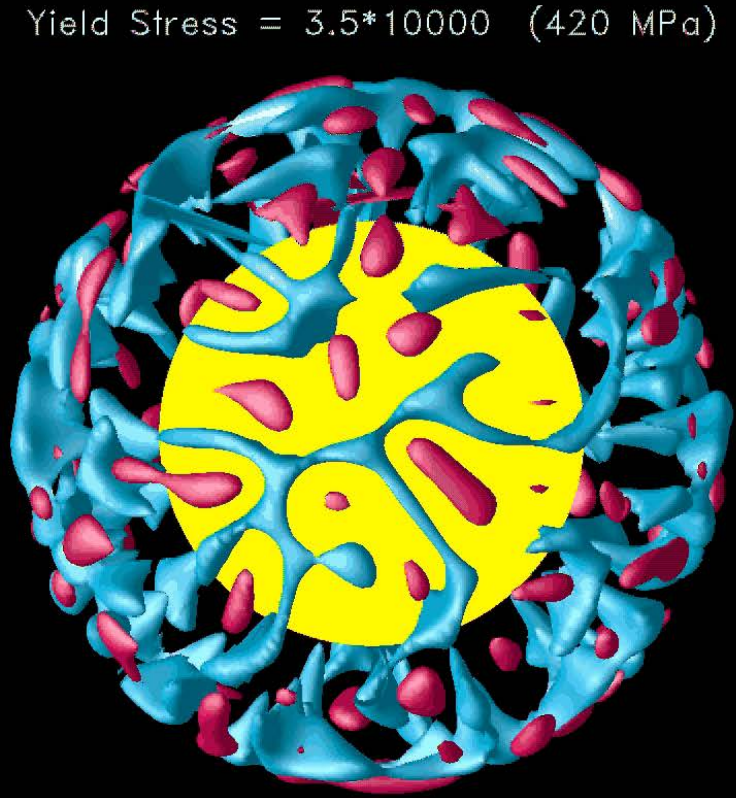


Stagnant lid convection



Stagnant lid convection





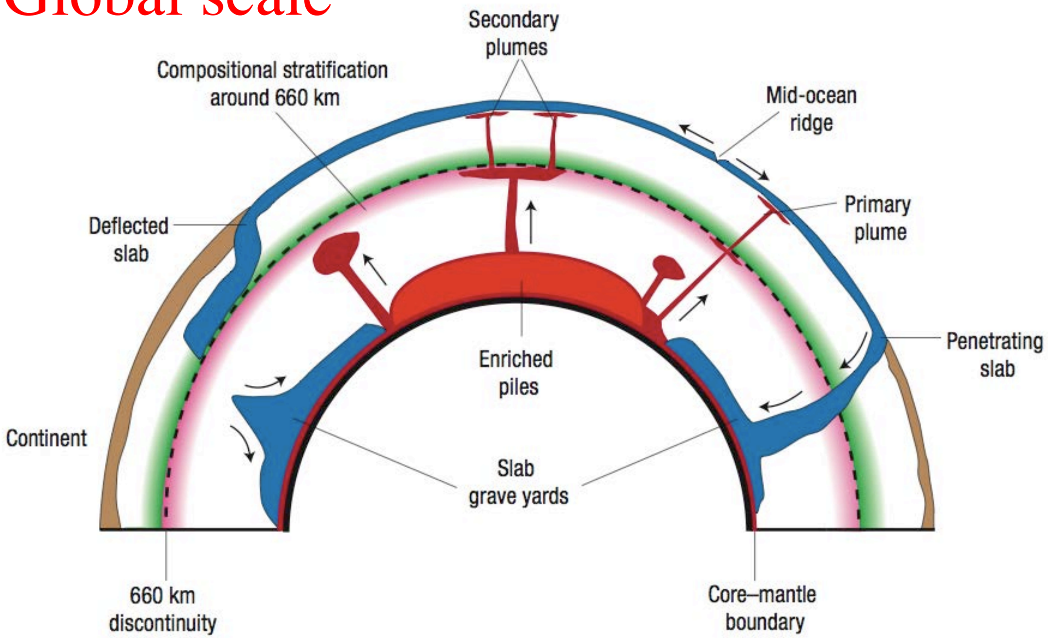
H. Van Heck

Why we don't understand plate tectonics at a fundamental level

- Rock deformation is complex
  - Viscous, brittle, plastic, elastic, nonlinear
  - Dependent on grain size, composition (major and trace elements, eg water)
- Multi-scale
  - Lengthscales from mm to 1000s km
  - Timescales from seconds - Gyr

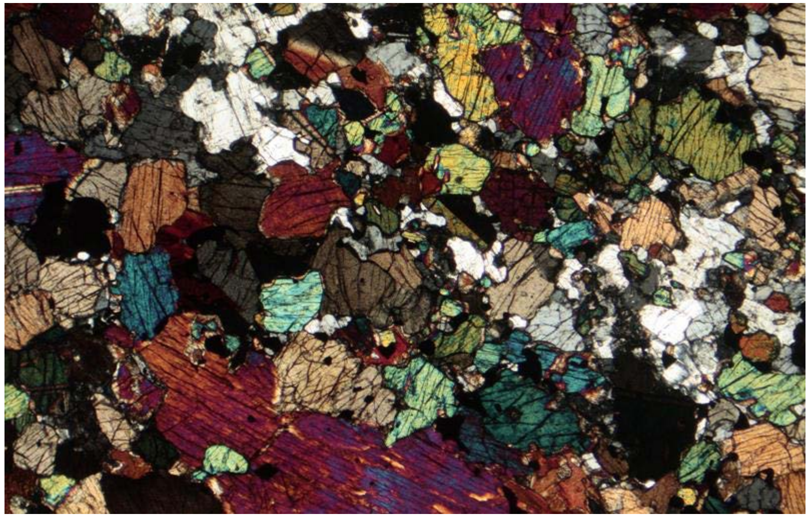
Multi-scale problem

Global scale



'Human' scale

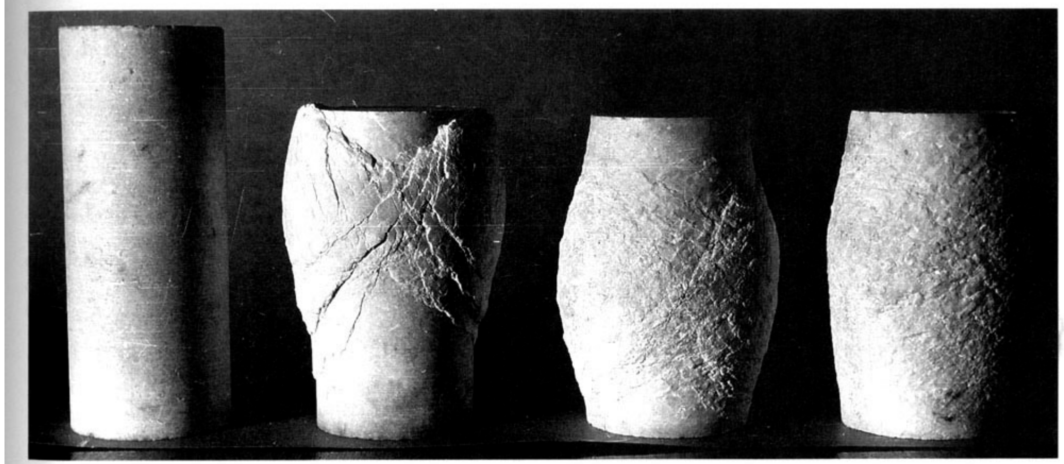
Micro scale



Strength of rocks

- Increases with confining pressure (depth) then saturates

Low-T deformation: Effect of P



Low T: Effect of P

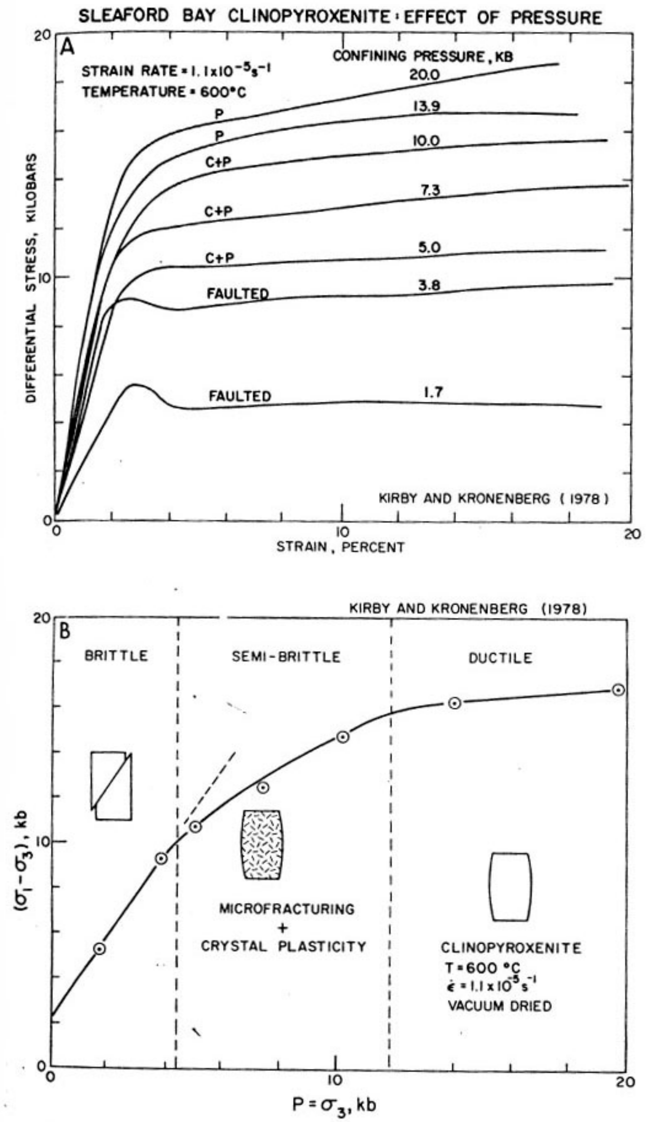
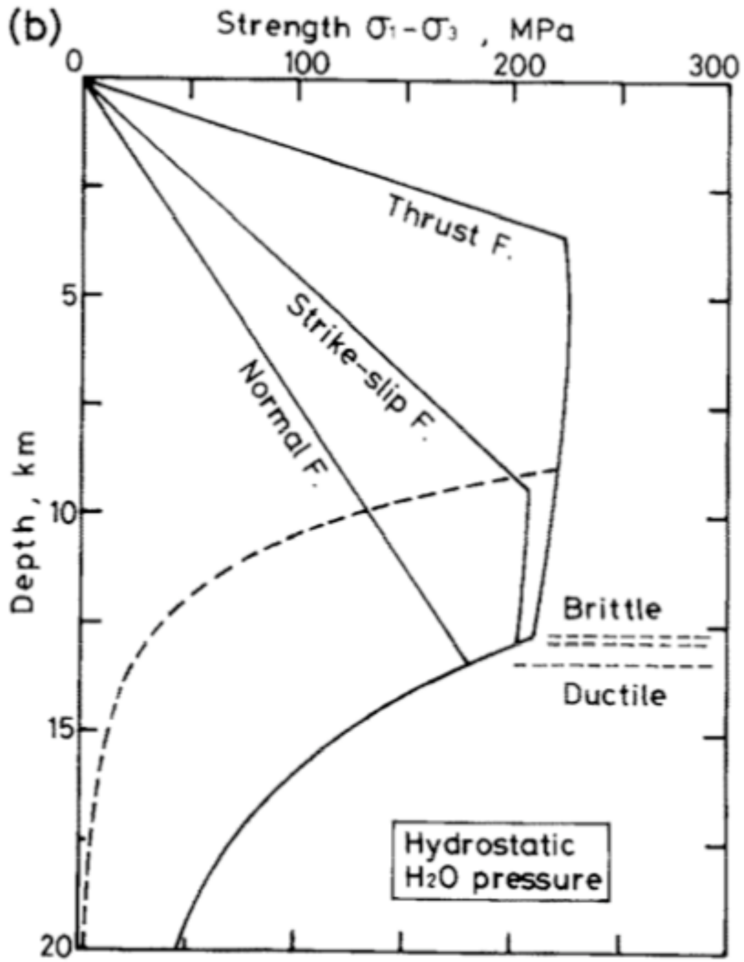


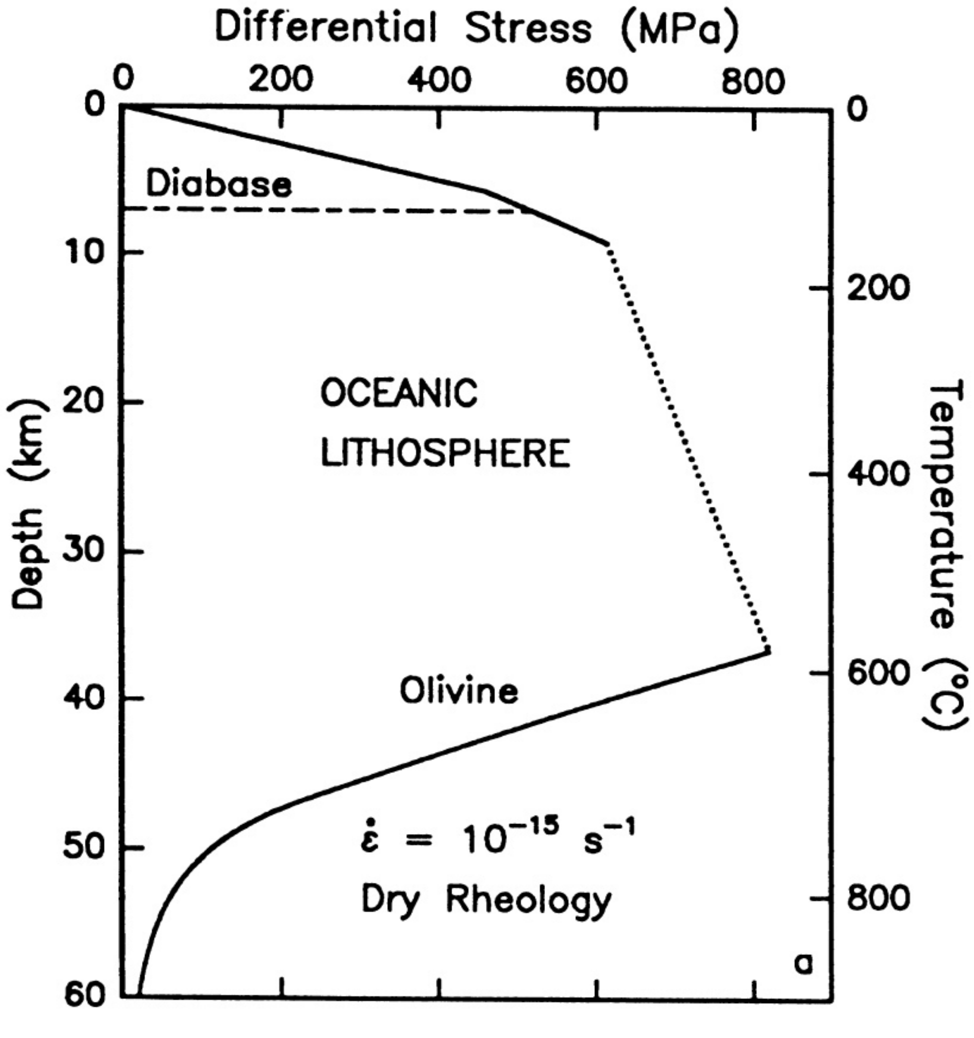
Fig. 6. Effect of confining pressure on the strength of Sleaford Bay clinopyroxenite tested in triaxial compression (S. H. Kirby and A. K. Kronenberg, unpublished data, 1978): (*a*) stress-strain curves, (*b*) ultimate strength or stress at 10% strain as a function of confining pressure.

Strength profile of lithosphere

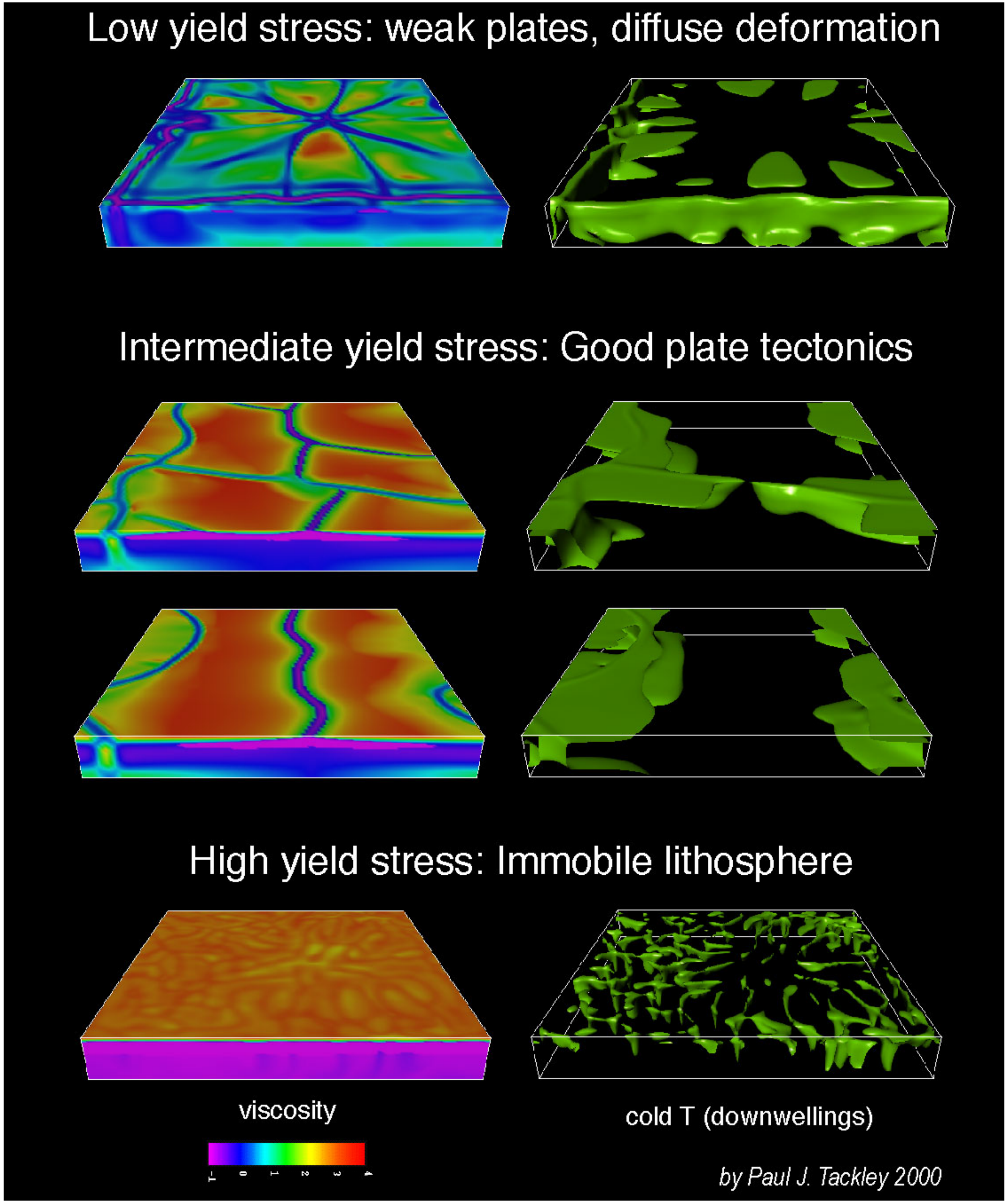
Continental (granite): Shimada 1993



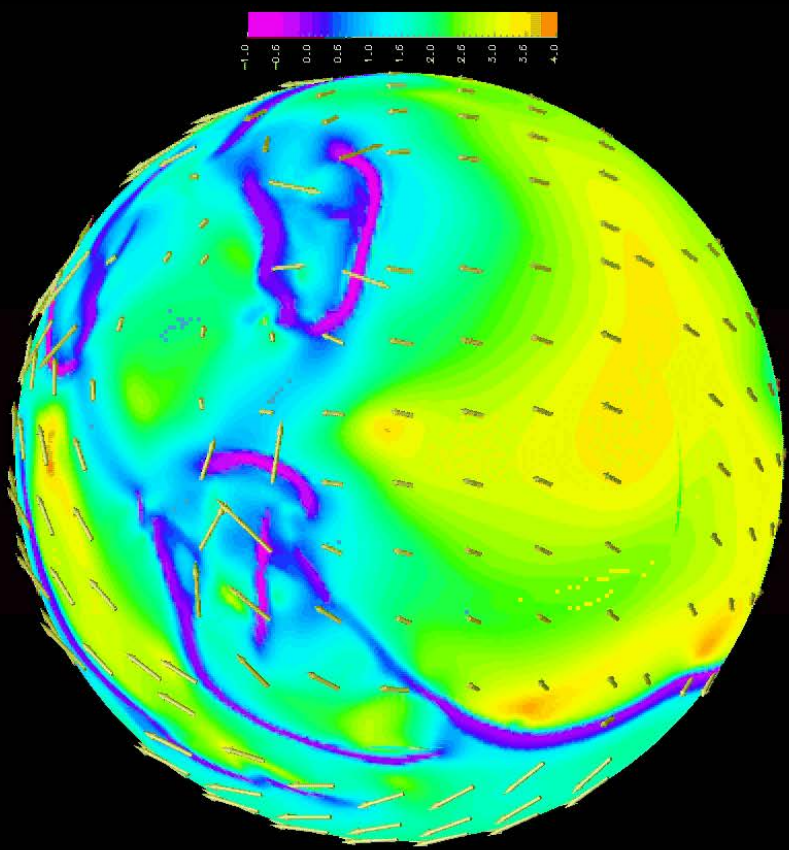
Oceanic: Kohlstedt 1995

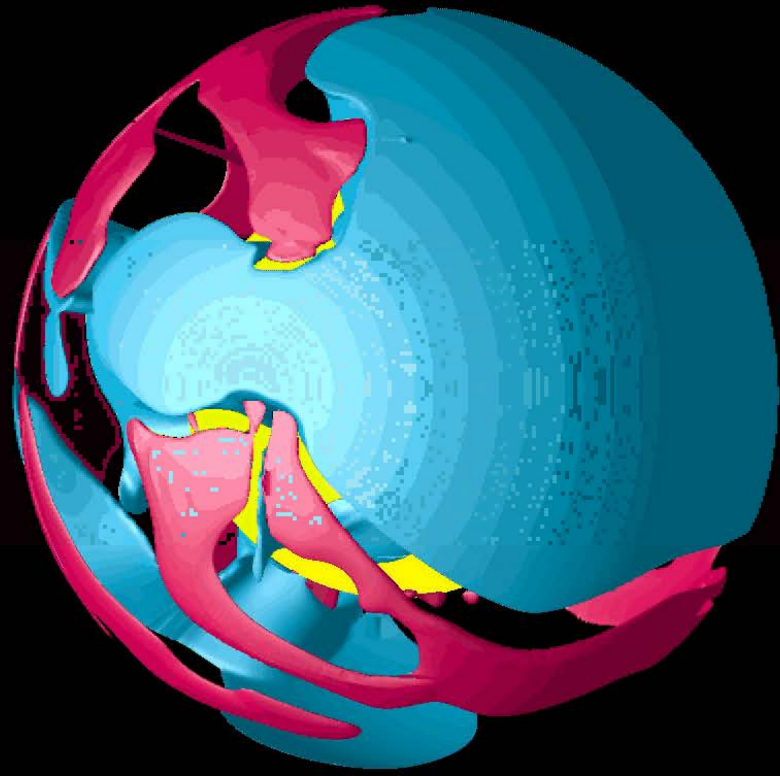


- Varying yield strength, including asthenosph.



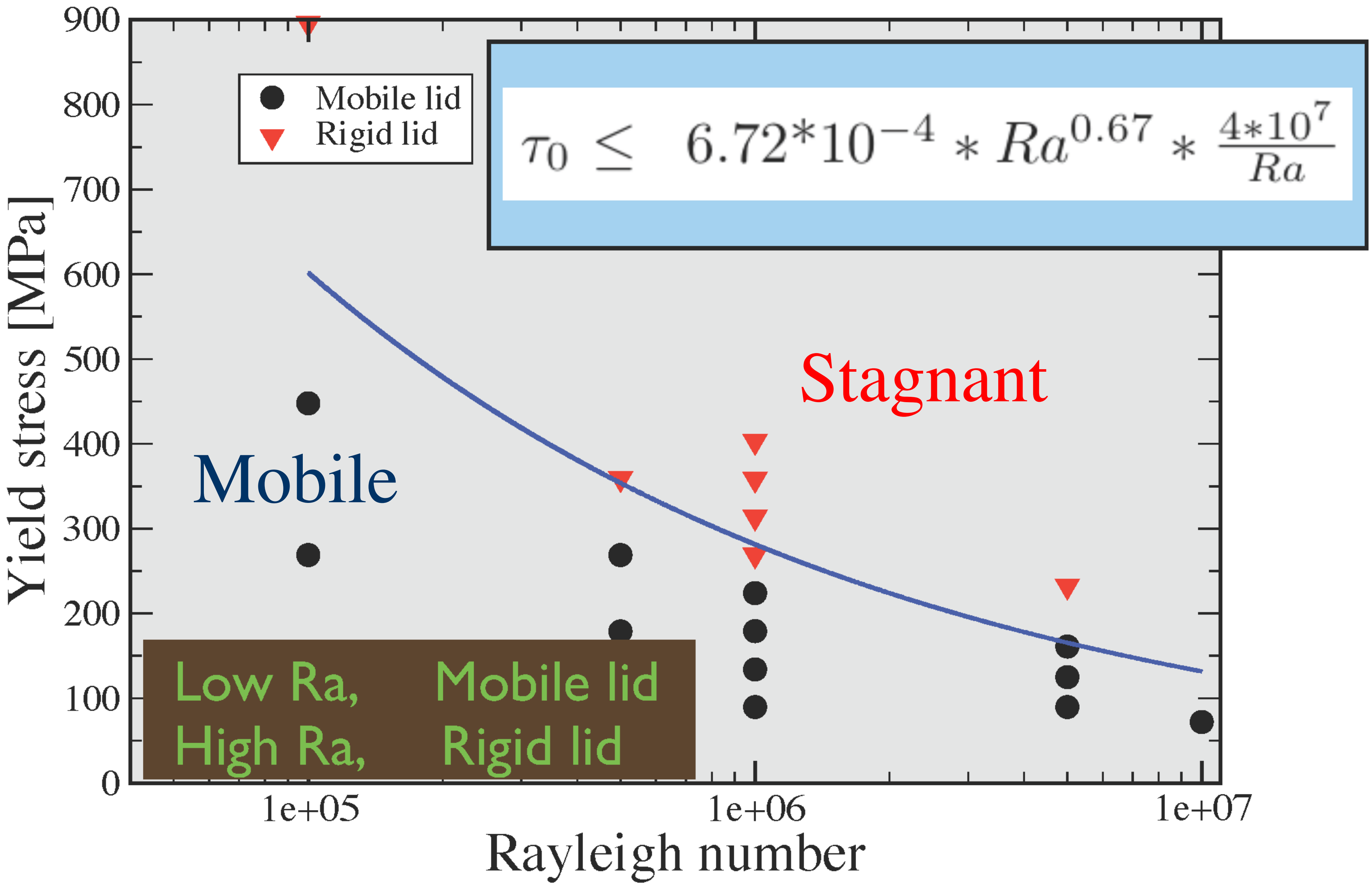
Mobile lid mode





H. Van Heck

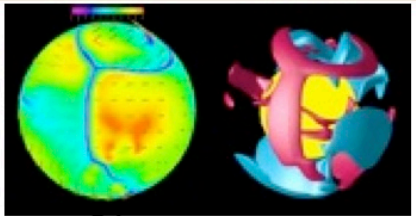
Rayleigh number versus yield stress



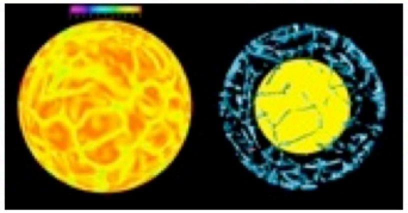
H. van Heck & Tackley

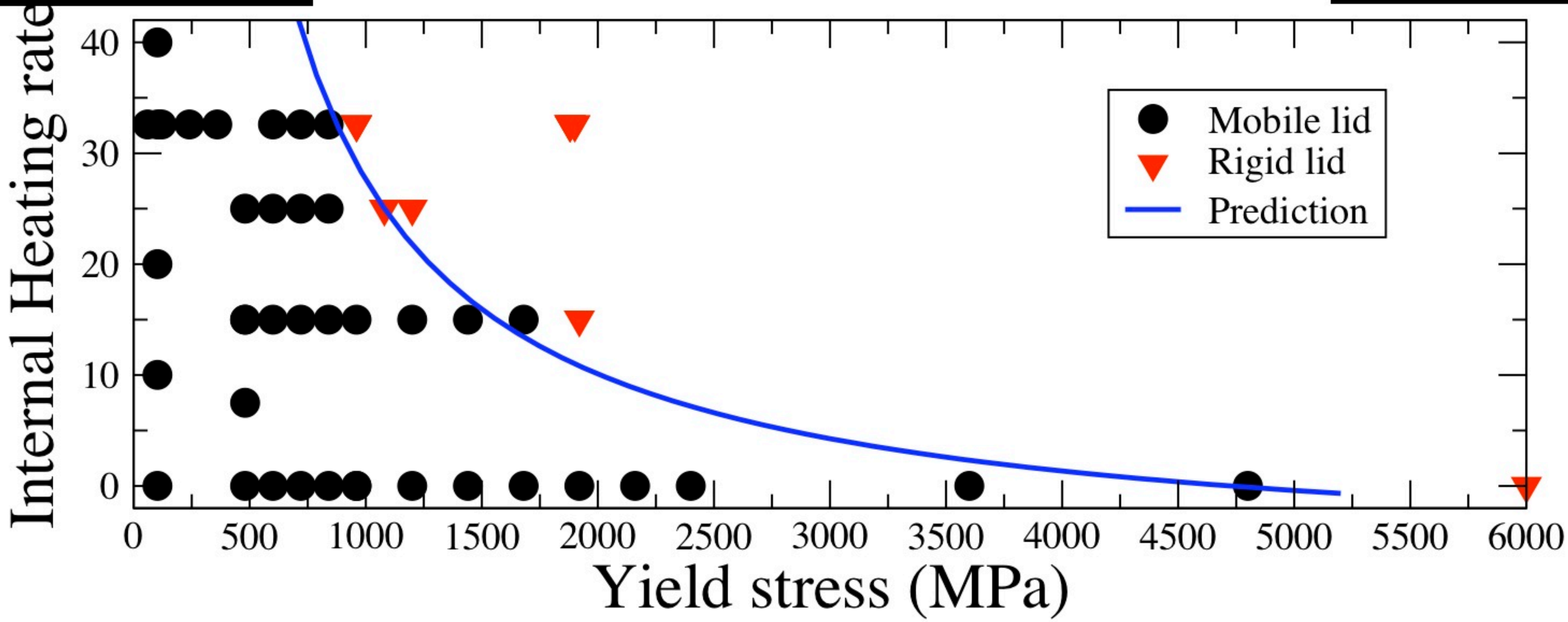
Internal heating rate

Strength of the lithosphere vs convective stresses



Yield stress versus internal heating rate





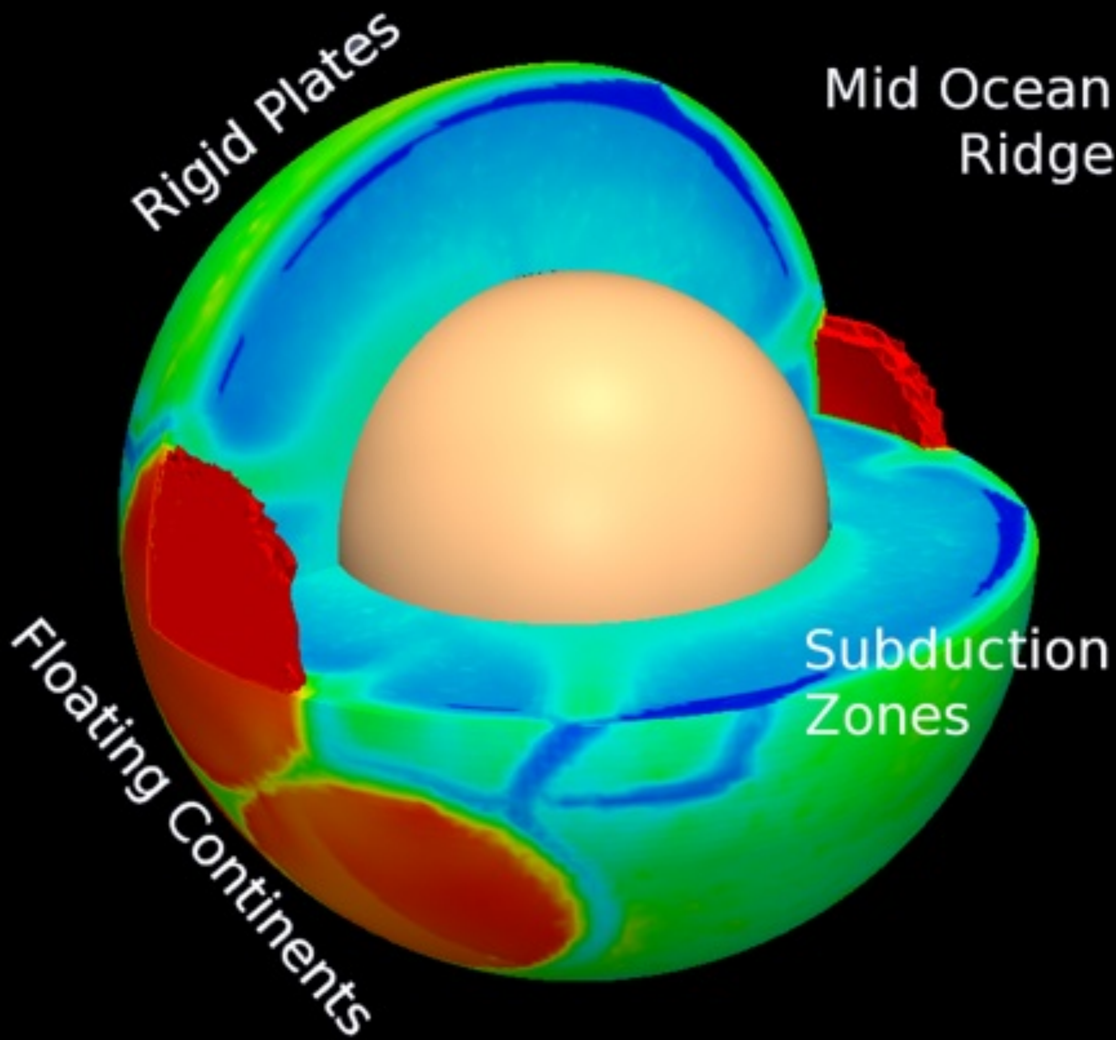
H. van Heck, PhD Thesis

Implications for terrestrial planet evolution

- Plate tectonics favoured at
  - higher mantle viscosity (lower Ra)
  - Lower internal (radioactive) heating
- Both predict transition stagnant lid->plates as planet cools.

Influence of continents on self-consistent plate tectonics?

Tobias Rolf

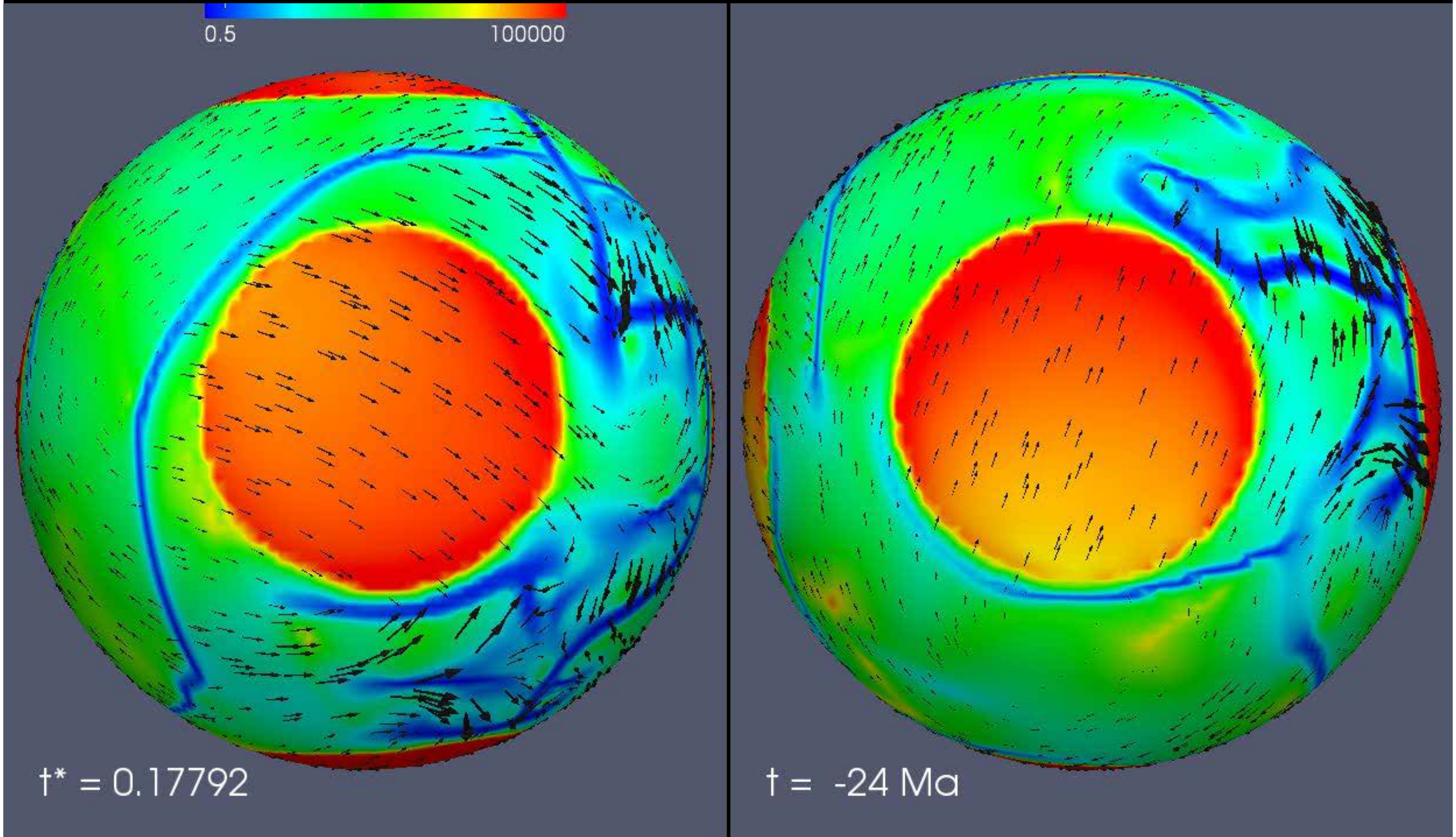


CRYSTAL2PLATE

How does plate tectonics work:
From crystal-scale processes to mantle convection with self-consistent plates

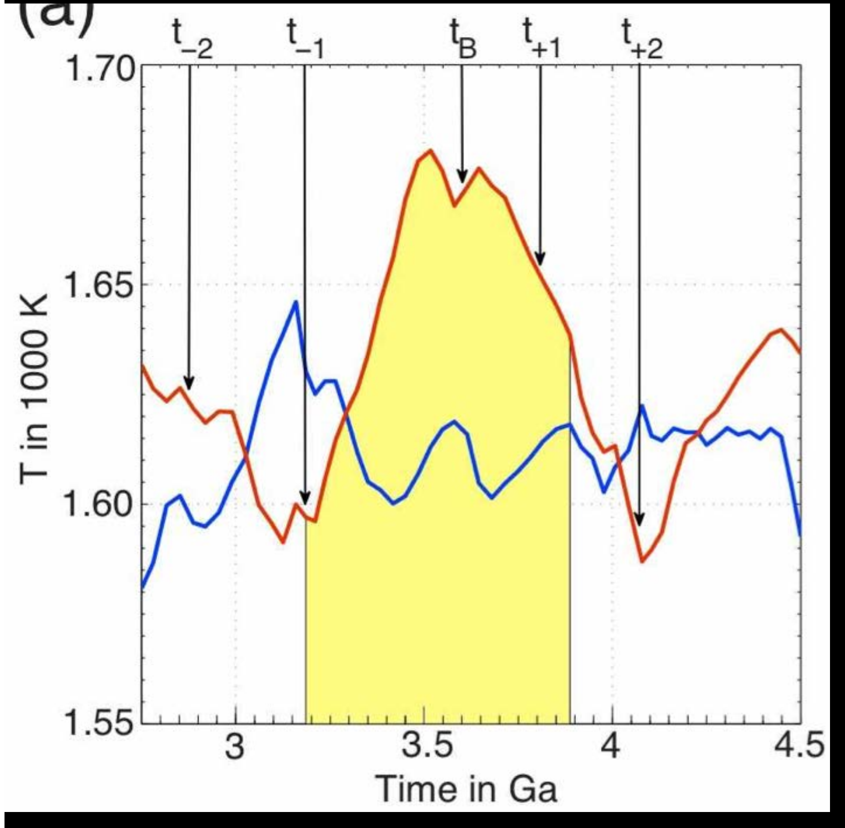
SEVENTH FRAMEWORK PROGRAMME

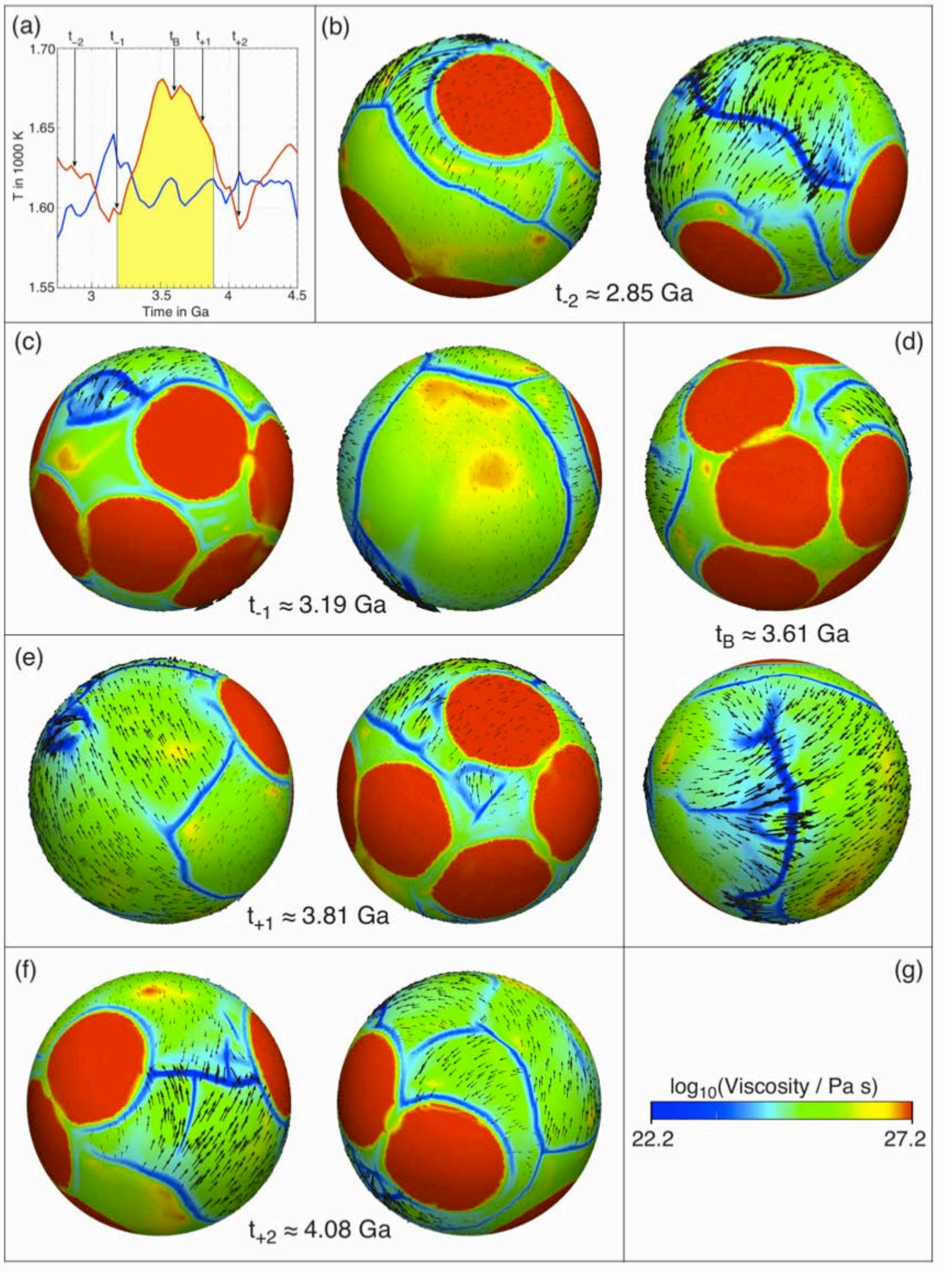
MARIE CURIE ACTIONS



6 continents

Supercontinent cycle





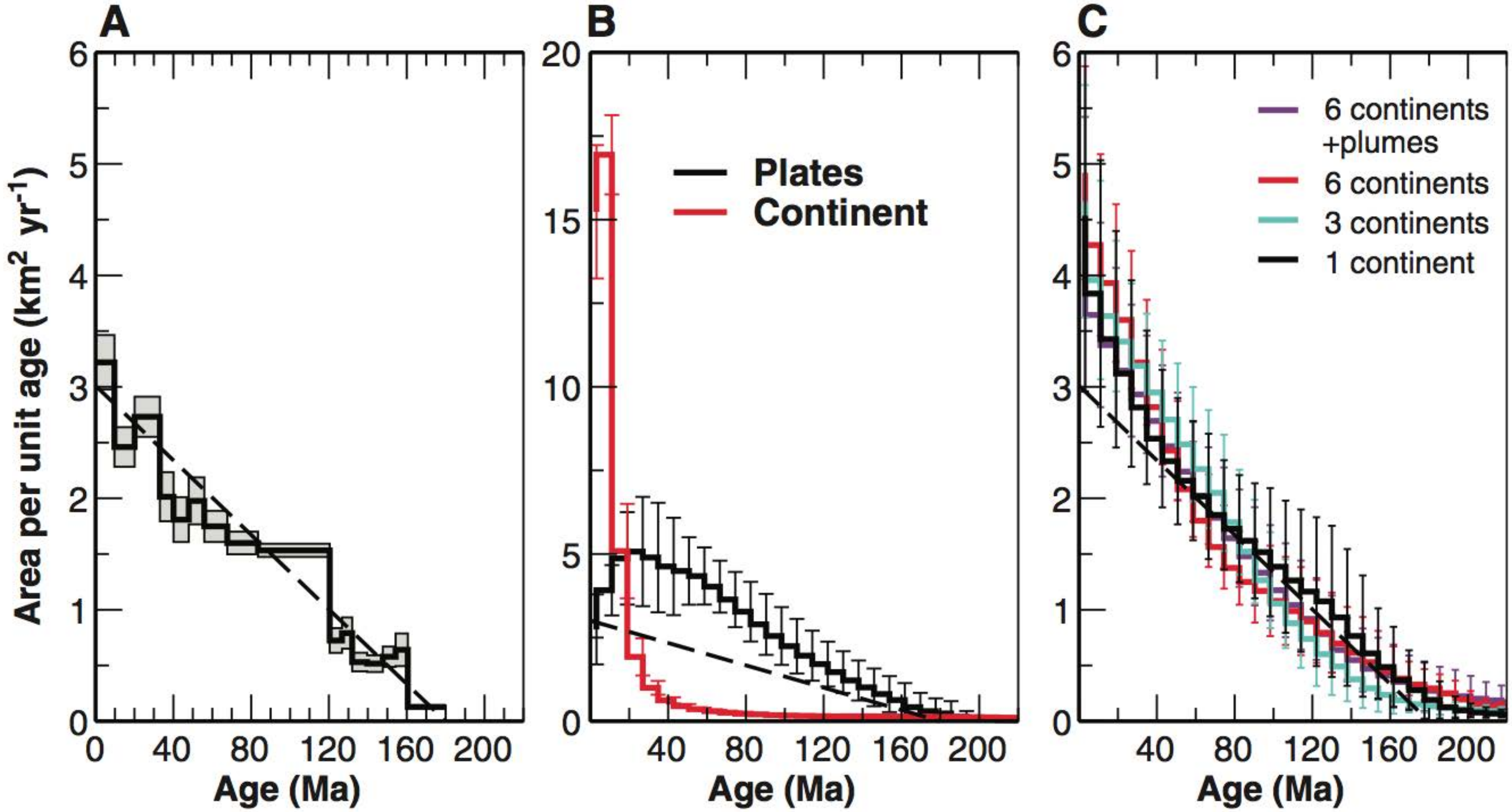
Warming under supercontinent

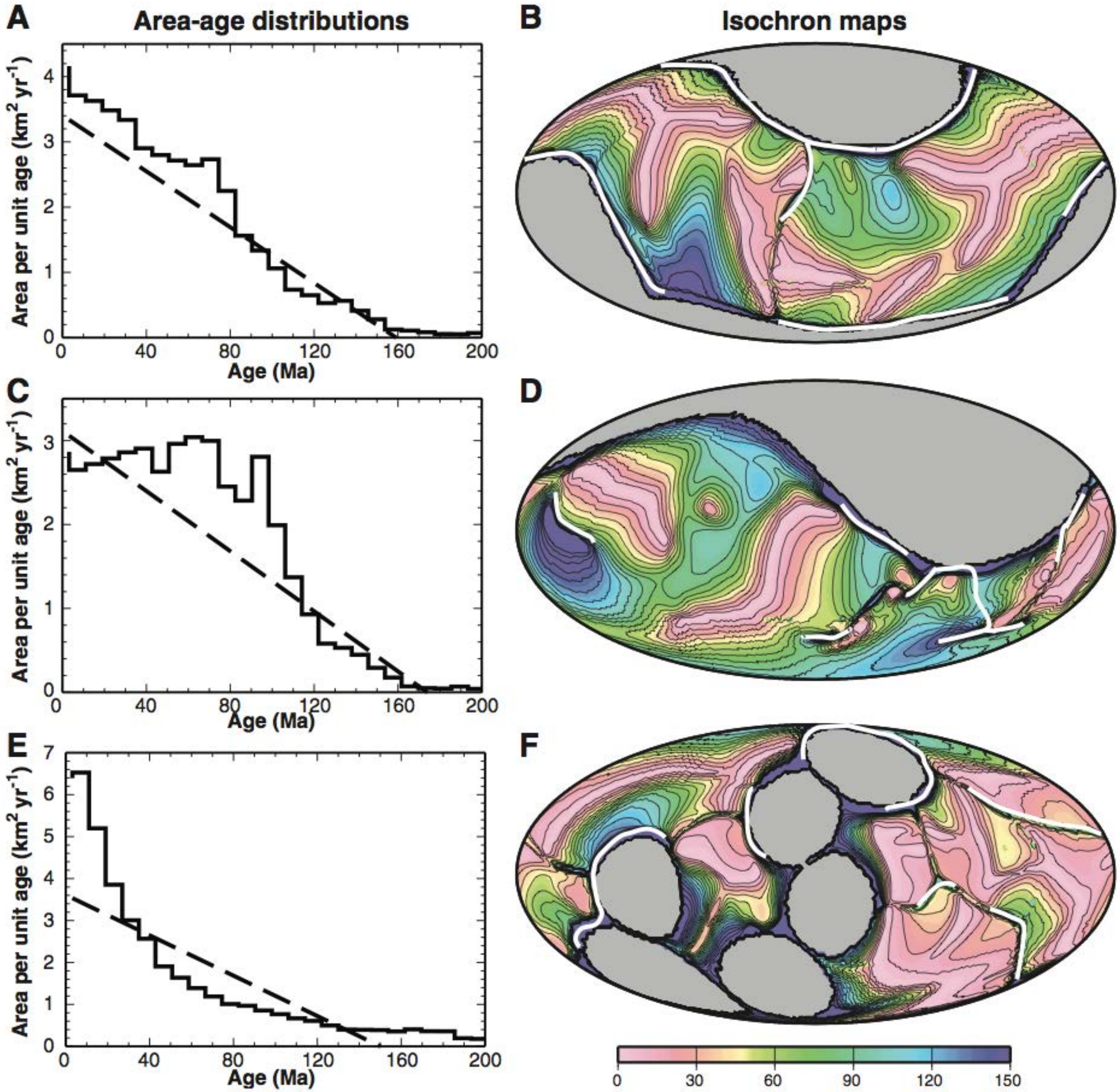
Dynamic Causes of the Relation Between Area and Age of the Ocean Floor

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

SCIENCE VOL 336 20 APRIL 2012

[redacted]





Distribution shape varies with time

Reason 1: geometry of plate boundaries

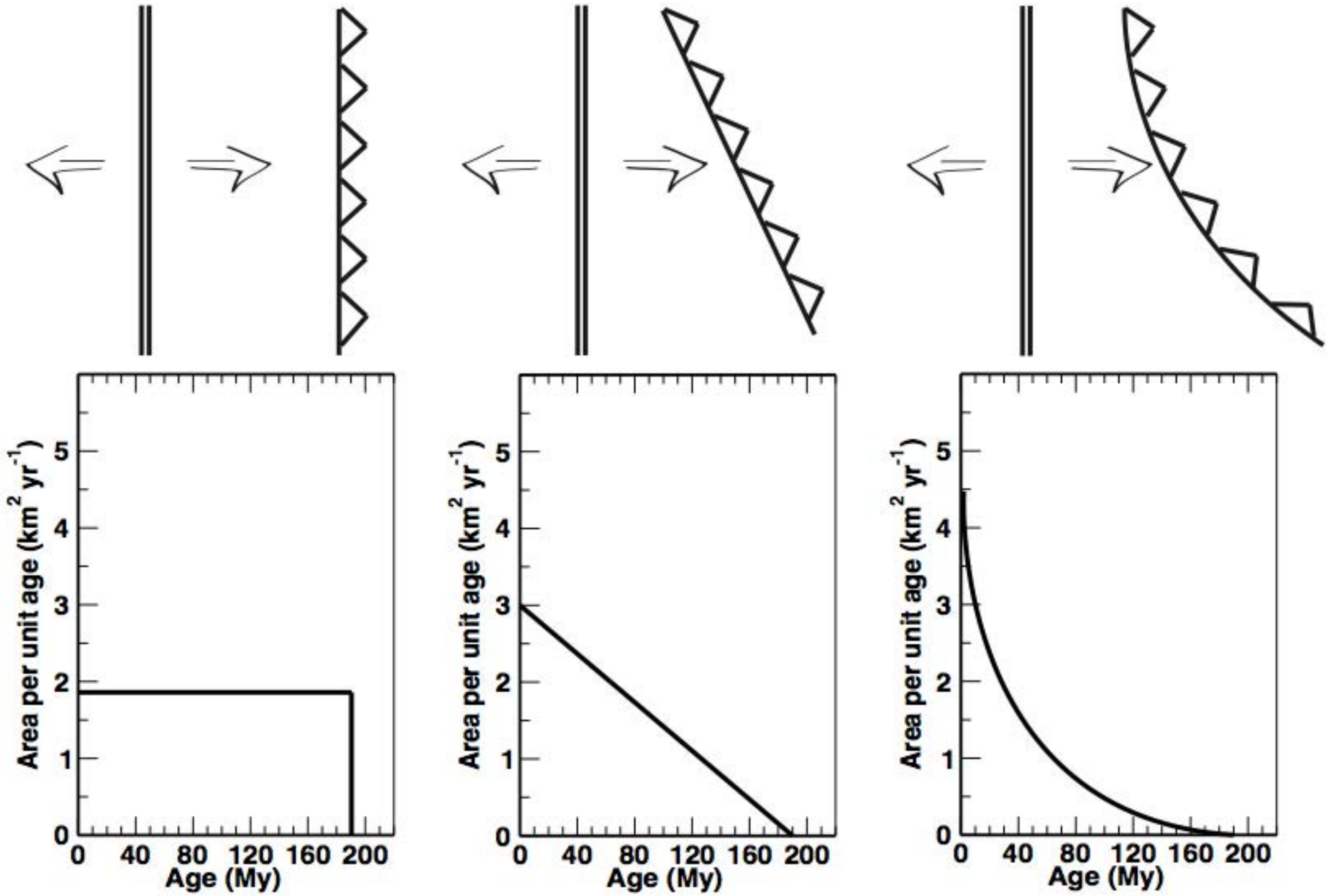


Figure 1: The shape of the area-age distribution depends on the geometry of plate boundaries.

Coltice et al. 2013 EPSL

Reason 2: time-dependence of seafloor production

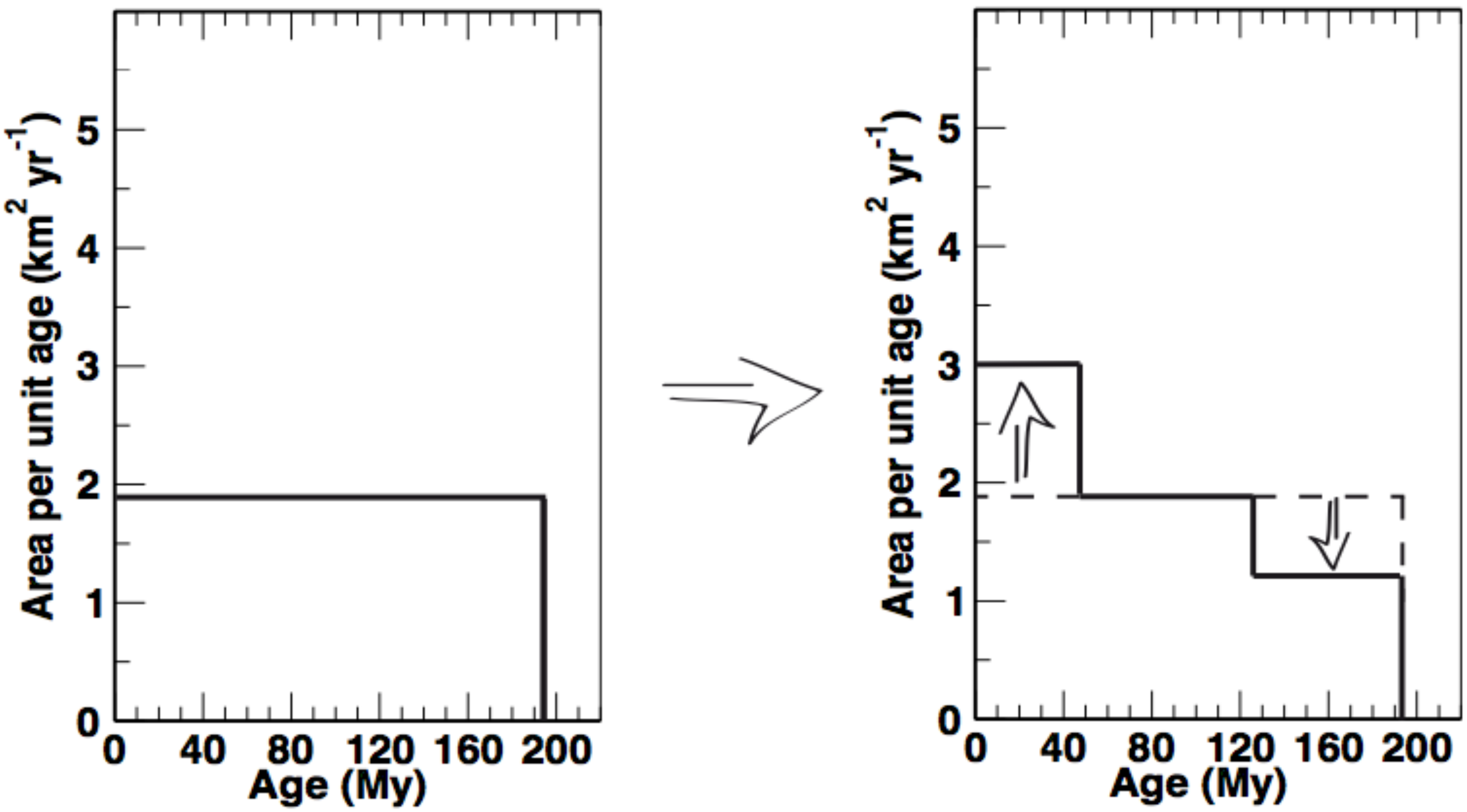
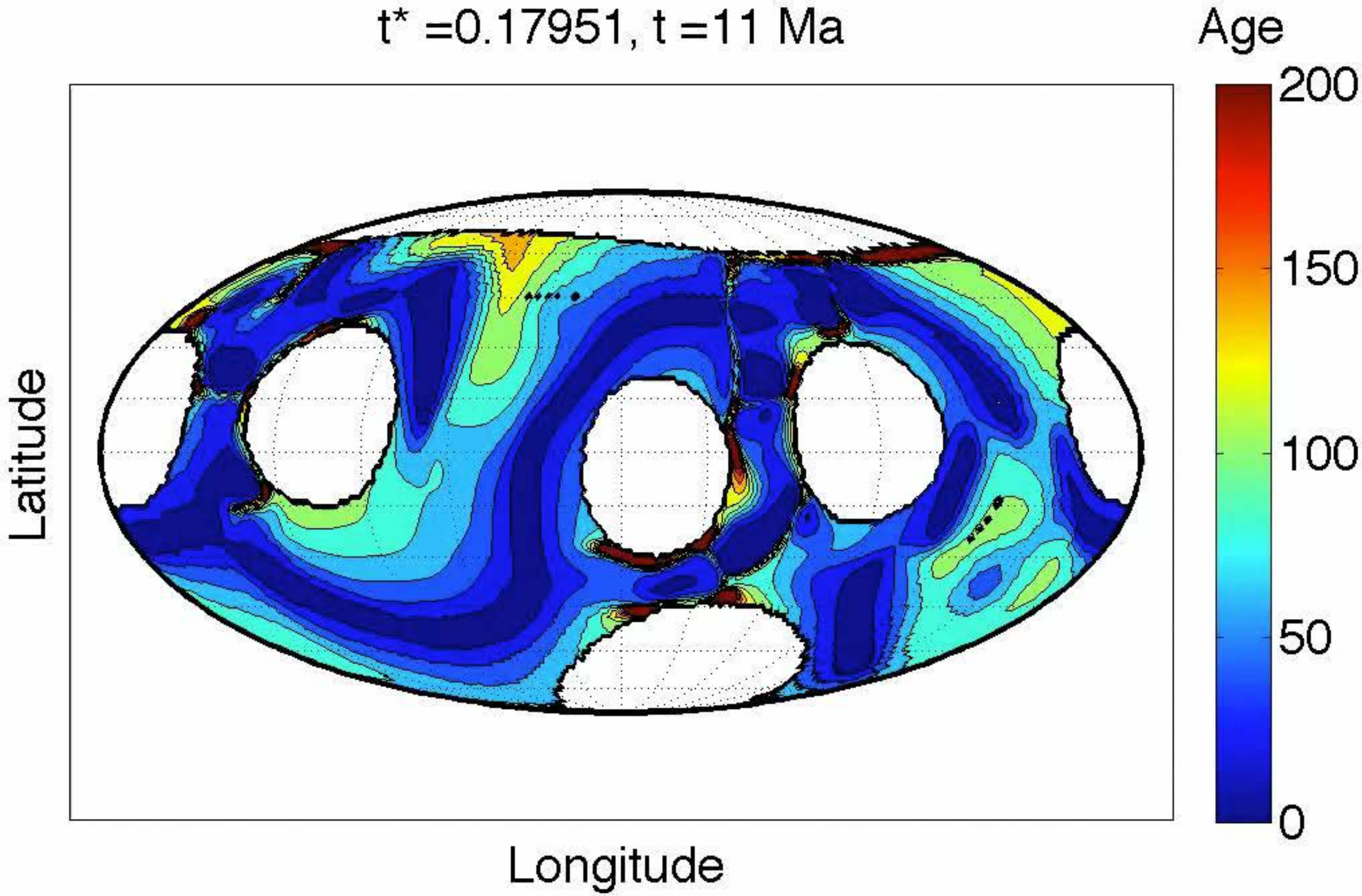


Figure 2: The shape of the area-age distribution depends on the time dependence of the production of new seafloor.

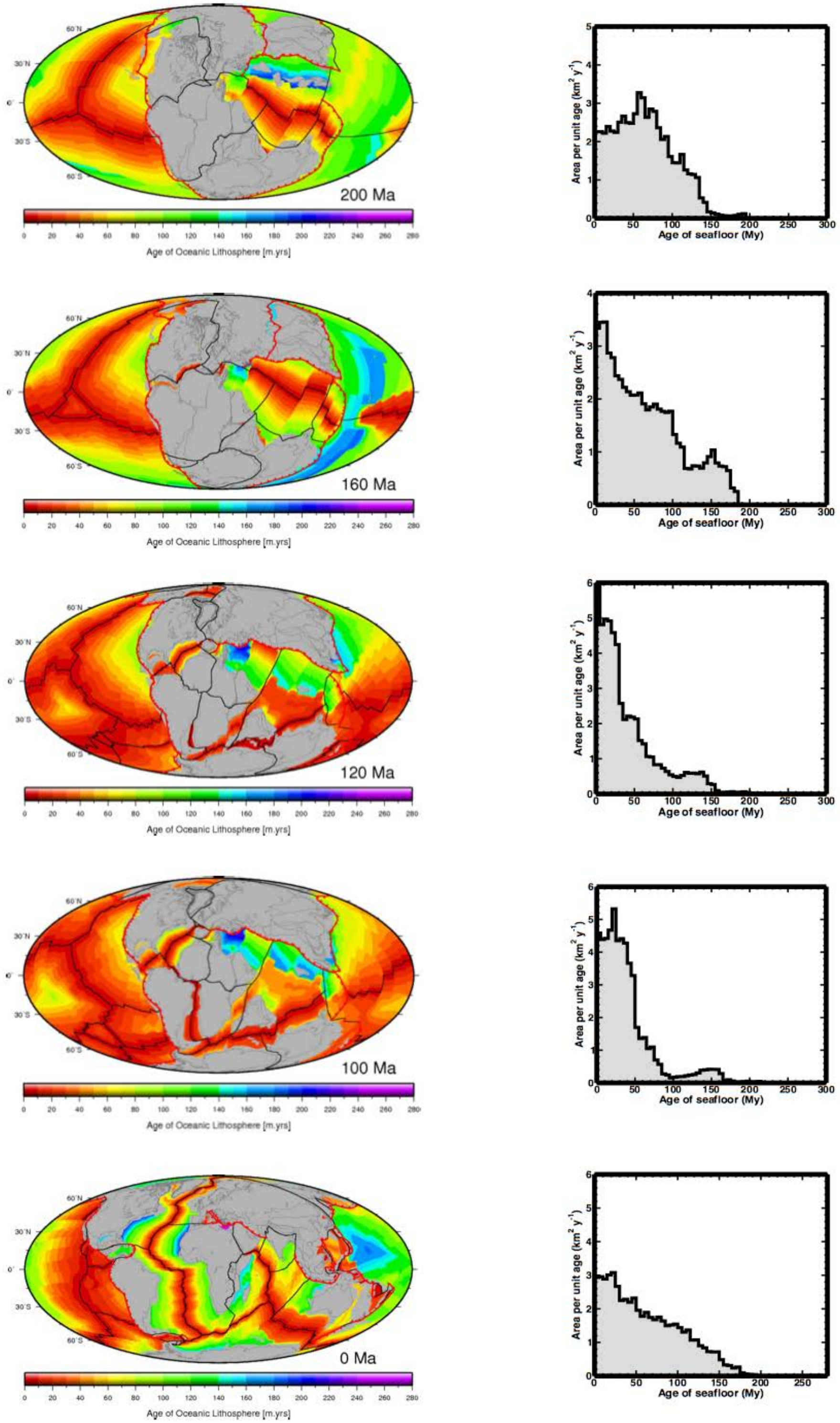
Coltice et al. 2013 EPSL


t* =0.17951, t =11 Ma
Age
200
150
100
50
0
Latitude
Longitude

The real Earth

Maps of reconstructed distribution of seafloor ages and associated area-age distributions in the past 200 Myr (Seton et al. 2012)

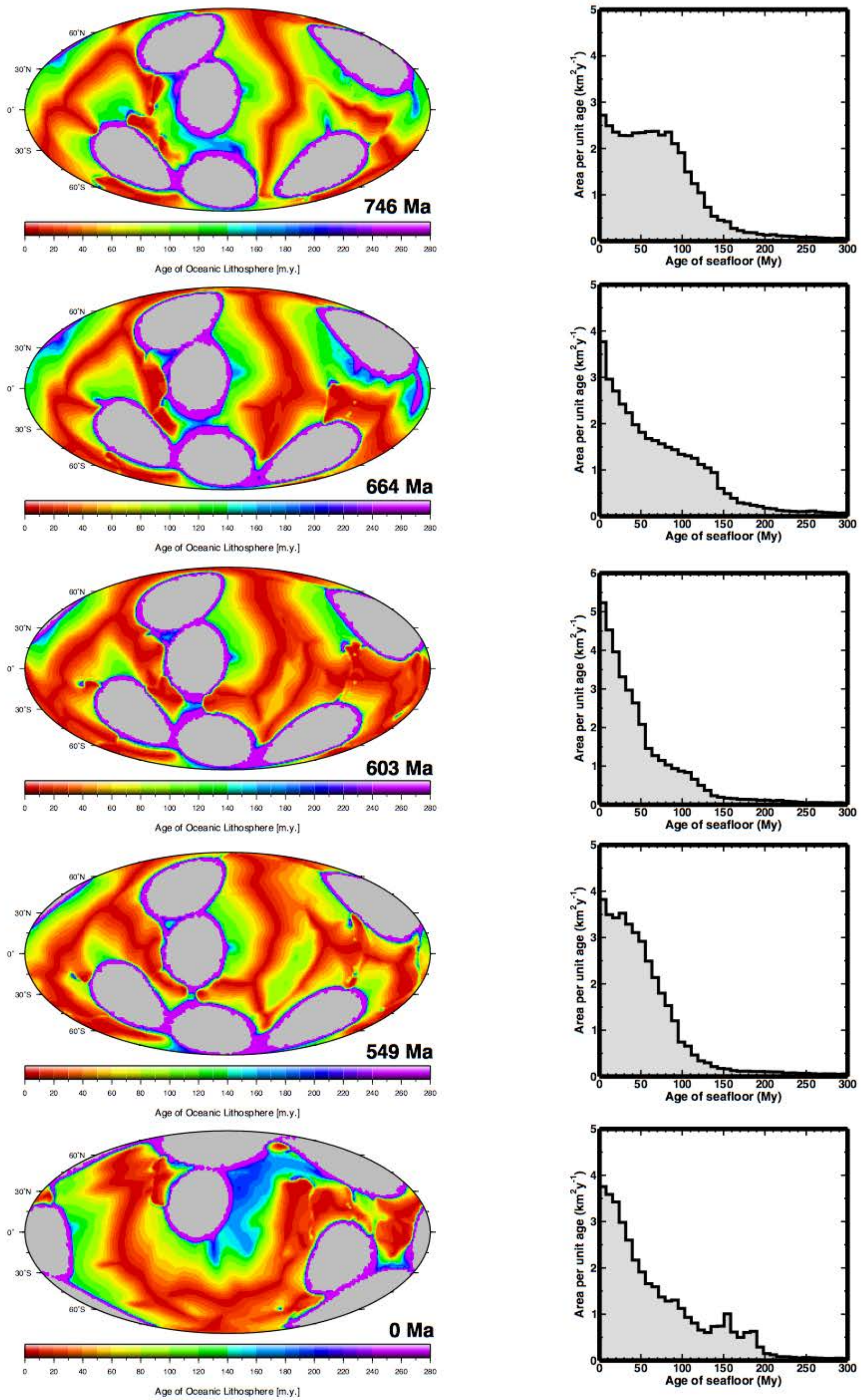
Coltice et al. 2013 EPSL



The simulated Earth

Synthetic maps of seafloor ages and associated area-age distributions in the mantle convection model with 6 continental rafts and 14% of core heating.

Coltice et al. 2013 EPSL



AUGURY
Reconstructing Earth's mantle convection

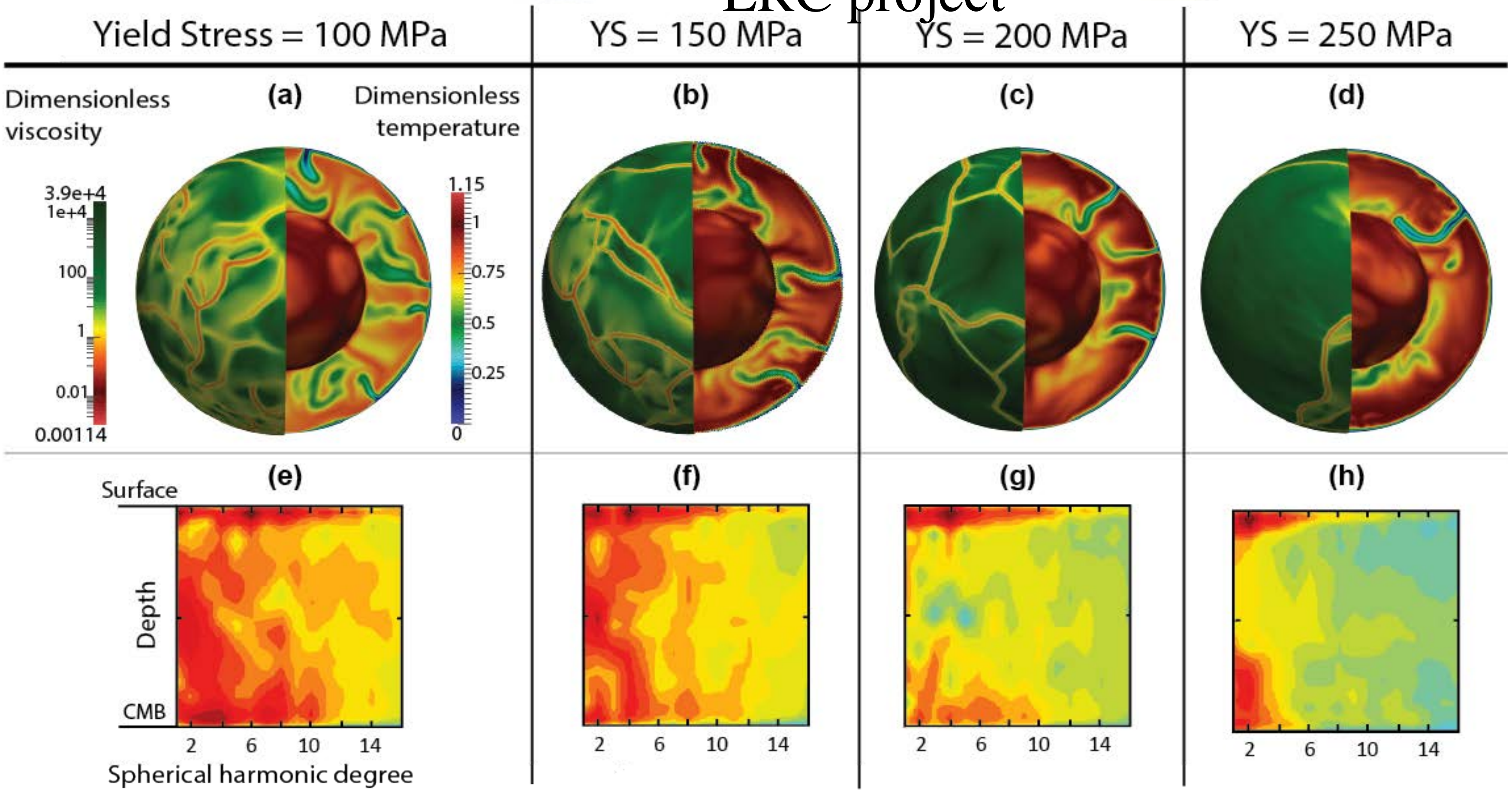
Subduction controls the distribution and fracmentation of Earth's tectonic plates, C. Mallard at al., Nature 2016

Influence of yield stress on plate distribution

Claire Mallard

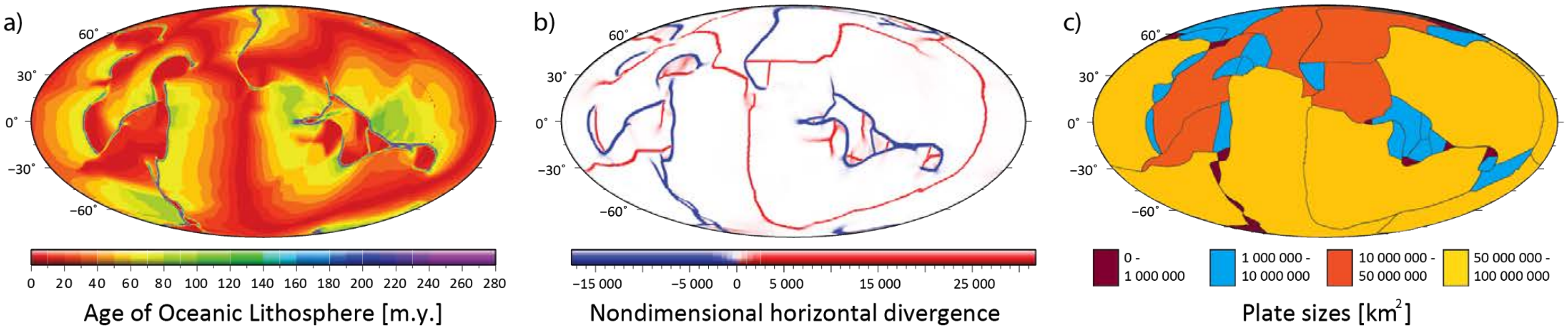
Nicolas Coltice
AUGURY ERC project

Dietmar Müller



Higher yield stress -> larger plates

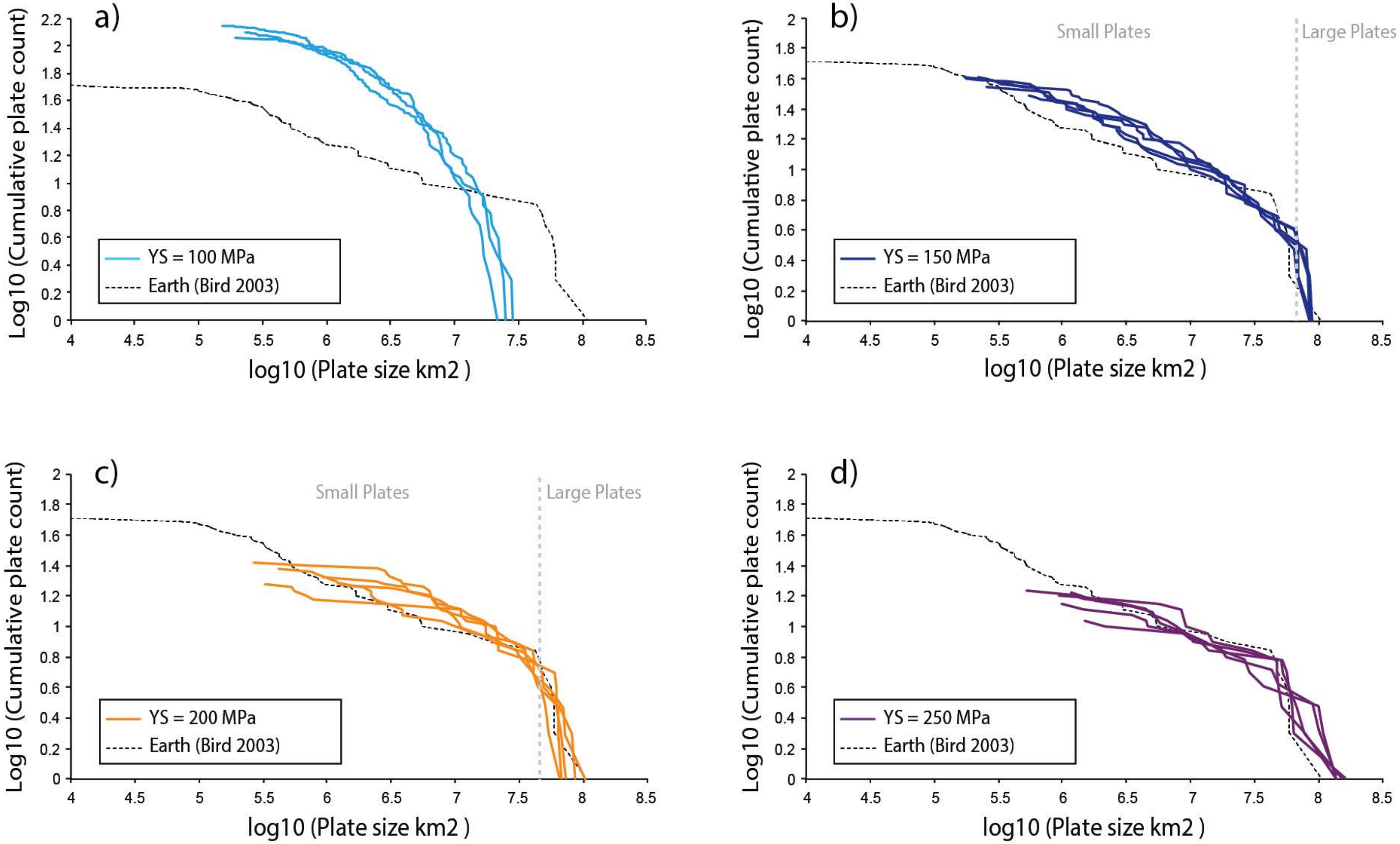
Generate plate maps



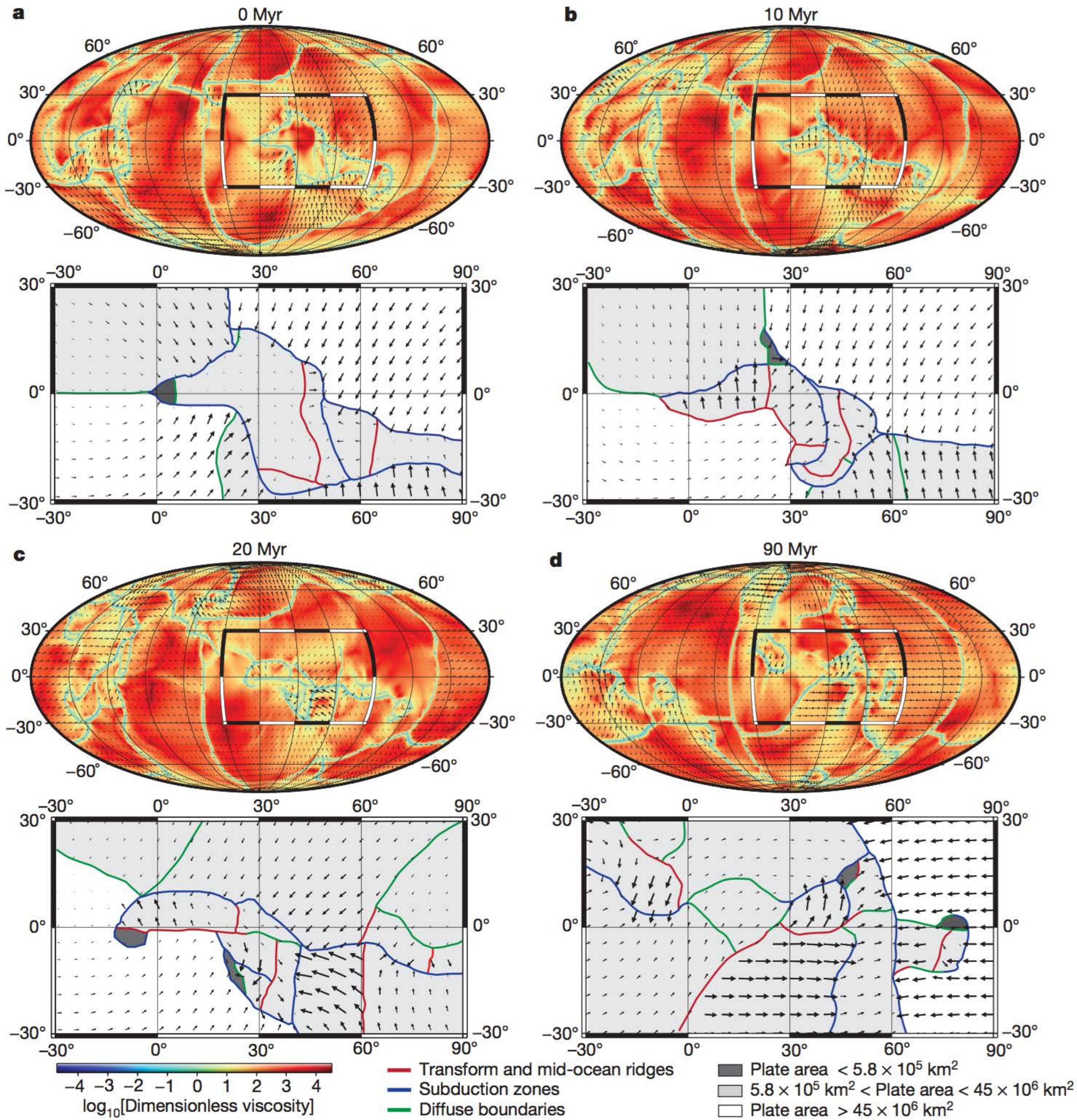
Plates are not a uniform size

-> a distribution from large to small

Plate size distribution



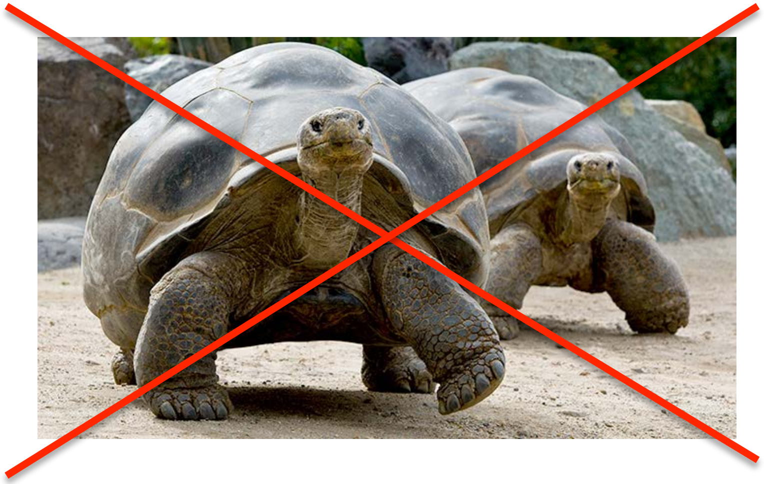
YS=200 MPa -> matches Earth!



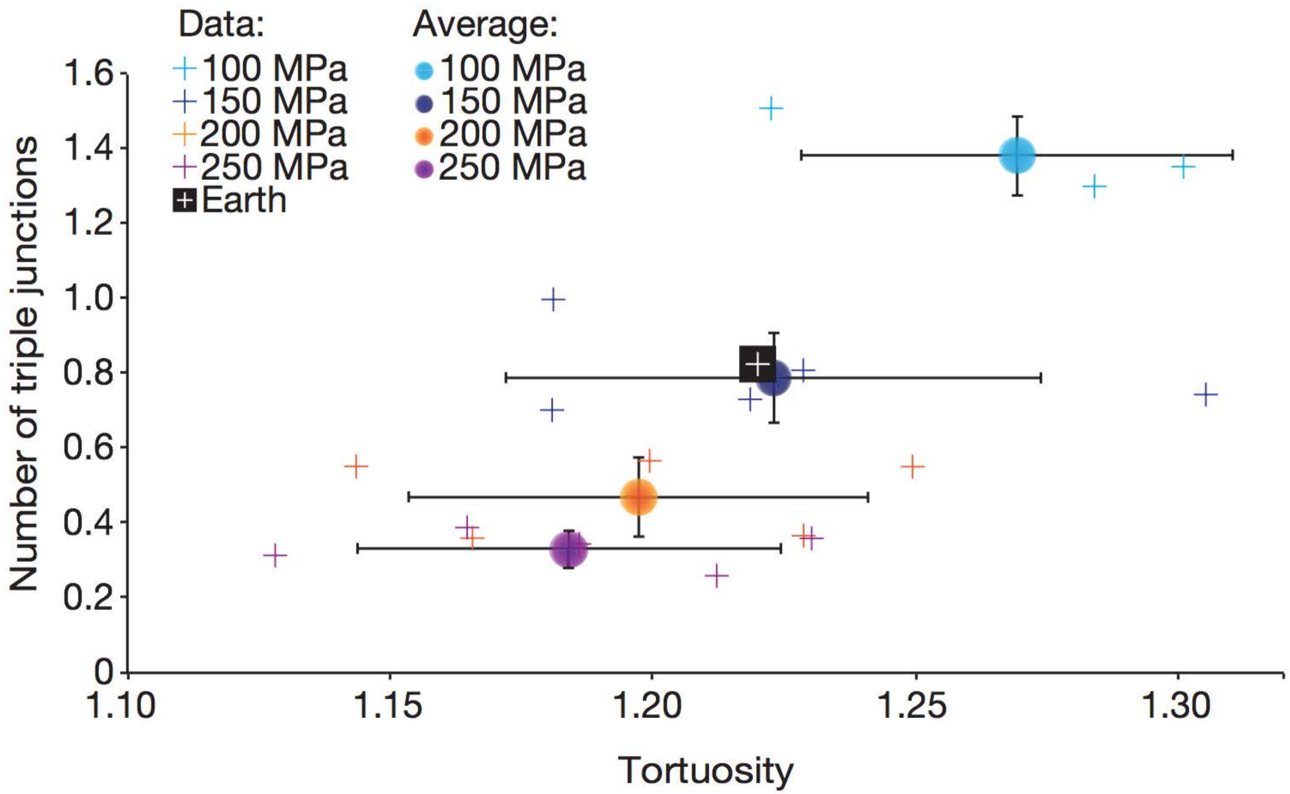
High curvature => new small plates form

Large plates stay ~same

Tortuosity!

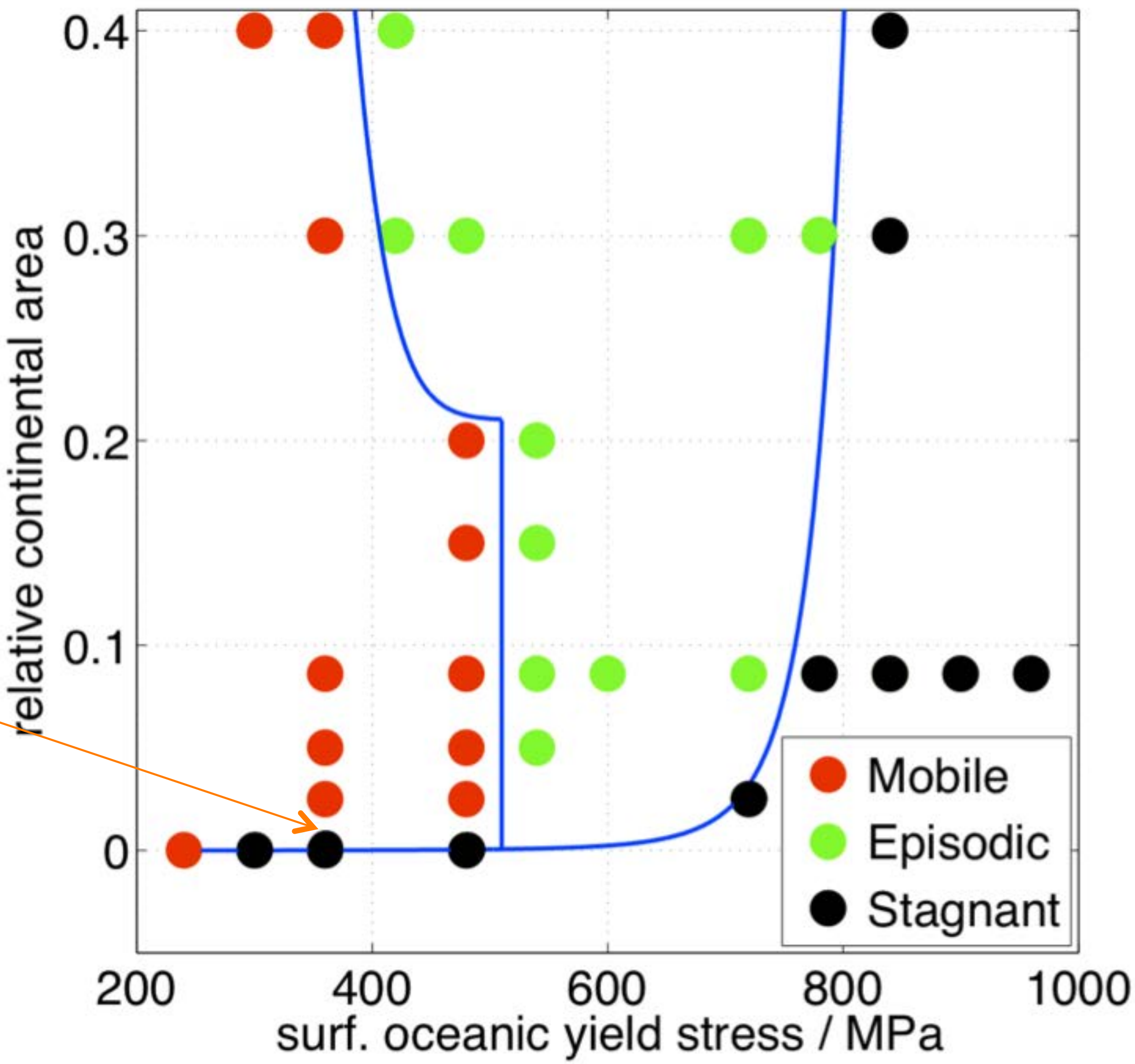


More tortuous -> more triple junctions

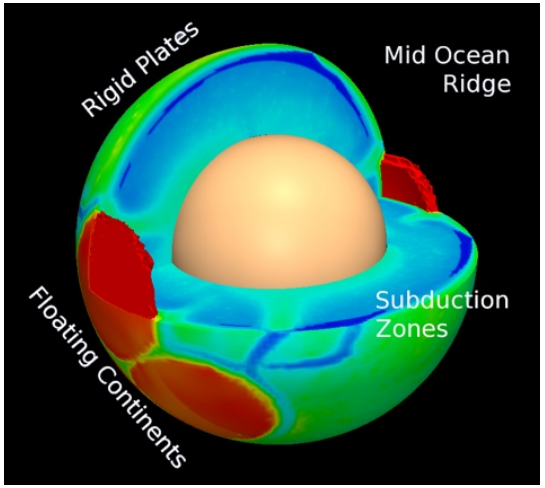


Hence,
-> a simple rheology reproduces many features of Earth’s plate tectonics (age-area distribution; size distribution) BUT
-> required yield stress is far below laboratory values.
WHY?

Continents help plate tectonics!



Presence of continent allows plate tectonics at higher yield stress

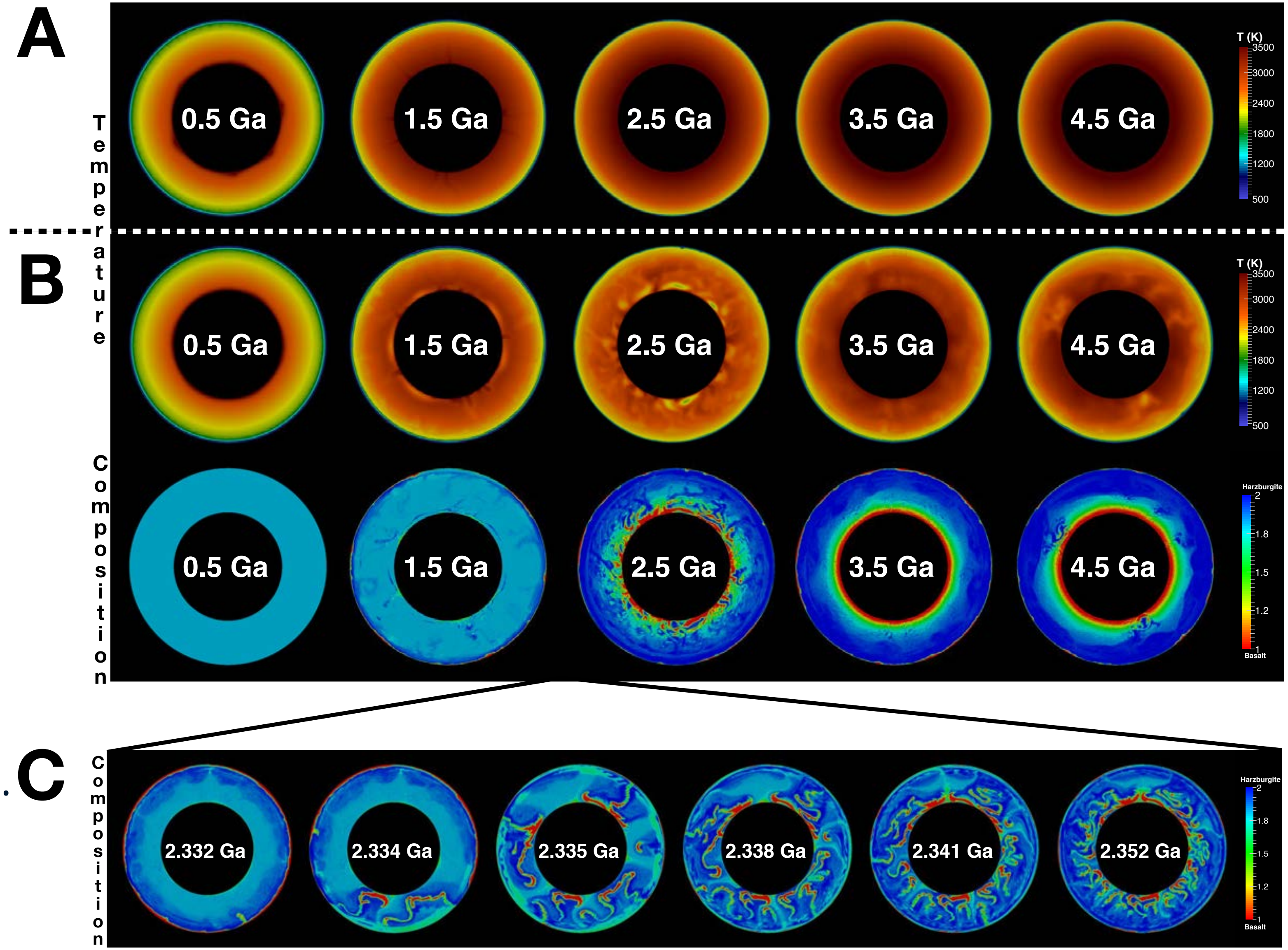


Rolf and Tackley, GRL 2011

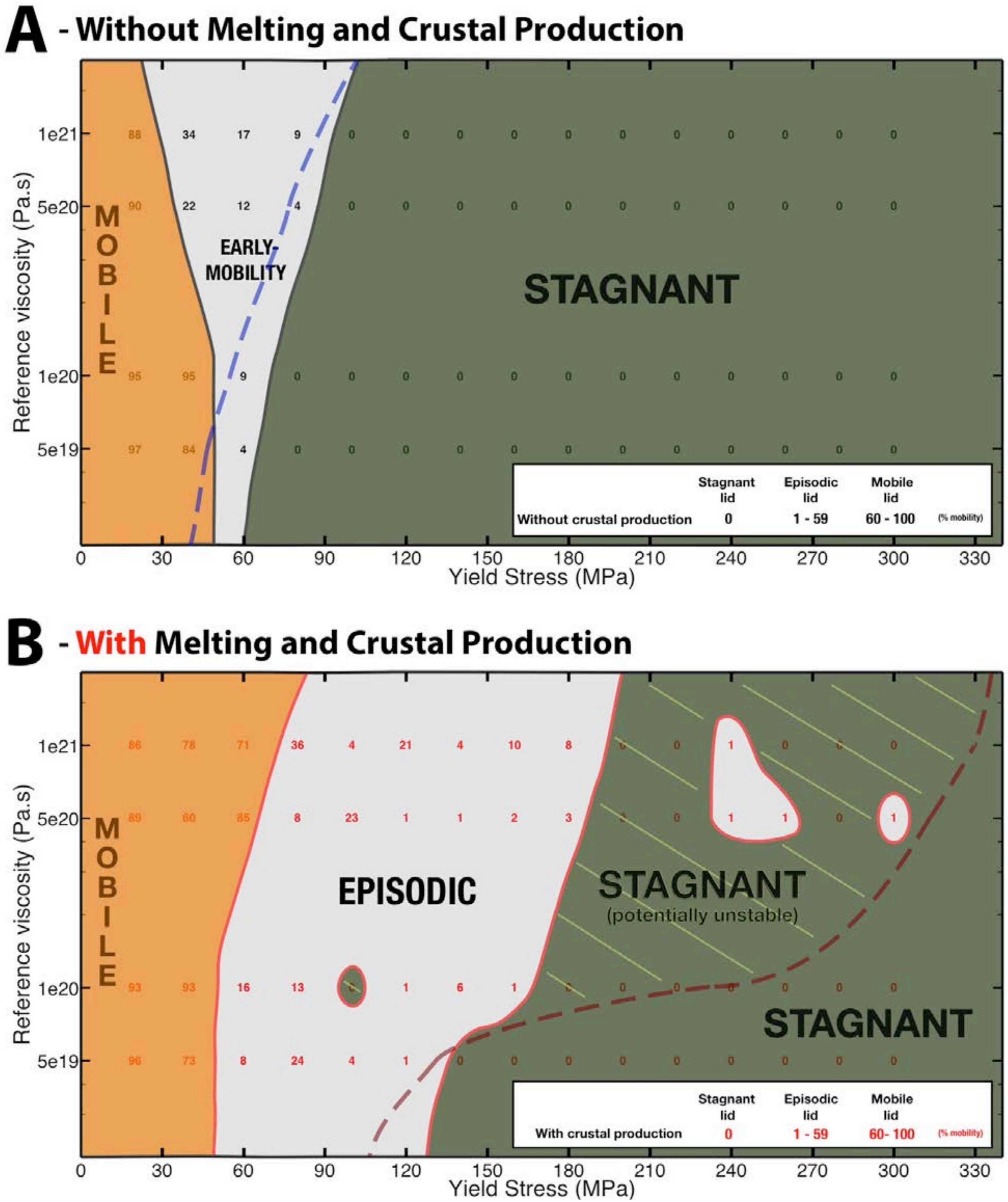
Magmatism->crust helps plate tectonics

Purely thermal
-> Stagnant

With magma & crust
Episodic plate tectonics

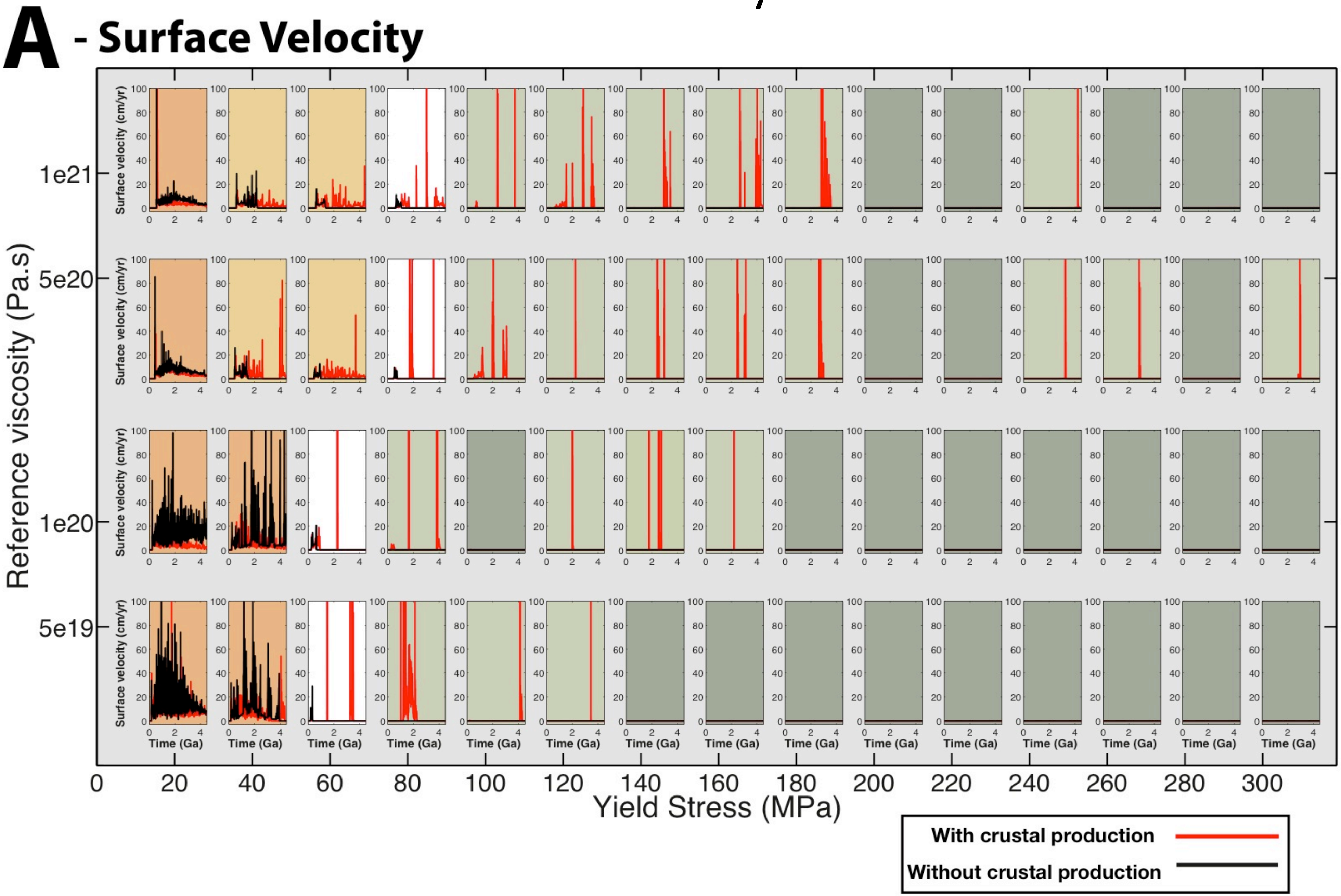


Diogo Lourenco A. Rozel & Tackley, EPSL 2016



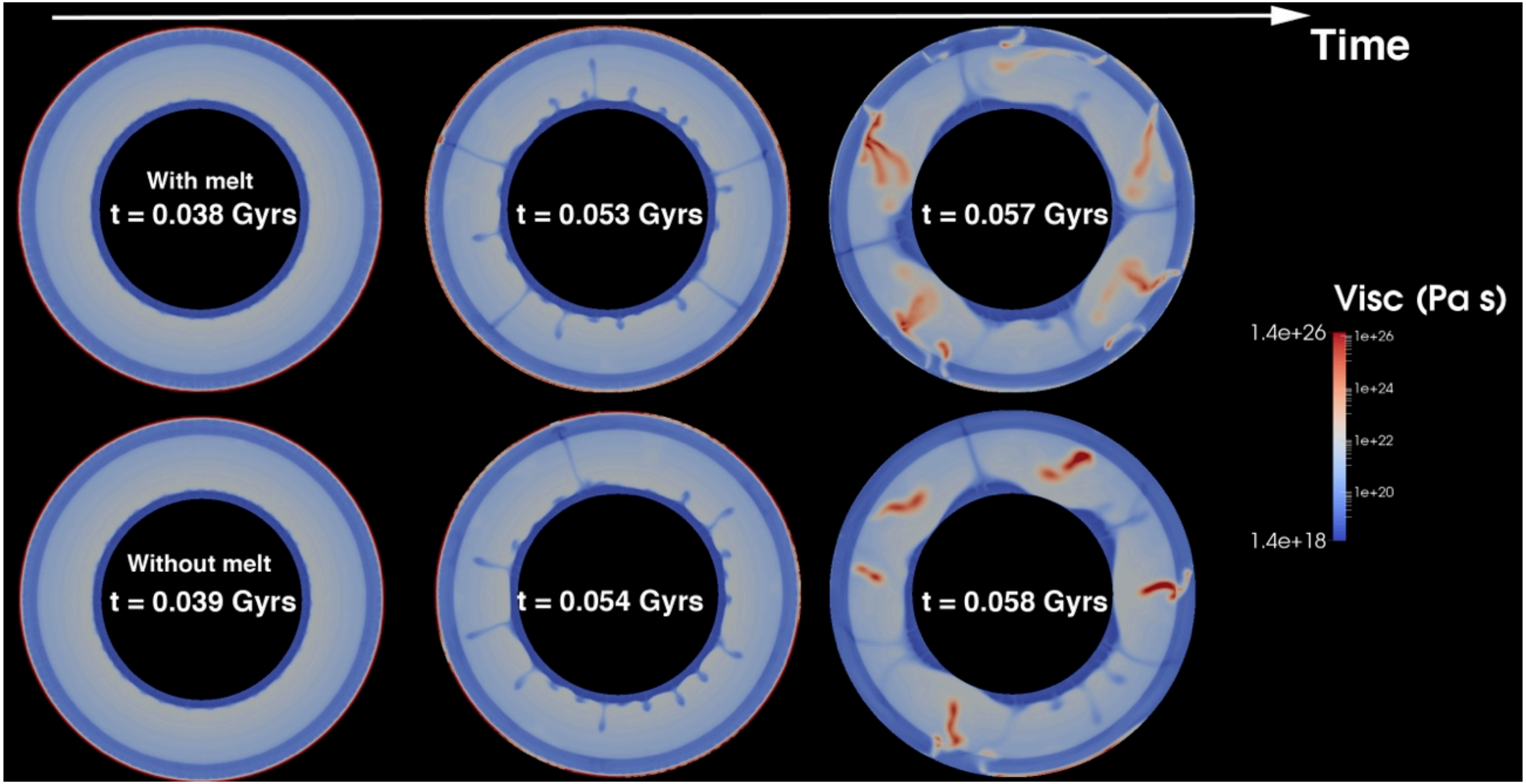
Lourenco et al.,
EPSL 2016

Surface velocity vs. time



Lourenco, Rozel & Tackley, EPSL 2016

Initiation of first subduction by plumes

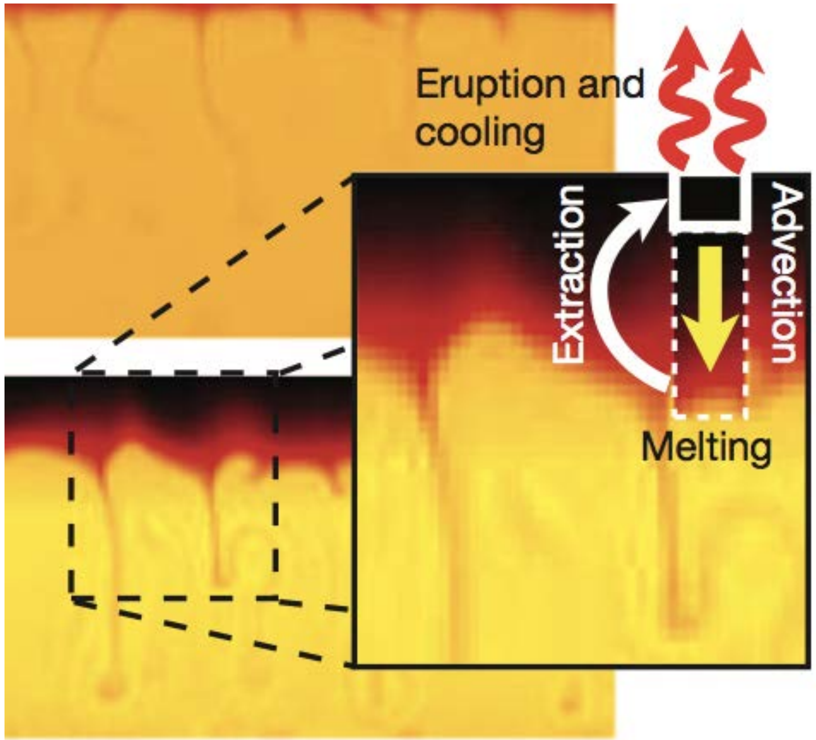


Nakagawa & Tackley, 2015

Summary

- The production of laterally-varying crust assists plate tectonics on Earth-like planets
- Broad parameter range in which episodic behaviour occurs

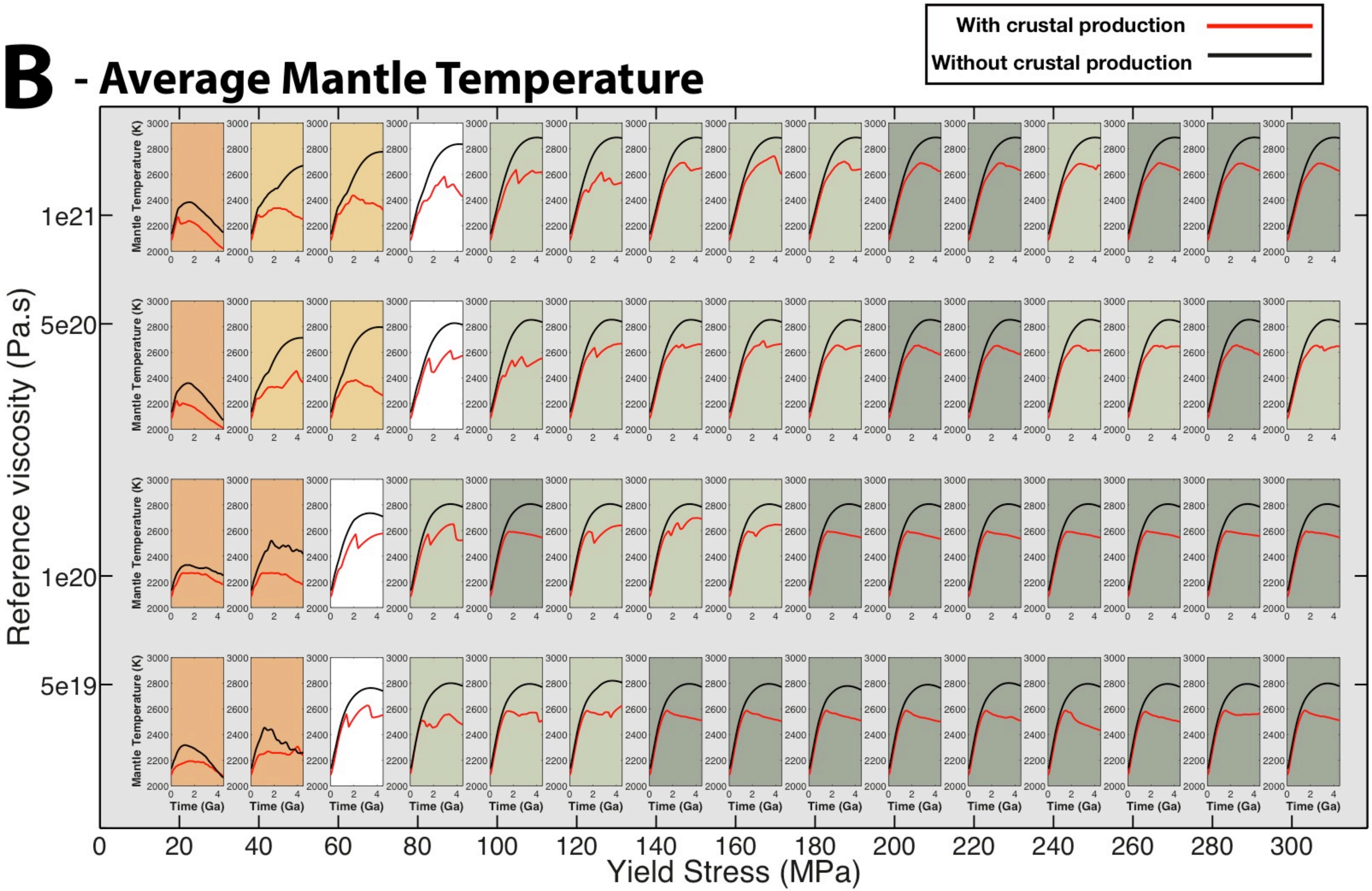
Extrusive heat pipe magmatism



(picture from Moore&Webb 2013)

-> COLD, STRONG crust/lithosphere

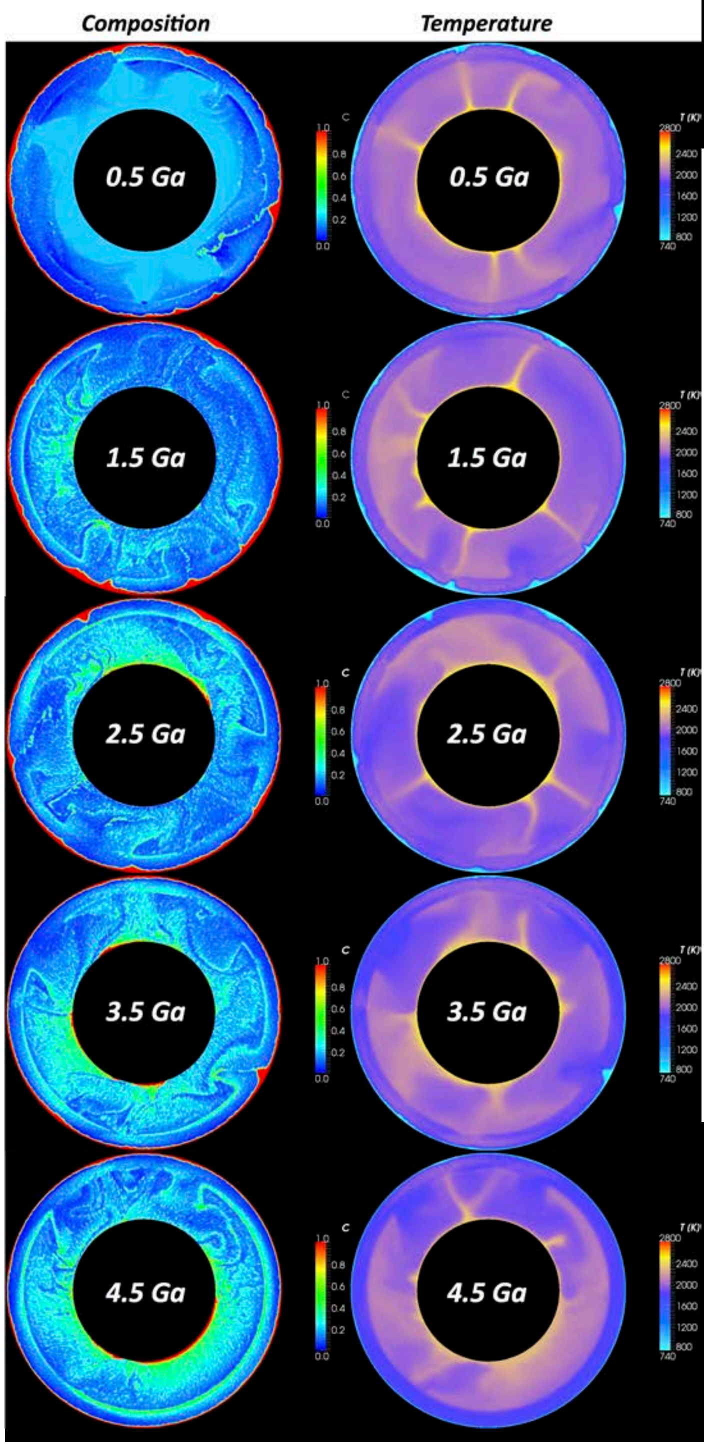
Temperature vs. time

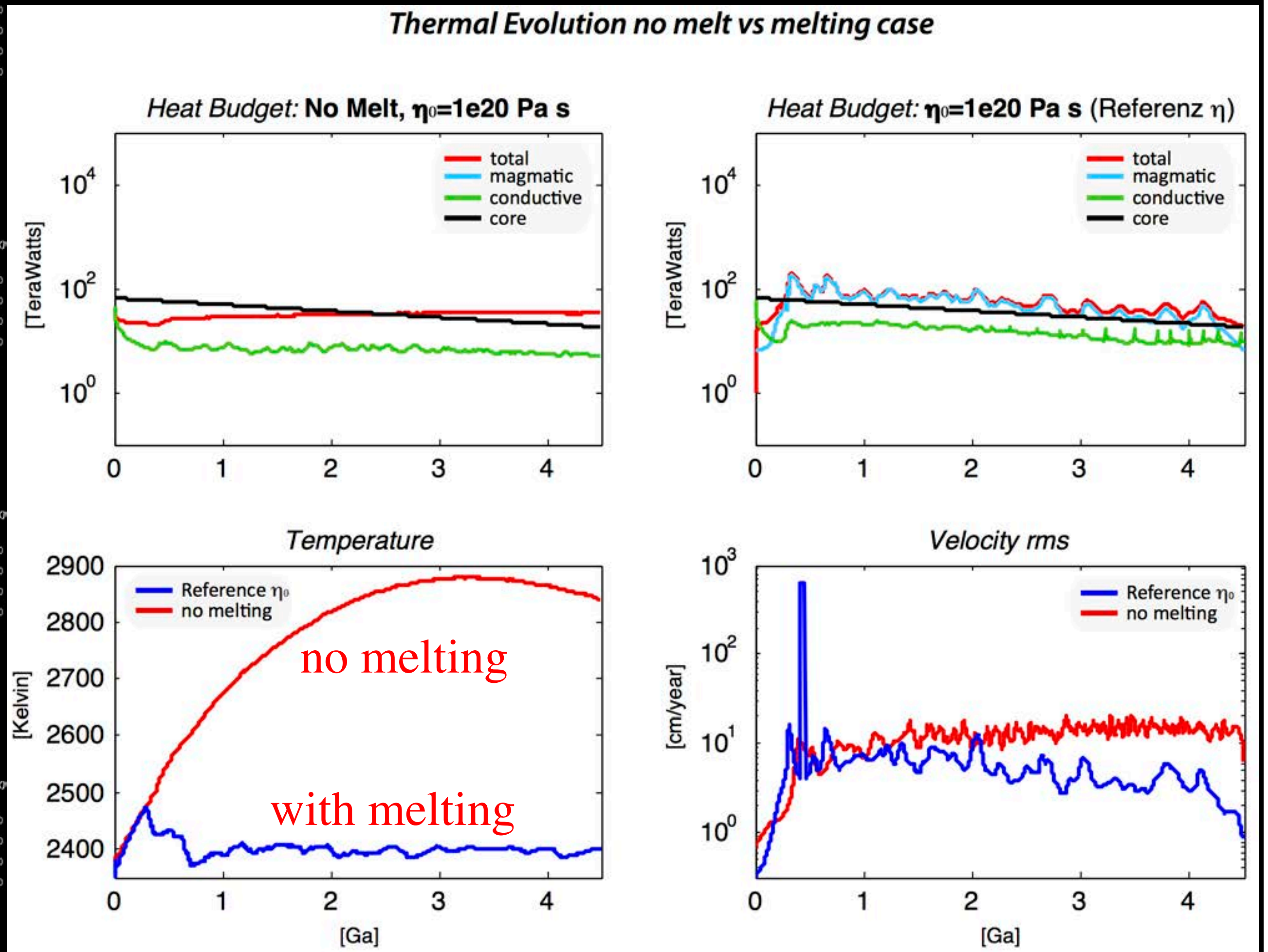


Lourenco, Rozel & Tackley, EPSL 2016

Venus

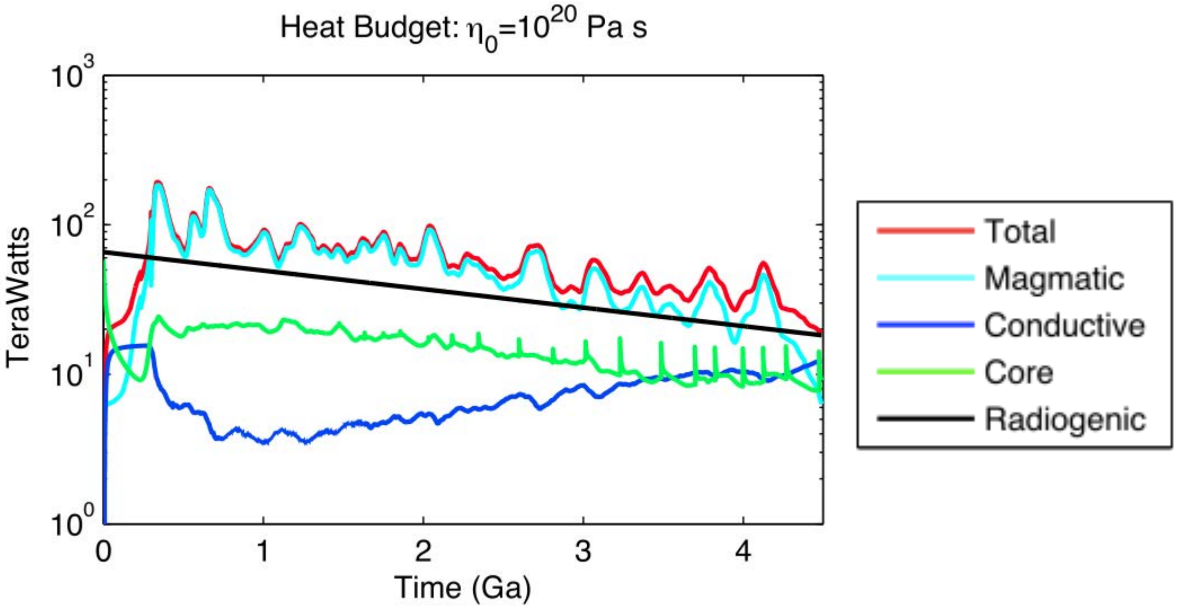
Reference Case: η=1e20 Pa s



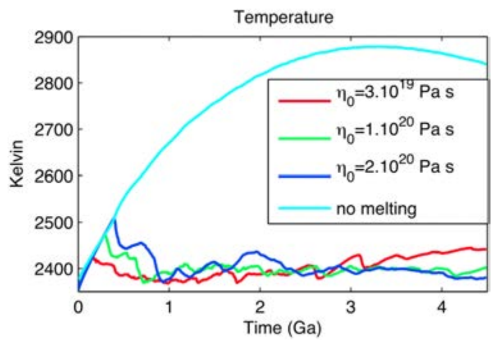


Armann & Tackley, 2012 JGR

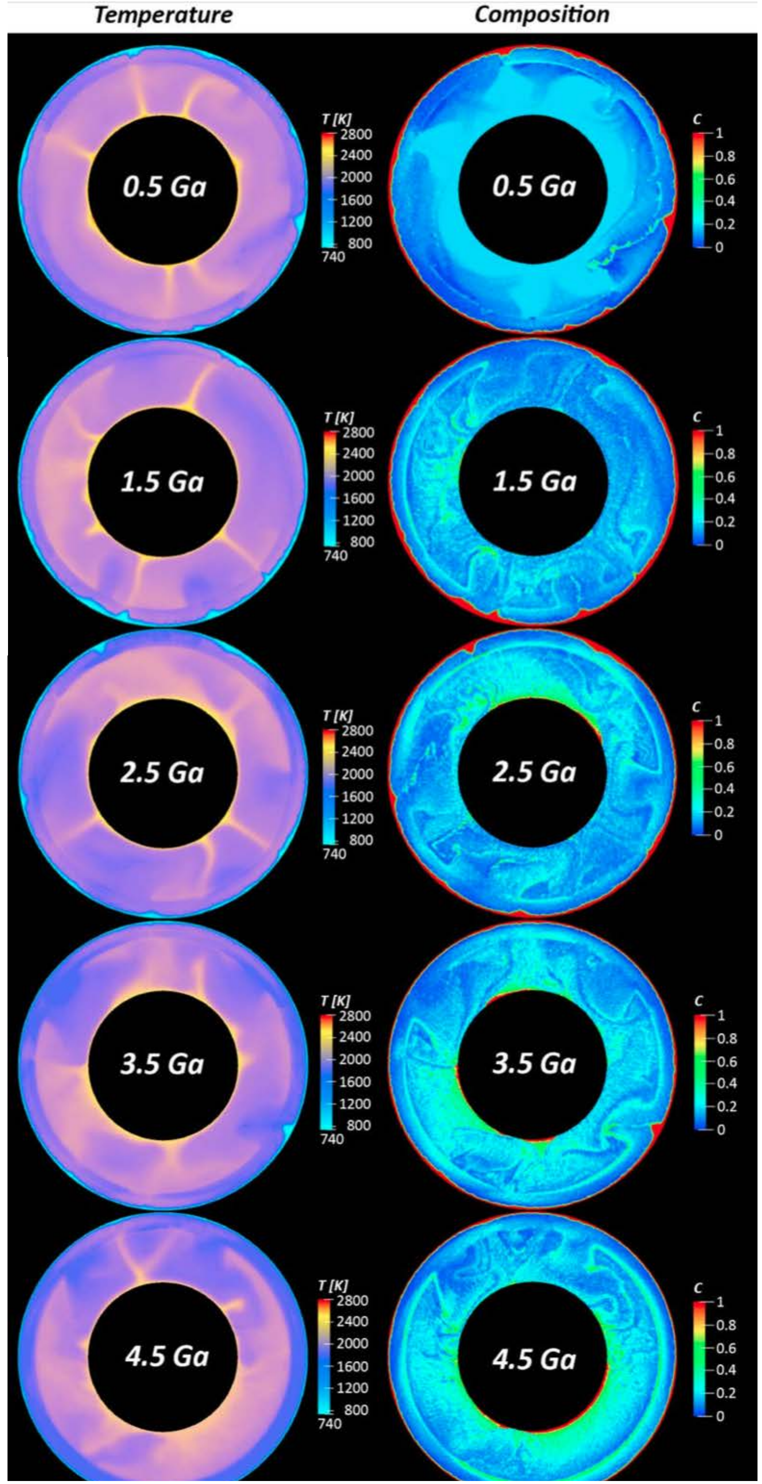
Stagnant lid; extrusive



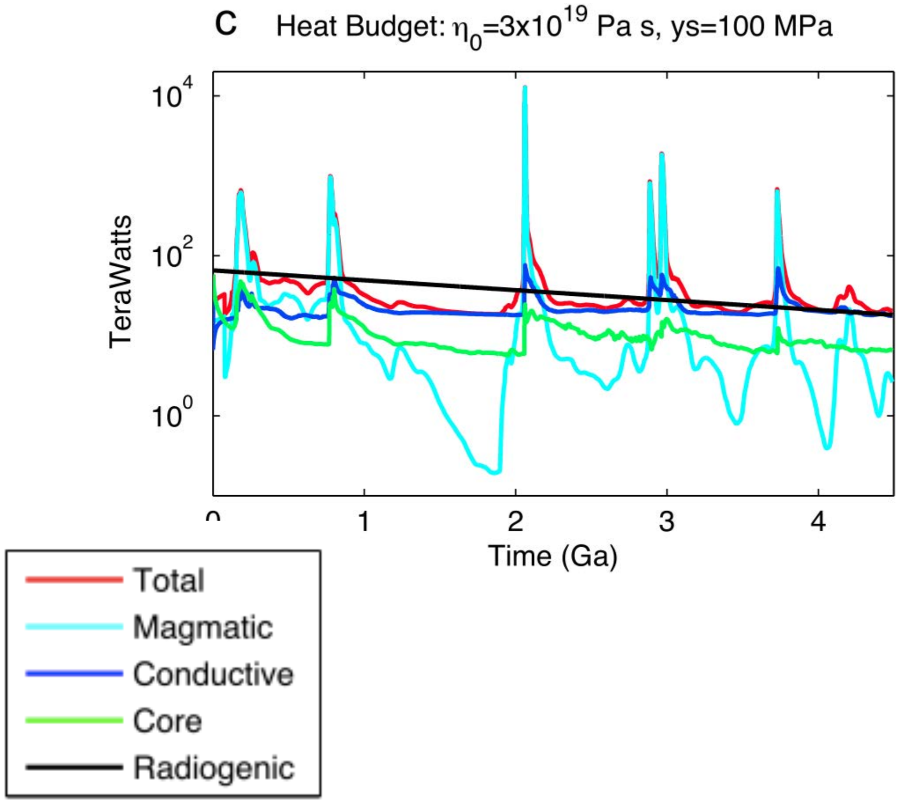
- 'magmatic heat pipe'
- Cold crust/lithosphere
- High resurfacing rate (300 km/Gyr) does not match observations

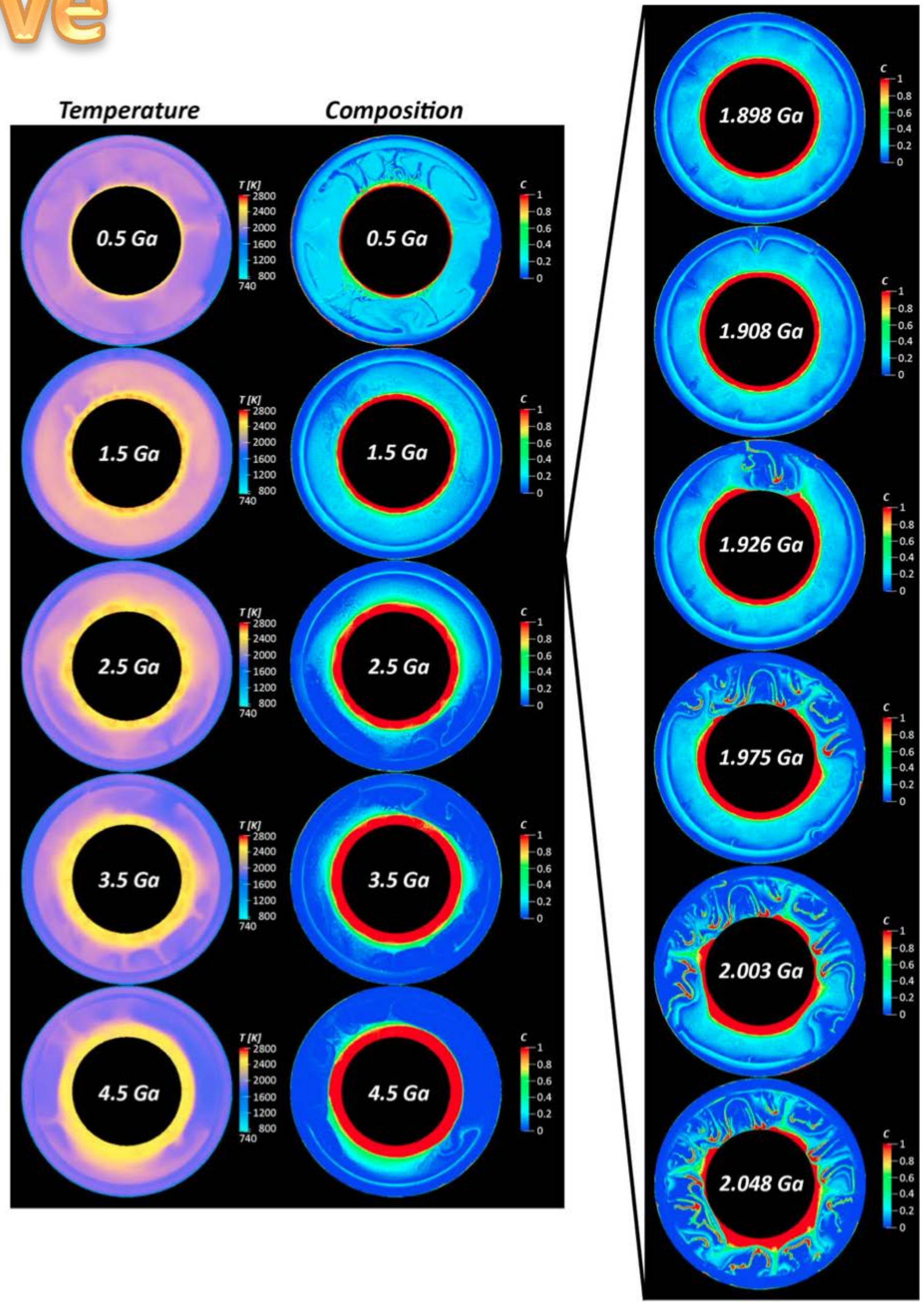


Magmatism => 'thermostat'.
No magmatism=> high T, massive melting



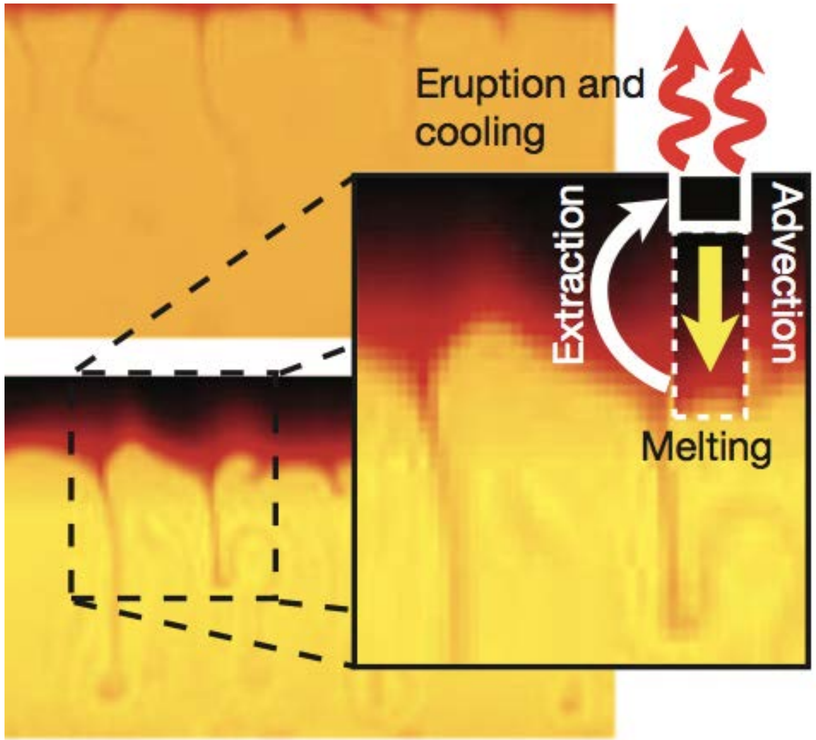
Episodic lid; extrusive





- Episodic overturn due to plastic yielding
- Better matches surface observations

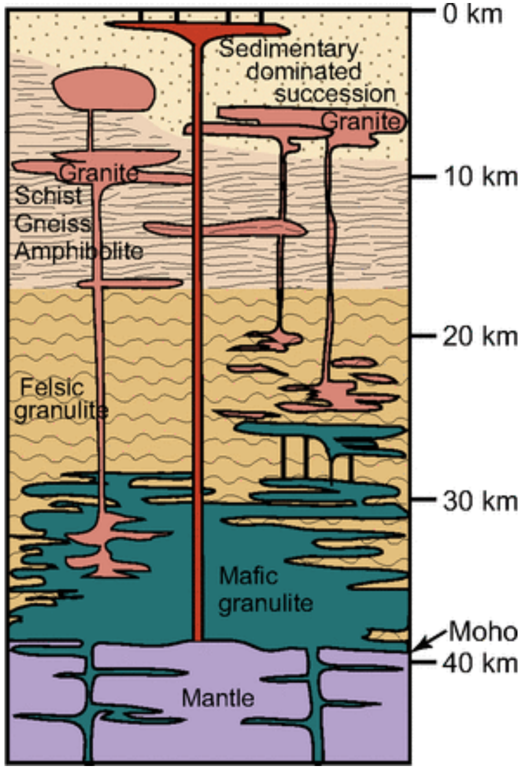
Extrusive heat pipe magmatism



(picture from Moore&Webb 2013)

-> COLD, STRONG crust/lithosphere

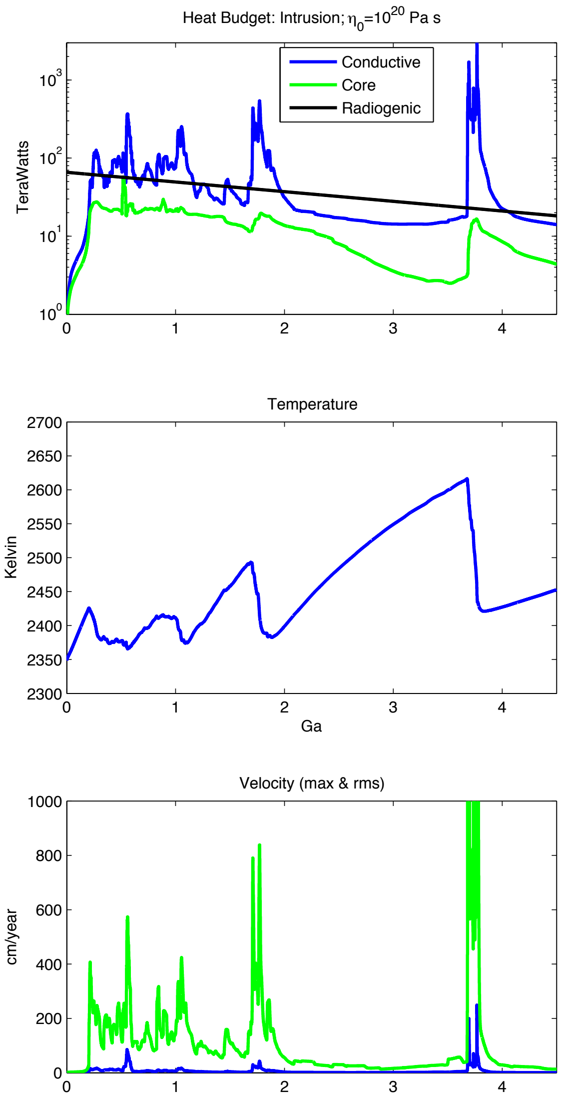
But probably most magmatism is intrusive

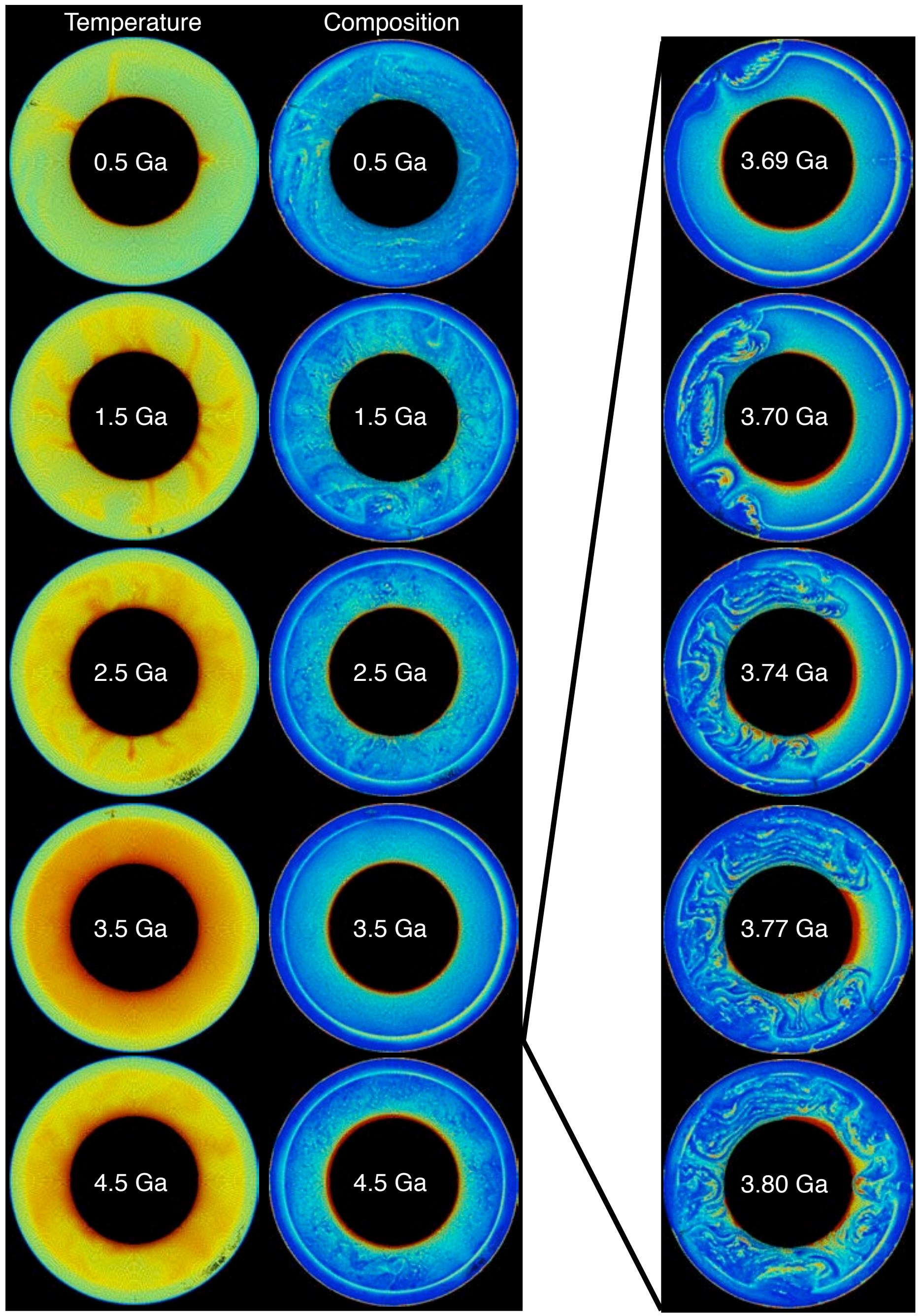


(picture from Cawood et al 2013)

-> WARM, WEAK crust/lithosphere

Intrusive magmatism; no plastic yielding

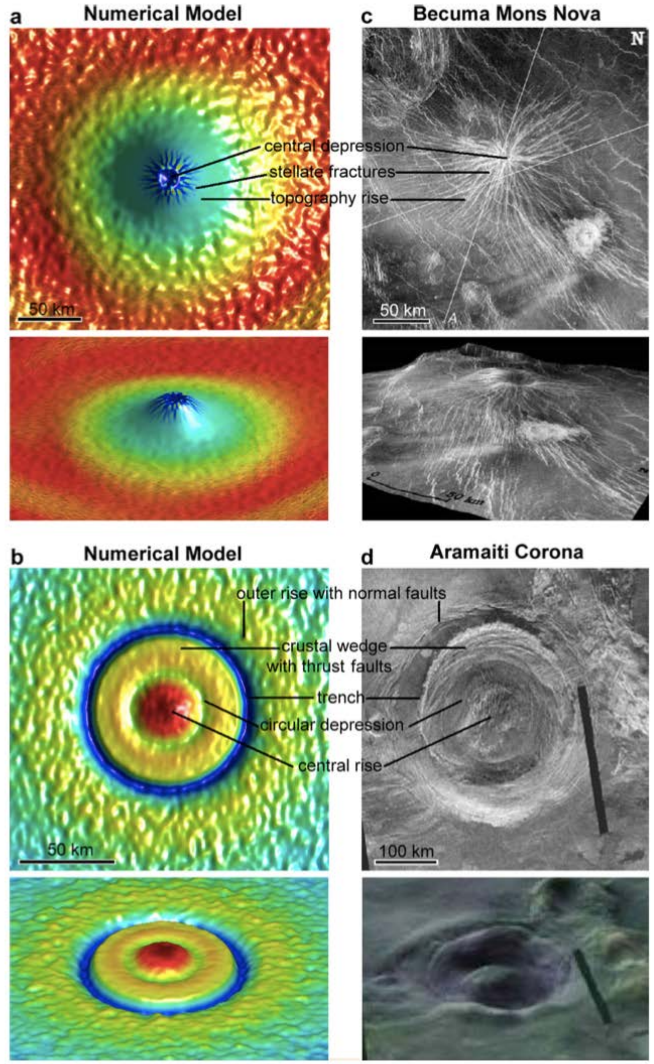


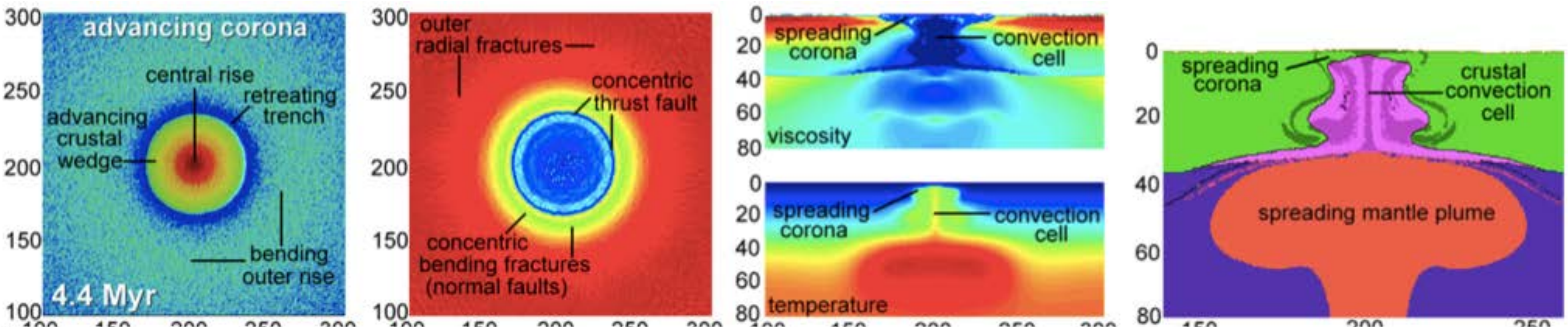


Intrusive magmatism; no plastic yielding

- Thin, weak crust & lithosphere
- Episodic overturn due to magmatic intrusion weakening lithosphere
- Also matches surface observations?

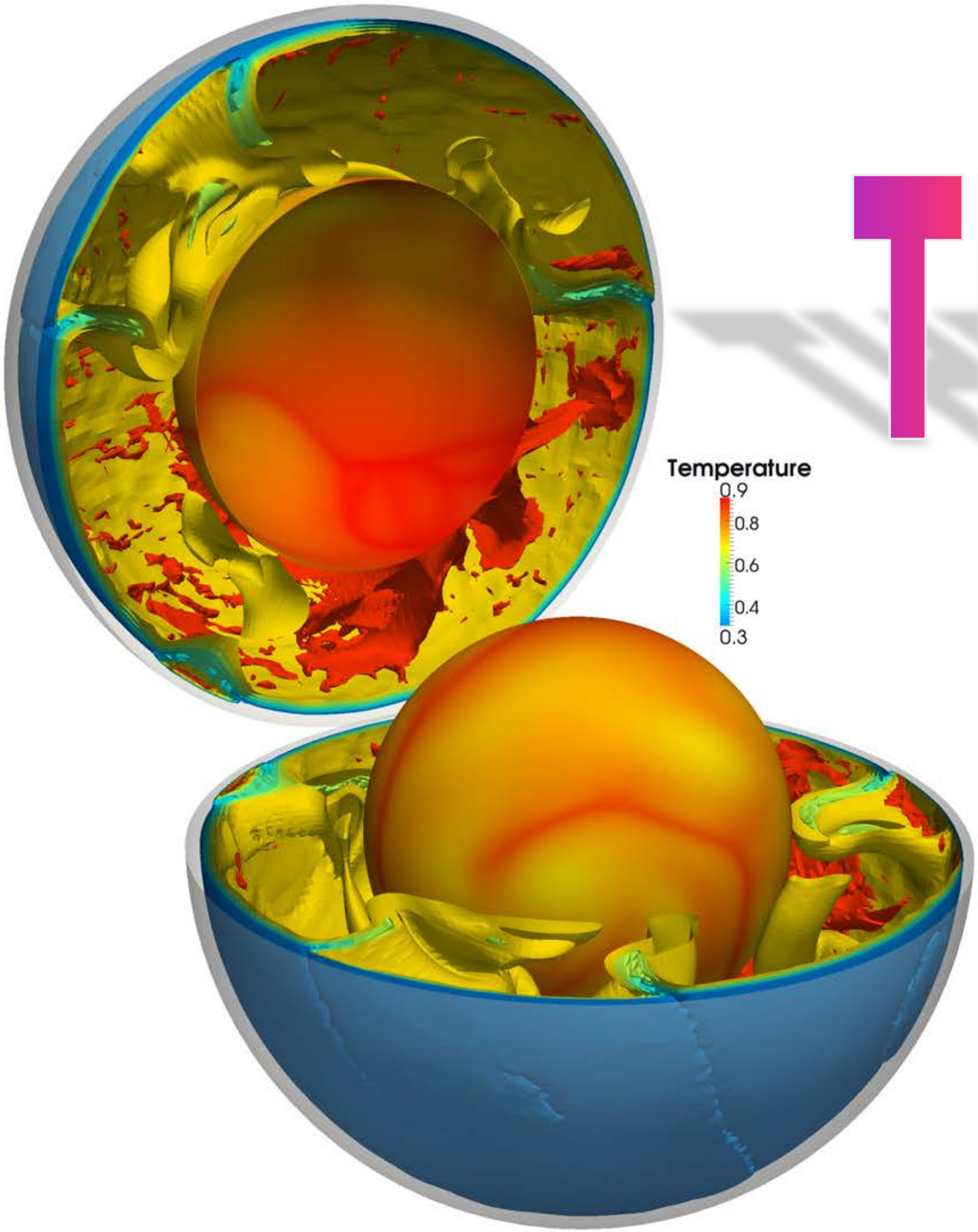
Coronae & Novae caused by magmatic intrusion? – Gerya 2014 EPSL





Conclusions

- Large-scale features of plate tectonics can be obtained with a simple description of plate boundaries
- Area-age distribution of oceanic lithosphere
- Size-number distribution of plates
- Melting and production of crust (oceanic or continental) play a big role in facilitating plate tectonics, as well as influencing other aspects of planetary evolution



THE END