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Mantle Convection in the Earth and Planets

Gerald Schubert

Department of Earth and Space Sciences
University of California, LA
U.S.A.

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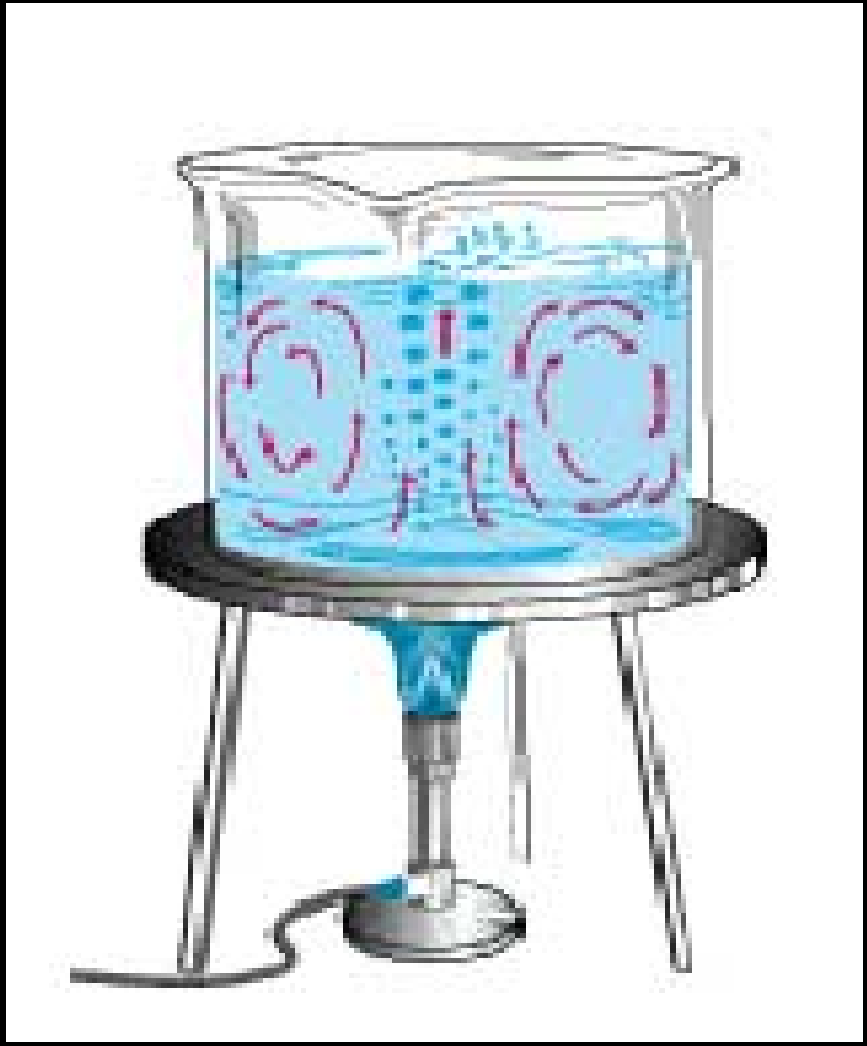
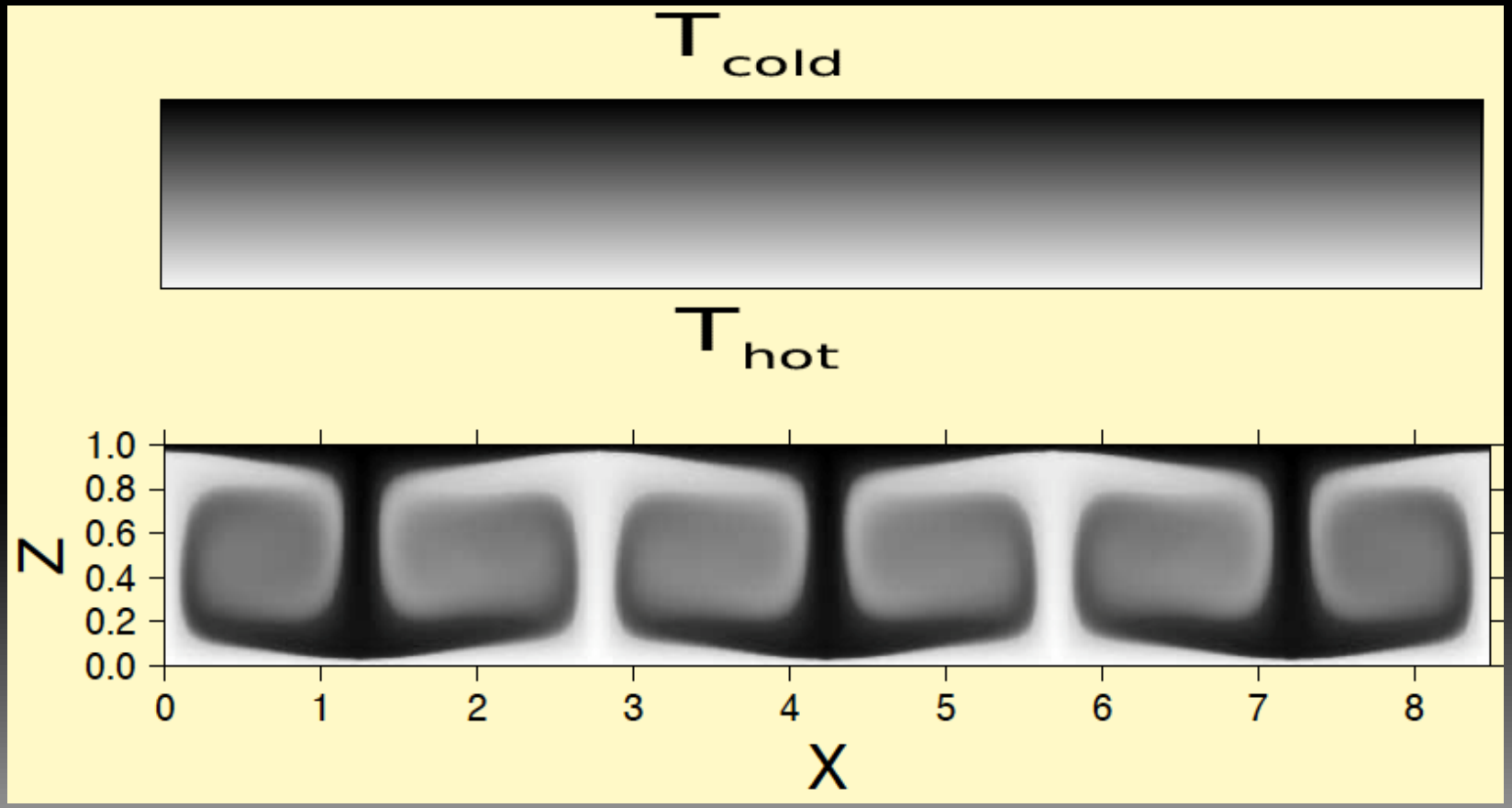
Thermal Convection

"hot stuff rises, cold stuff falls"



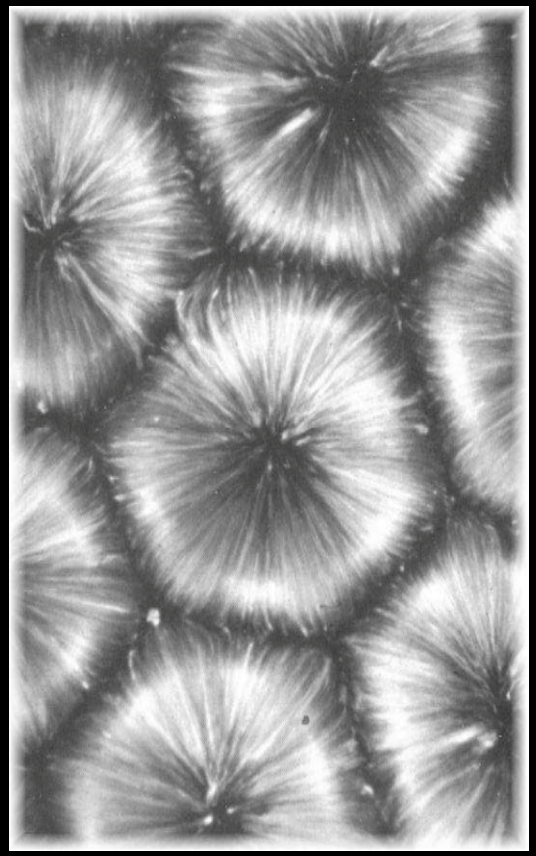
- Most materials...
  - Get less dense when heated
  - More dense when cooled
- Hot stuff buoyant relative to surroundings: rises
- Cold stuff relatively heavy: falls

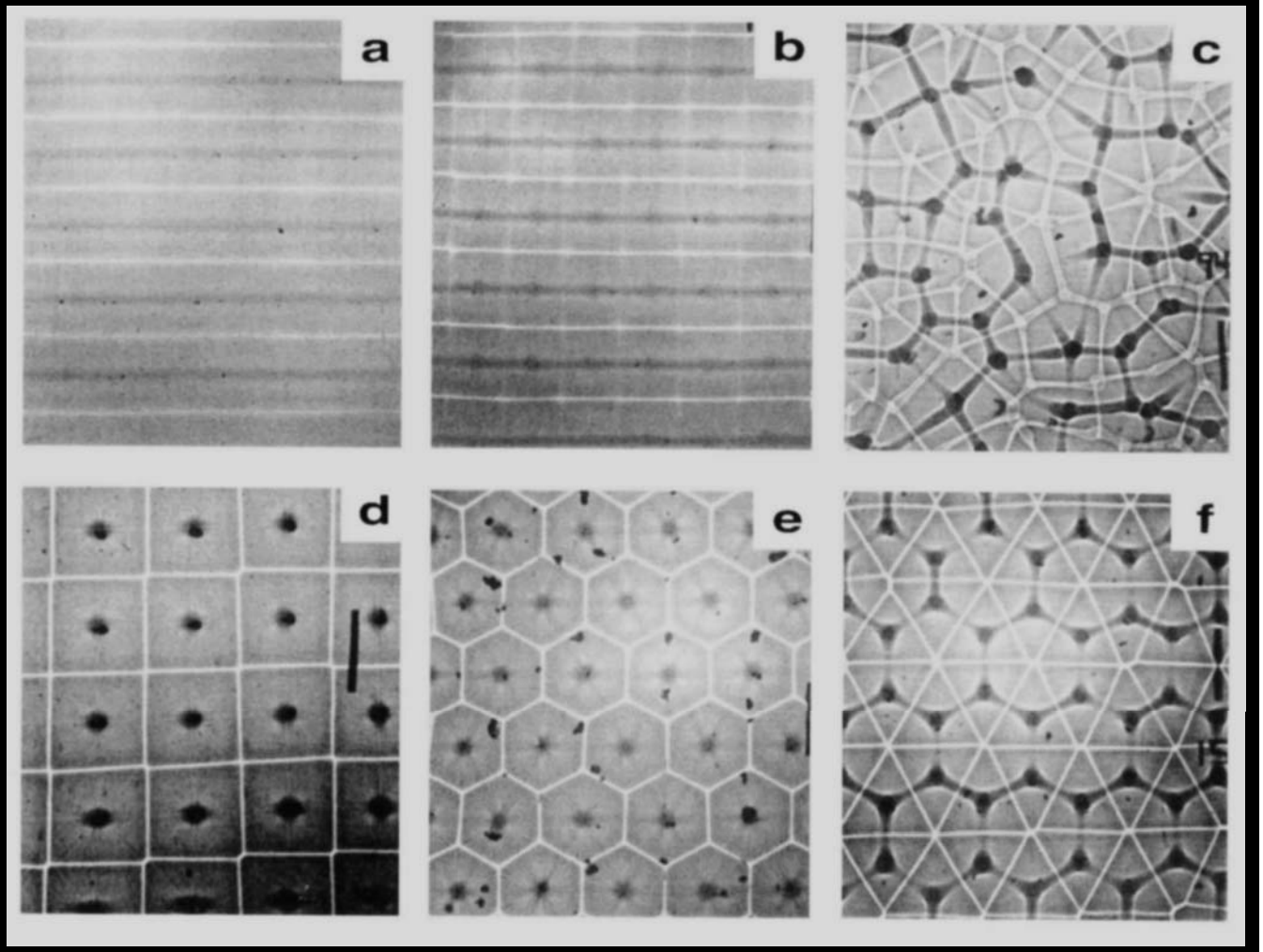
The simplest form of thermal convection is Rayleigh-Bénard convection (flat, plane layer, basally heated).



Symmetric upwellings and downwellings are not Earth-like.

Rayleigh-Bénard convective planforms (top view).





Basic Equations of Thermal Convection
Boussinesq, Infinite Prandtl Number

$\nabla \cdot \vec{u} = 0$, conservation of mass

$0 = -\nabla p' - \bar{\rho}\vec{g}\bar{\alpha}T' + \bar{\mu}\nabla^2\vec{u}$, conservation of momentum

$\bar{\rho}\bar{c}_p \frac{DT'}{Dt} = \bar{k}\nabla^2 T' + \bar{\rho}H$, conservation of energy

$Pr = \nu/\kappa$

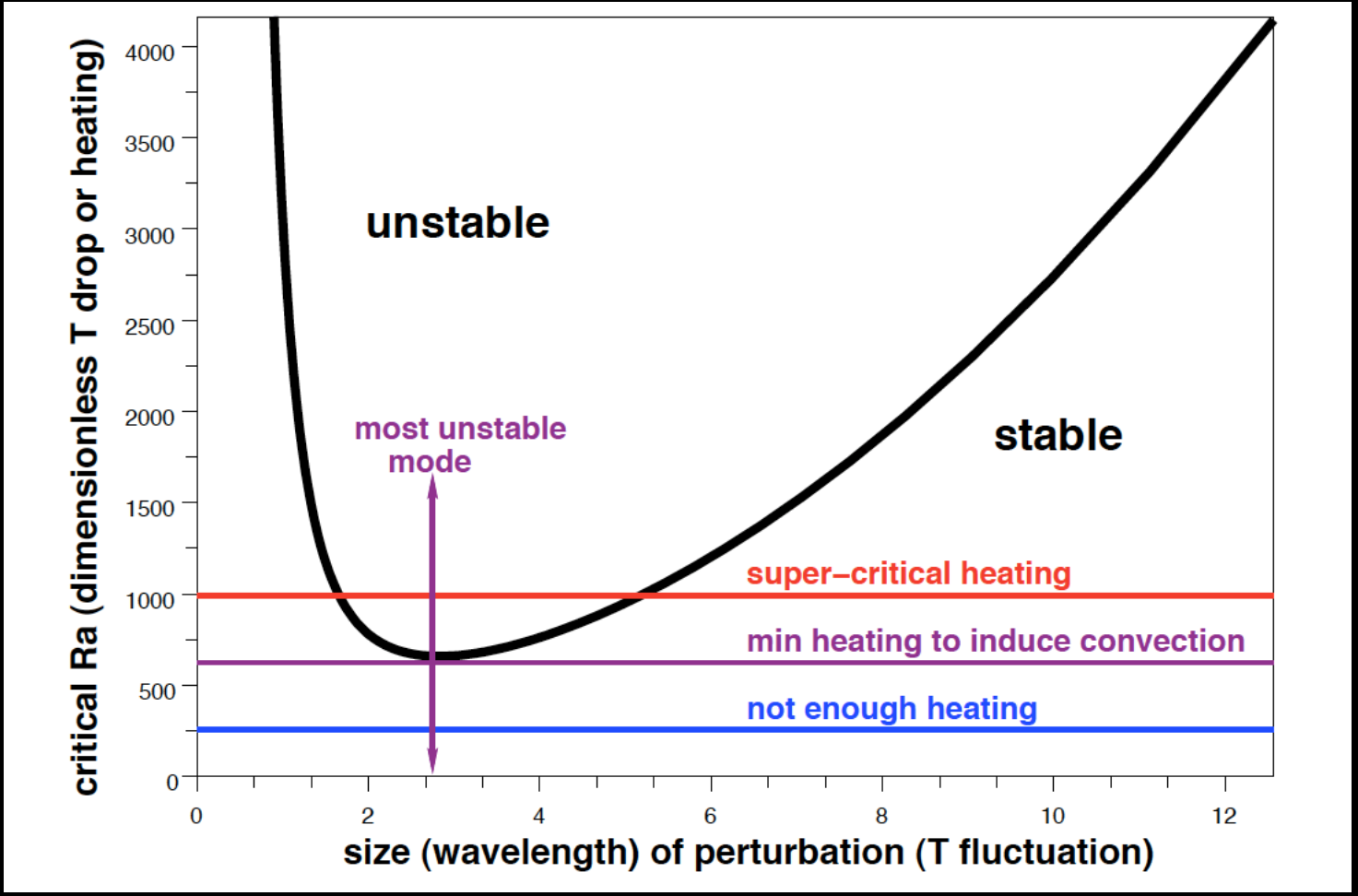
$\boldsymbol{Ra} = \bar{\alpha}\bar{\boldsymbol{g}}\Delta \boldsymbol{T}\boldsymbol{d}^3/\nu\kappa$

The Rayleigh number characterizes the competition between forcing by thermal buoyancy, and damping by viscosity and thermal diffusion.

Ra must exceed a certain value, called the critical Rayleigh number Ra_c for convection to occur.

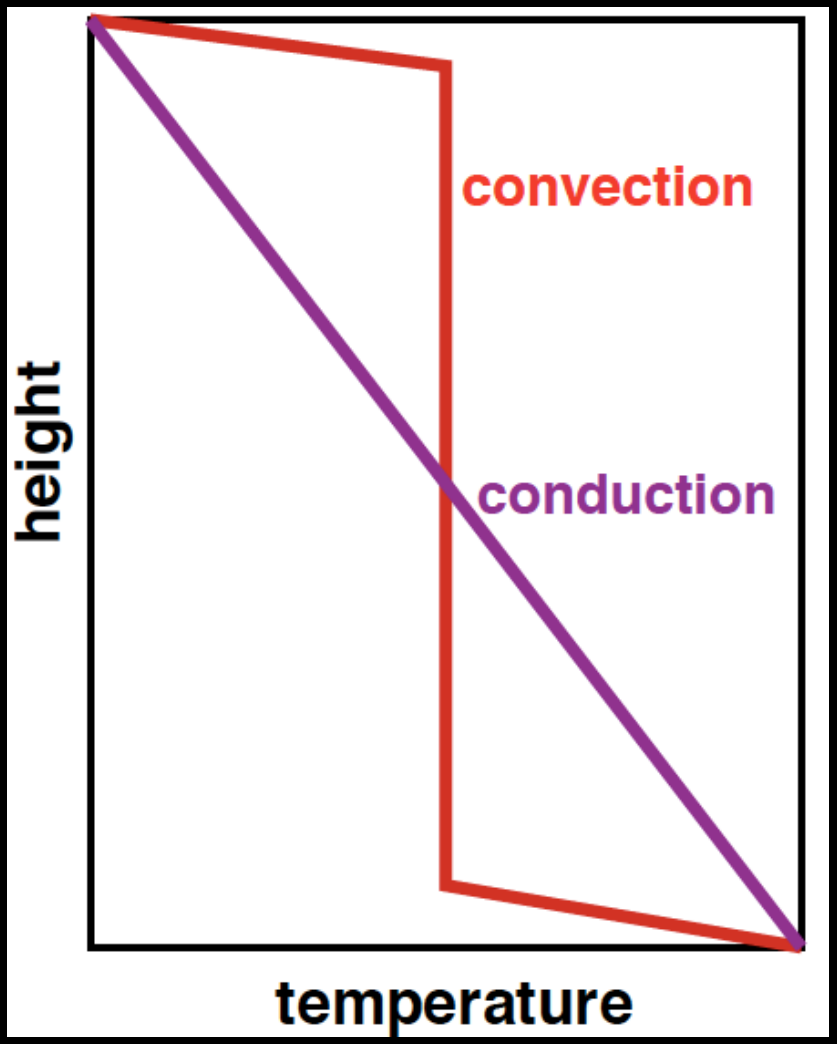
For $Ra < Ra_c$ the layer is stable and transports heat by conduction.

For $Ra > Ra_c$ the layer will be convectively unstable and transport heat more rapidly via convection.



Thermal boundary layers and the Nusselt number

For a Rayleigh number Ra above the critical value Ra_c, convective circulation will mix the fluid layer, and the mixing of the fluid will become more effective the more vigorous the convection, i.e., as Ra is further increased. With very large Ra and vigorous mixing most of the layer is largely uniform and isothermal. Most of the fluid is at the mean temperature between the two boundary temperatures. However the temperature still must drop from the well-mixed warm interior to the cold temperature at the top, and to the hotter temperature at the bottom. The narrow regions accommodating these jumps in temperature are called thermal boundary layers.



Thermal boundary layers and the Nusselt number

Nu = Nusselt number= Heat transfer across layer in convective regime/
Heat transfer across layer by conduction

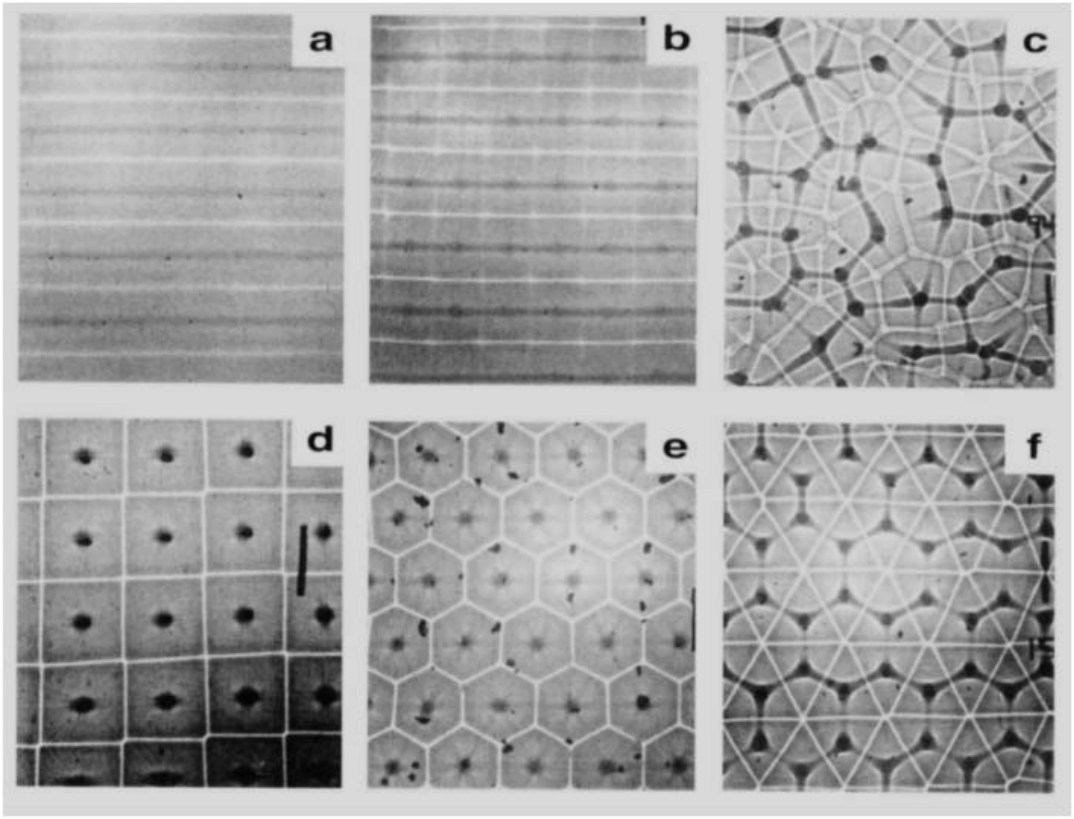
$Nu = q_{convection}/k\Delta T/d$

Howard [1966] argued that vigorous convective heat transport across the bulk of the well-mixed fluid layer is so fast it is not the rate limiting factor in releasing heat (only conduction across the thermal boundary layer is), and thus heat flow should be independent of fluid depth d; this implies since $Ra \sim d^3$ then $Nu \sim Ra^{1/3}$, which yields a convective heat flow $Nu(k\Delta T/d)$ that is independent of d. In general, since the fluid is conductive for $Ra < Ra_c$, one often writes that $Nu = (Ra/Ra_c)^{1/3}$. This relationship also implies that the ratio of thermal boundary width to fluid layer depth is $\delta/d = Ra^{-1/3}$, which shows that the boundary layers become increasingly thin as convective mixing of the layer becomes more vigorous.

Boundary Layer Thickness and Identification of the Oceanic Lithosphere as a Thermal Boundary Layer

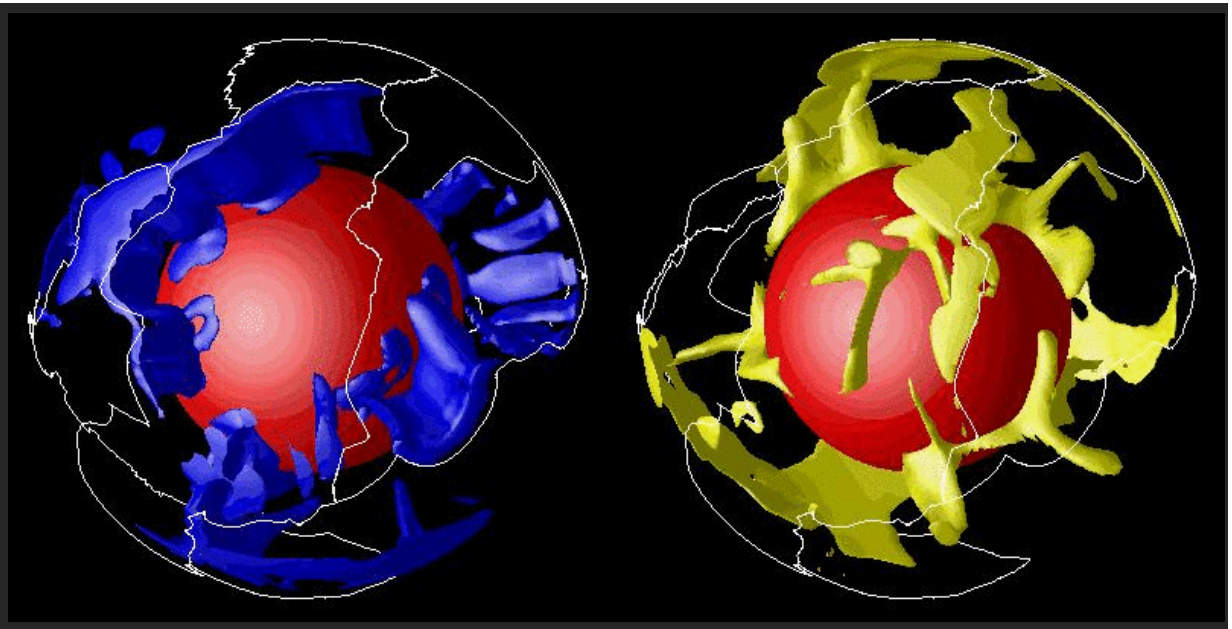
The relation $\delta \sim Ra^{-1/3}$ applies to the horizontally averaged boundary layer thickness. However, boundary layers change with time or distance from their first formation, e.g., where an upwelling impinges on the top boundary. As the fluid in the boundary layer moves from an upwelling to a downwelling it cools and the boundary layer thickens as more material cools next to the cold surface. The thickening depends on the thermal diffusivity (with units of m^2/s) and the residence time or age t near the cold boundary (i.e., time since leaving the upwelling). Simple dimensional considerations show that the boundary layer thickness goes as $(\kappa t)^{1/2}$; this corresponds to the well known $(age)^{1/2}$ law for subsidence of ocean sea floor with age since formation at mid-ocean ridges, implying that sea-floor gets deeper because of the cooling and thickening boundary layer (lithosphere).

Patterns of Convection



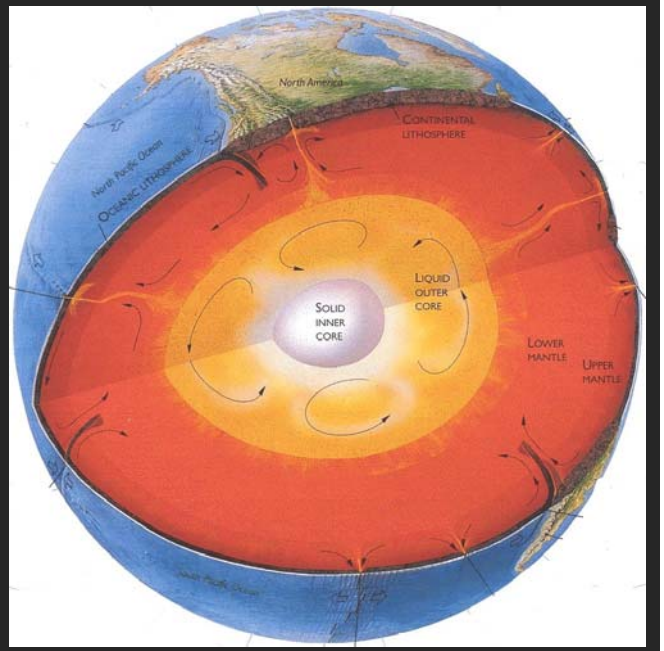
Patterns of convection from laboratory experiments in rectangular tank by White [1988] (left), and numerical simulations in a spherical shell by Zhong et al. [2000].

Mantle convection is the thermal convection that occurs in Earth's mantle as it cools to space.

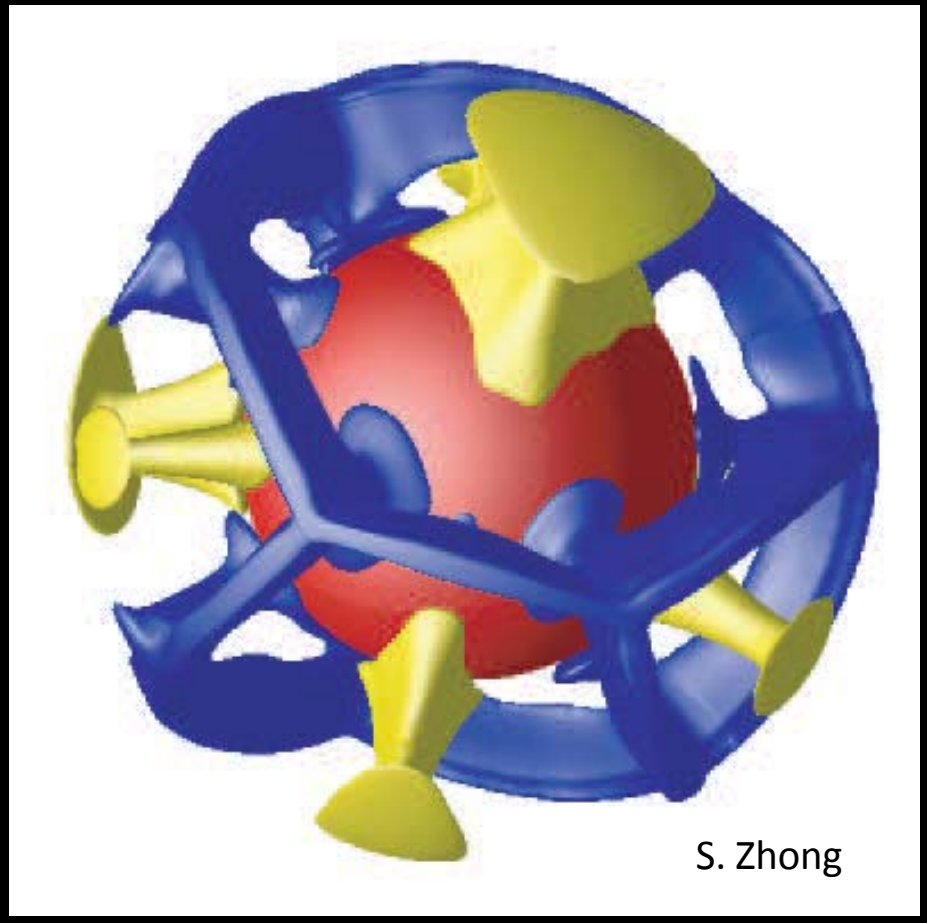


S. Zhong, Univ. Colorado

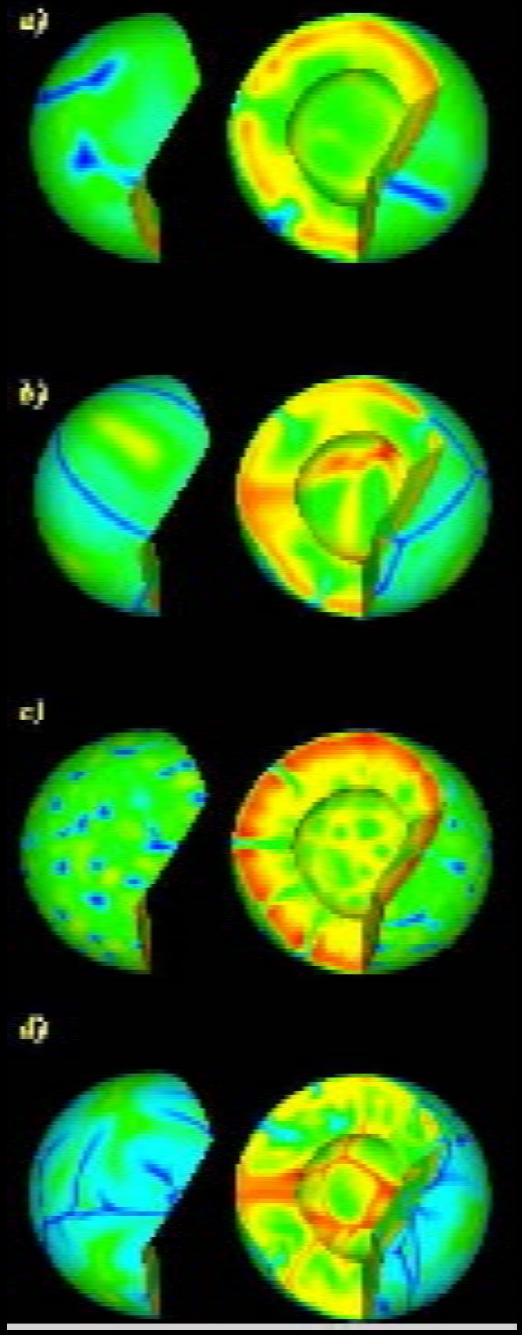
- **Earth's mantle**
- 2900 km of solid rock between crust and core
- Rock near surface cools and is heavy
- Rock near molten iron core heats and is light
- **Mantle convects slowly (1-10cm/yr)**
- **Governs how fast the entire planet cools to space**



Simple mantle convection models do a reasonable job predicting slab-like downwellings and Hawaiian plume-like upwellings but not mid-ocean ridges.

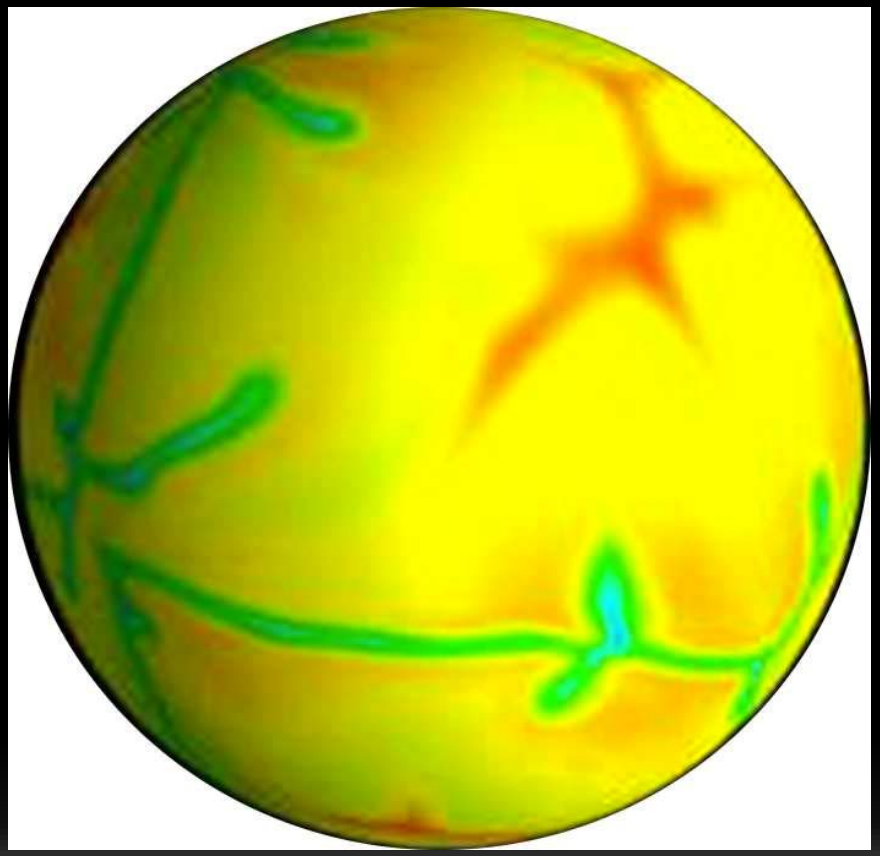


S. Zhong

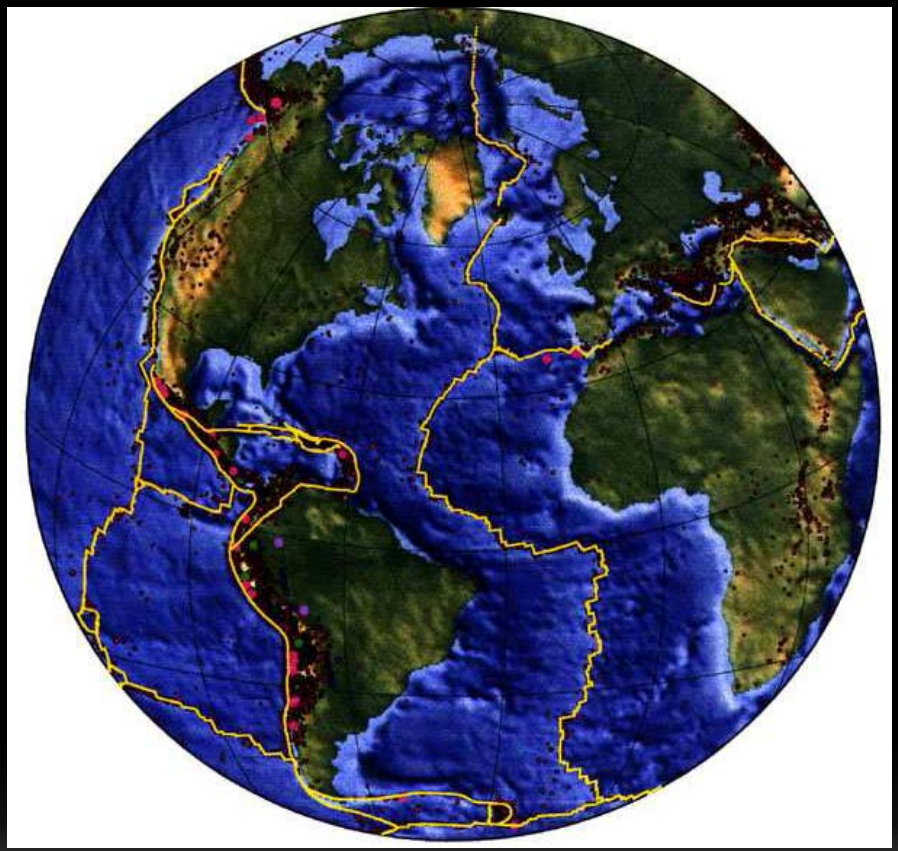


However….

While these models look like this at the surface….



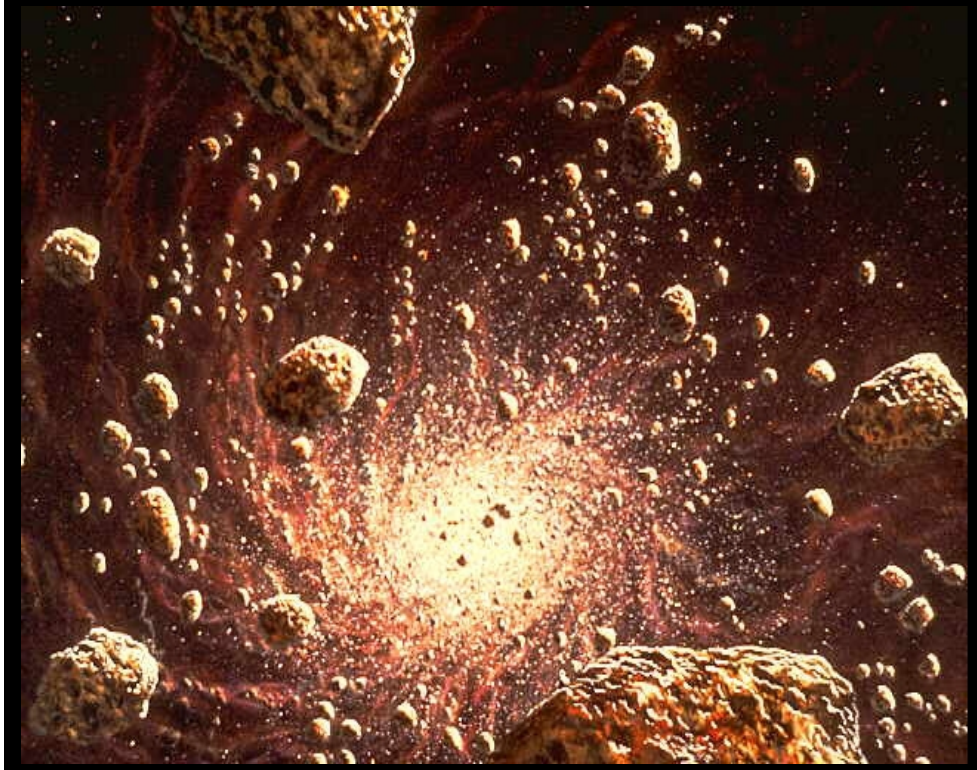
…actual mantle convection at the Earth's surface looks like this



That is……PLATE TECTONICS

Mantle convection is enormously more complicated than thermal convection

- One of the main complications is plate tectonics, but there are many others.
- Complex rheology related to plate tectonics. Viscosity depends on temperature, pressure, stress, water content, grain size.
- Solid-solid phase changes.
- Temperature- and pressure-dependent thermal conductivity and thermal expansivity.
- Heating is from within and below.
- Melting and compositional heterogeneity.
- Continents.



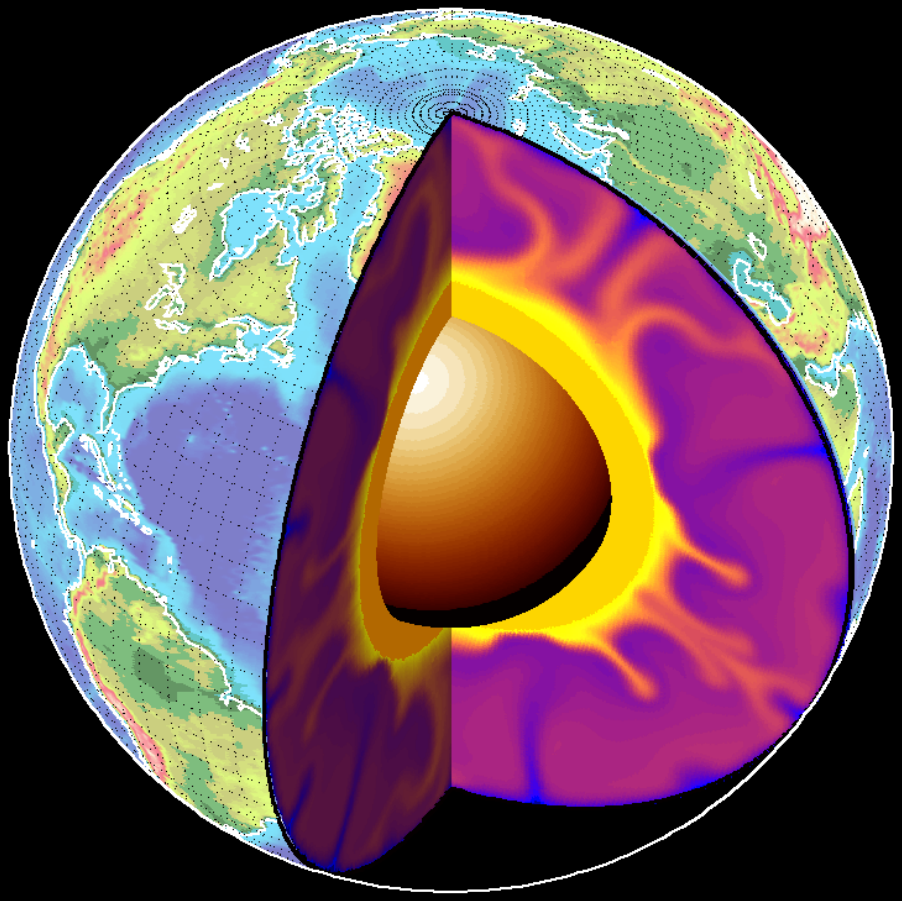
- In the beginning….
- Earth “accretes” about 4.6 billion yrs ago
  - Energy of colliding/sticking bodies stored as heat

Subsequent impacts continue to store heat.
Leaves present-day energy source which is...

Primordial Heat

(heat left over from planet formation).

Mantle Convection Basics

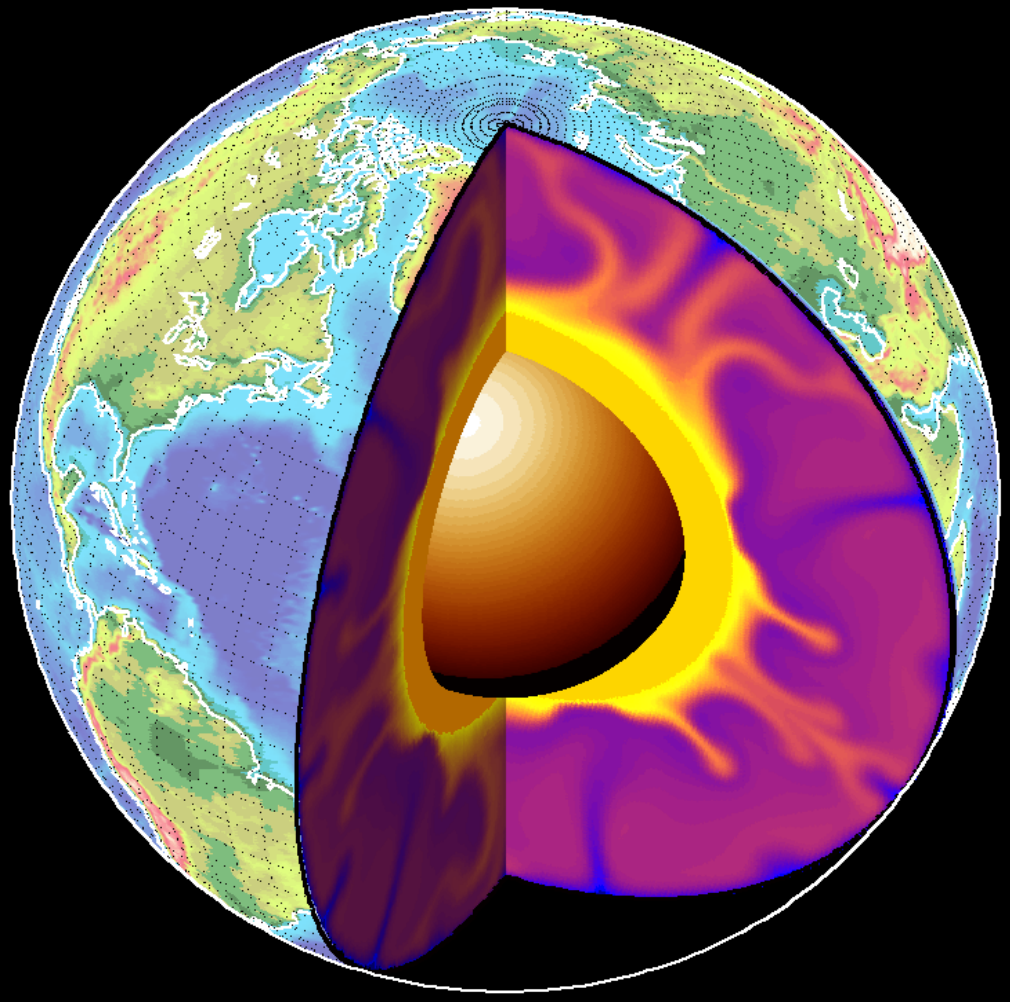


- Mantle is heated by radioactive decay of U, Th, K; also loses primordial heat,
  - heated probably to a lesser extent by the molten iron outer core
- Mantle is viscous
  - 10^{21}–10^{22} Pa s (vs 1Pa s for syrup)
- Rayleigh number = convective vigor

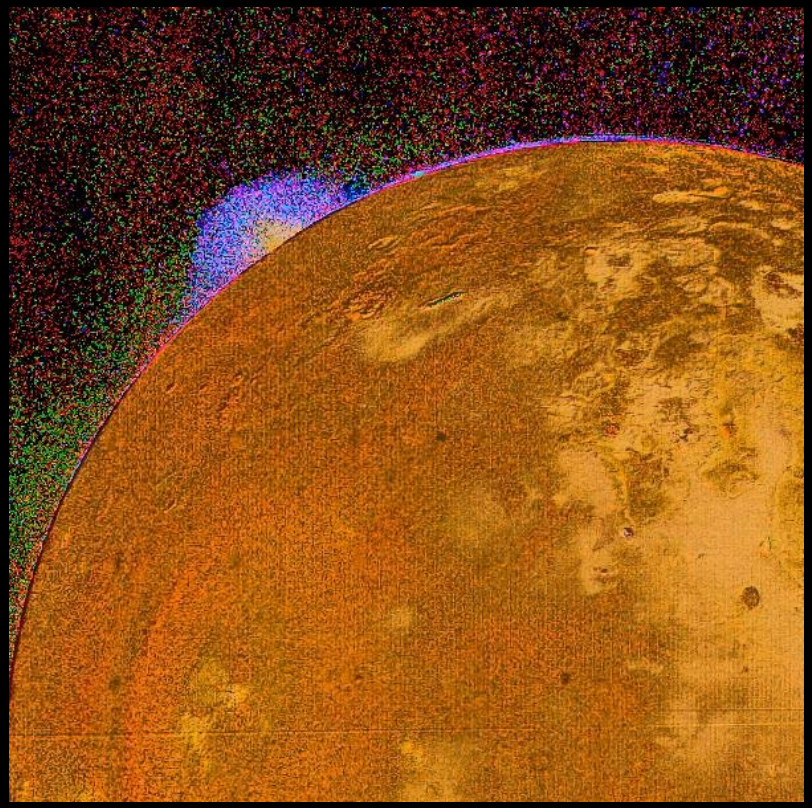
$$Ra = \frac{g\alpha\Delta T d^3}{\nu\kappa}$$

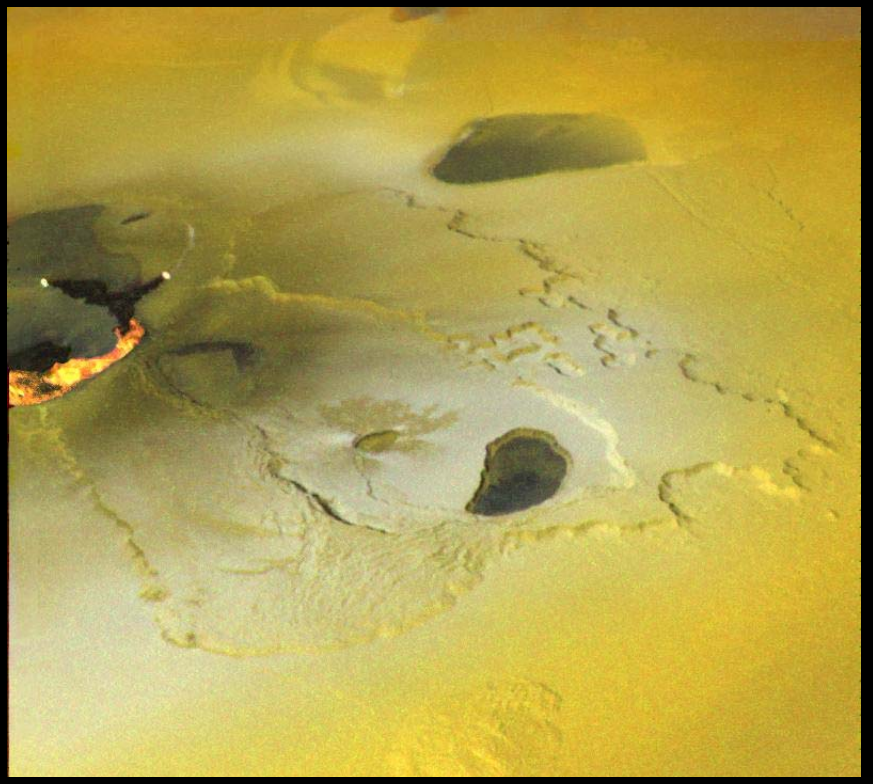
- Ra = 1000 for onset of convection
- $Ra_{mantle} = 10^9$

Earth cools to space



- **Total heat output from Earth about 44 TW**
  - **About 20-50 % from primordial heat**
  - **About 50-80 % from radioactive decay of U, Th, K**
- **Fuel for geological activity**
- **Compare: solar heating is about 170,000 TW**

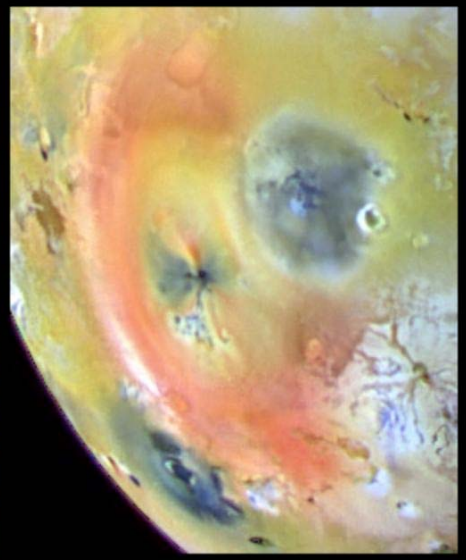


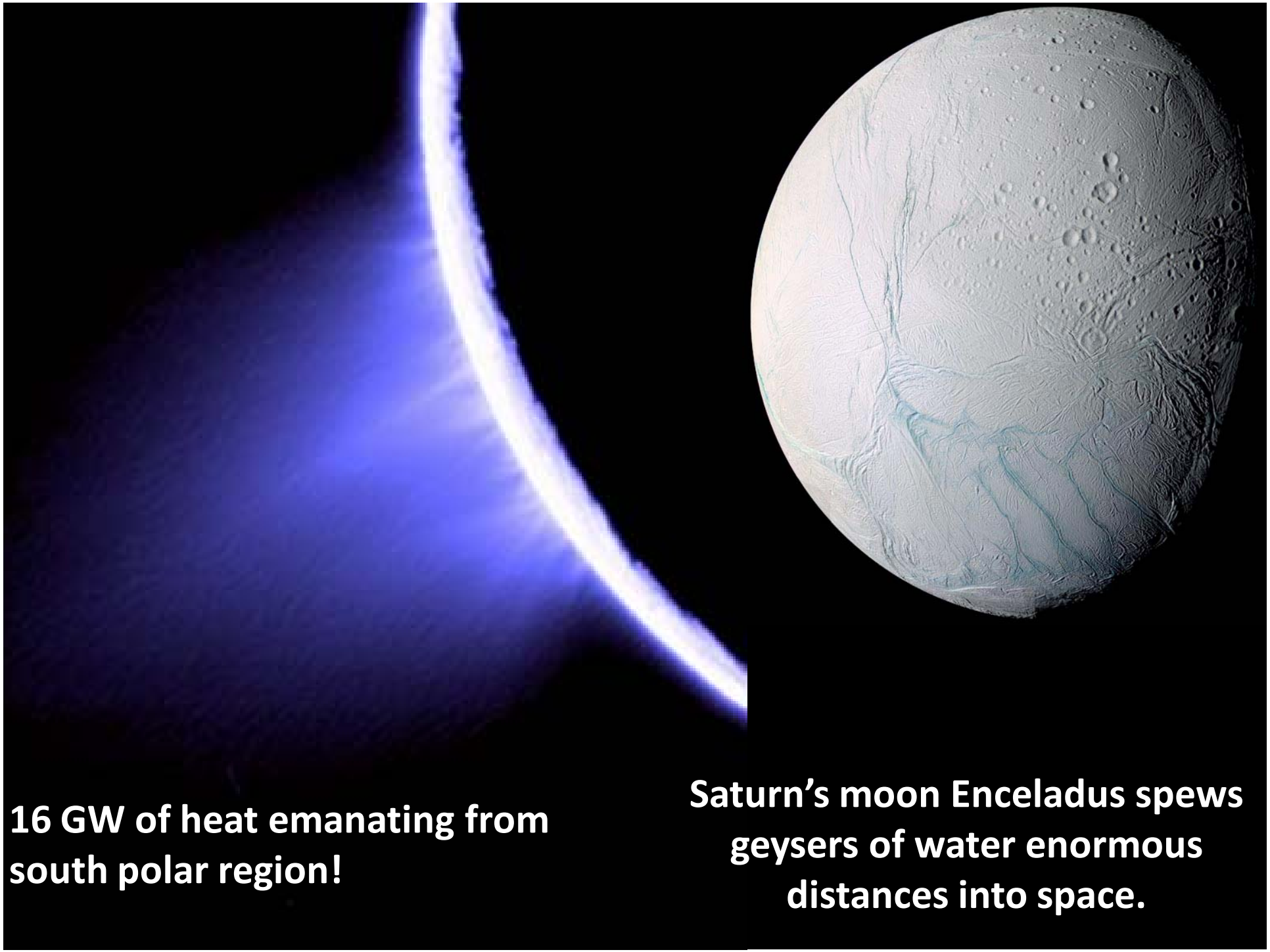


Io

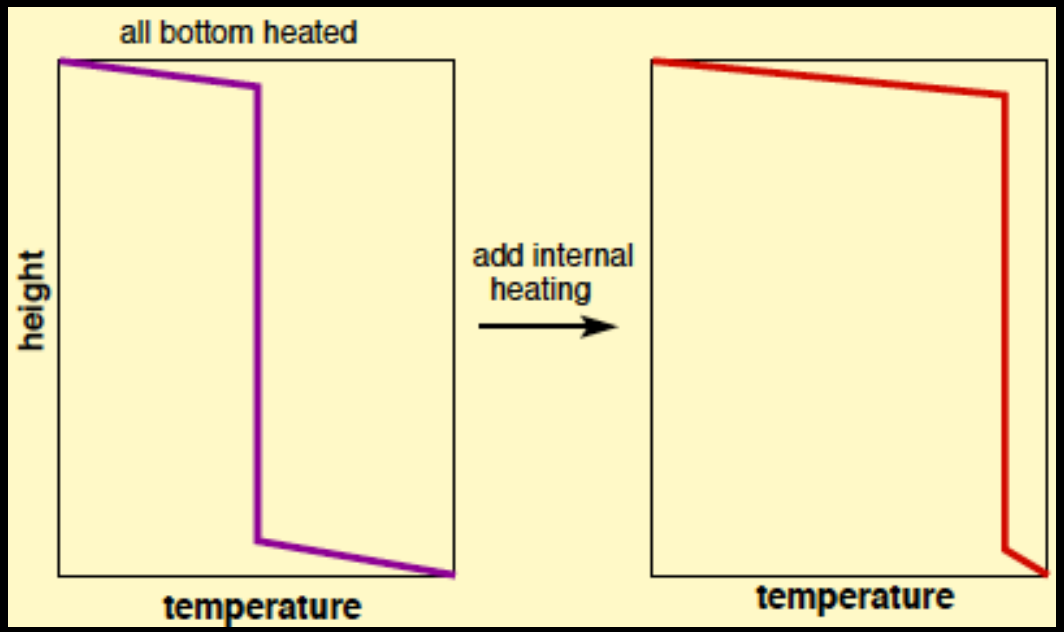
Heat flow: 100-200 TW

Heating by tidal dissipation.

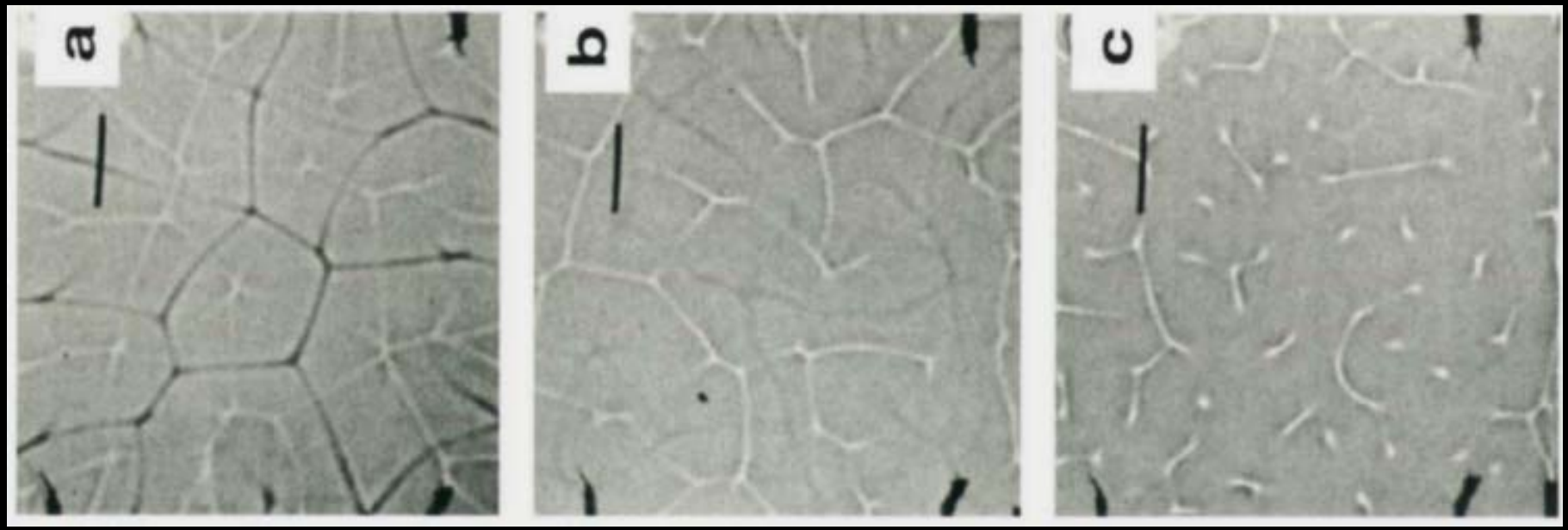



16 GW of heat emanating from south polar region!
Saturn's moon Enceladus spews geysers of water enormous distances into space.

Internal Heating



- 70-90% of heat output from mantle is thought to come from radiogenic sources and loss of primordial heat
- less from heating at base by core
- flow dominated by down-wellings



Weinstein and Olson (1990)

Plate Tectonics

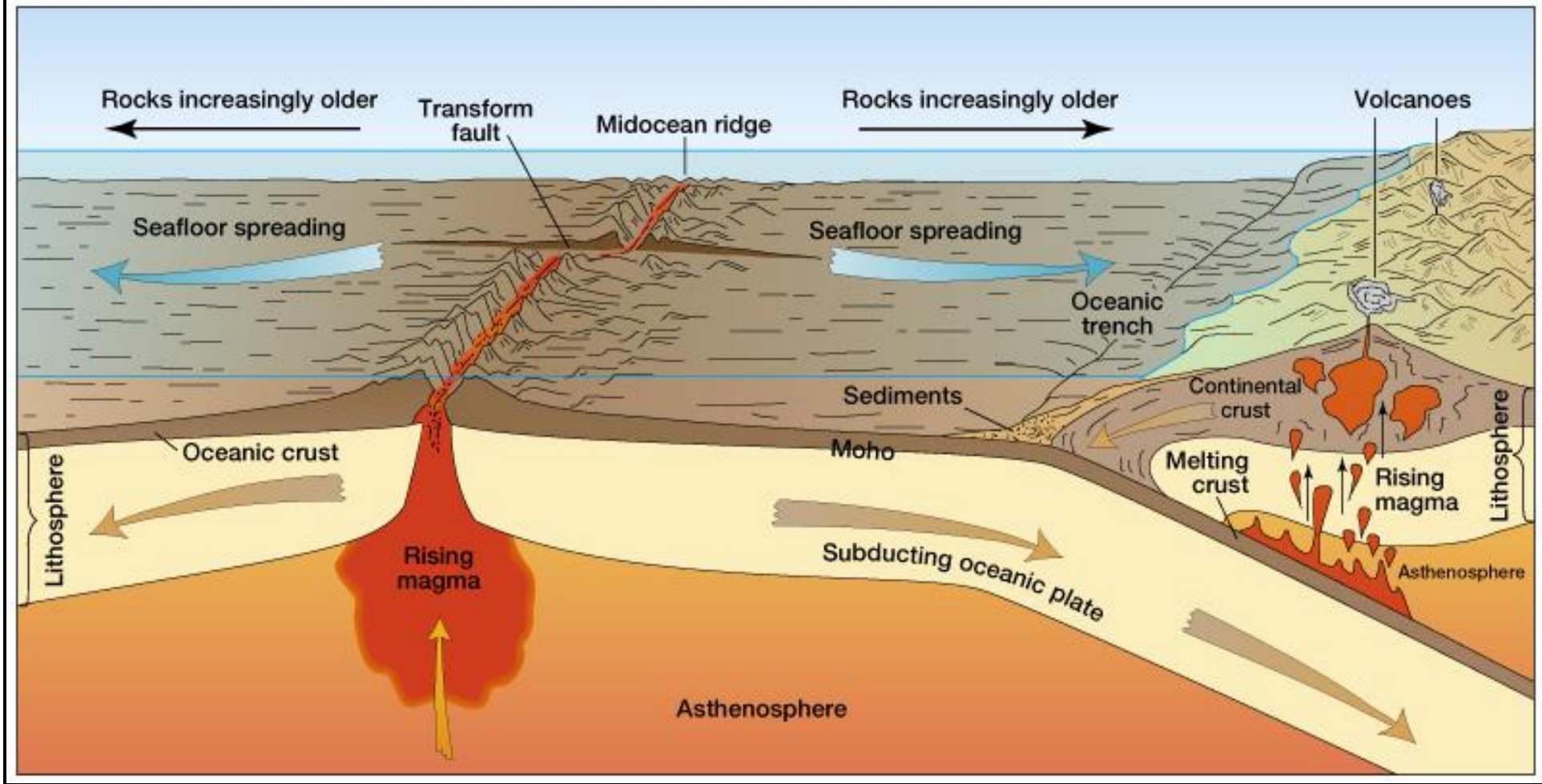
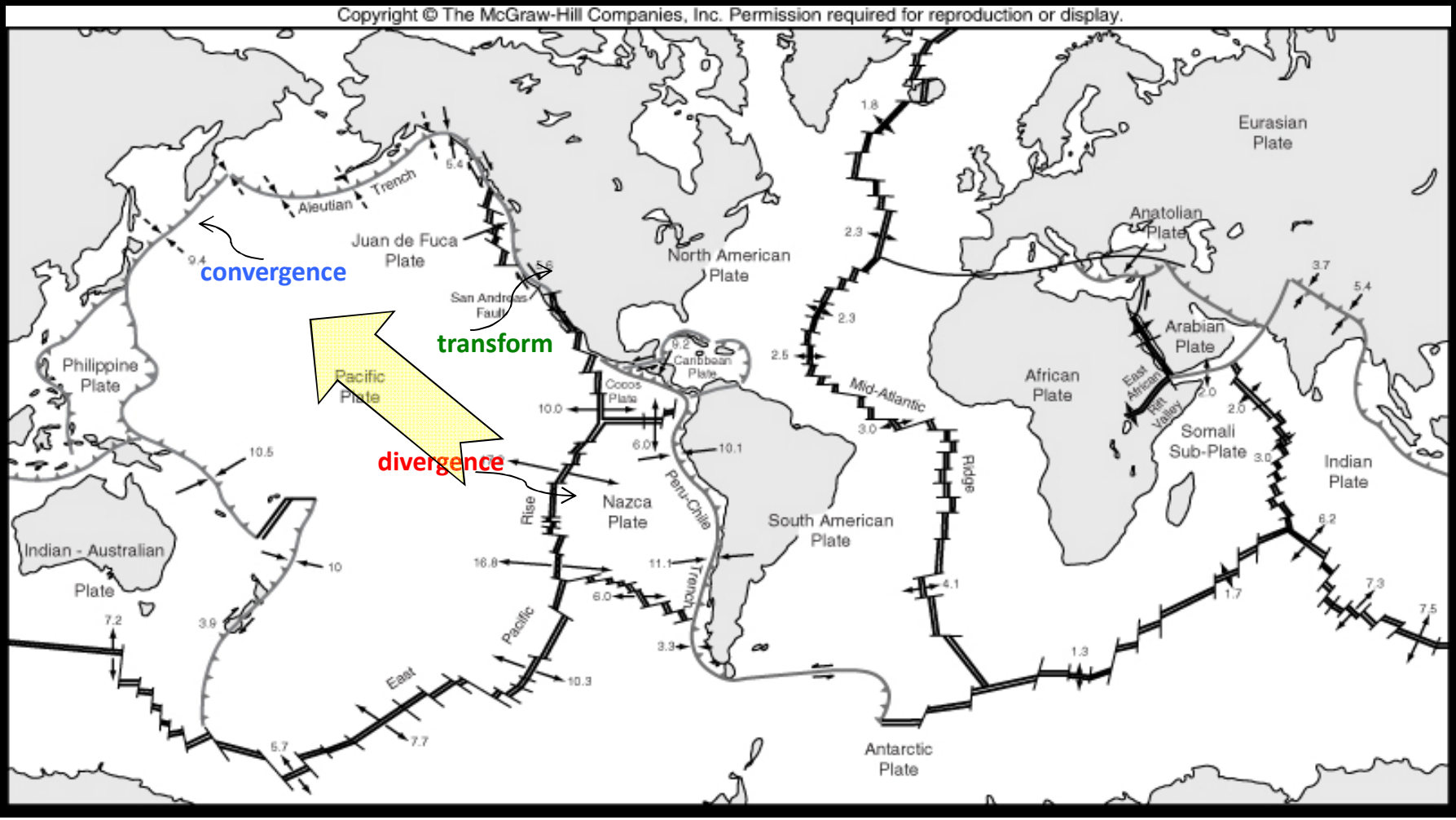


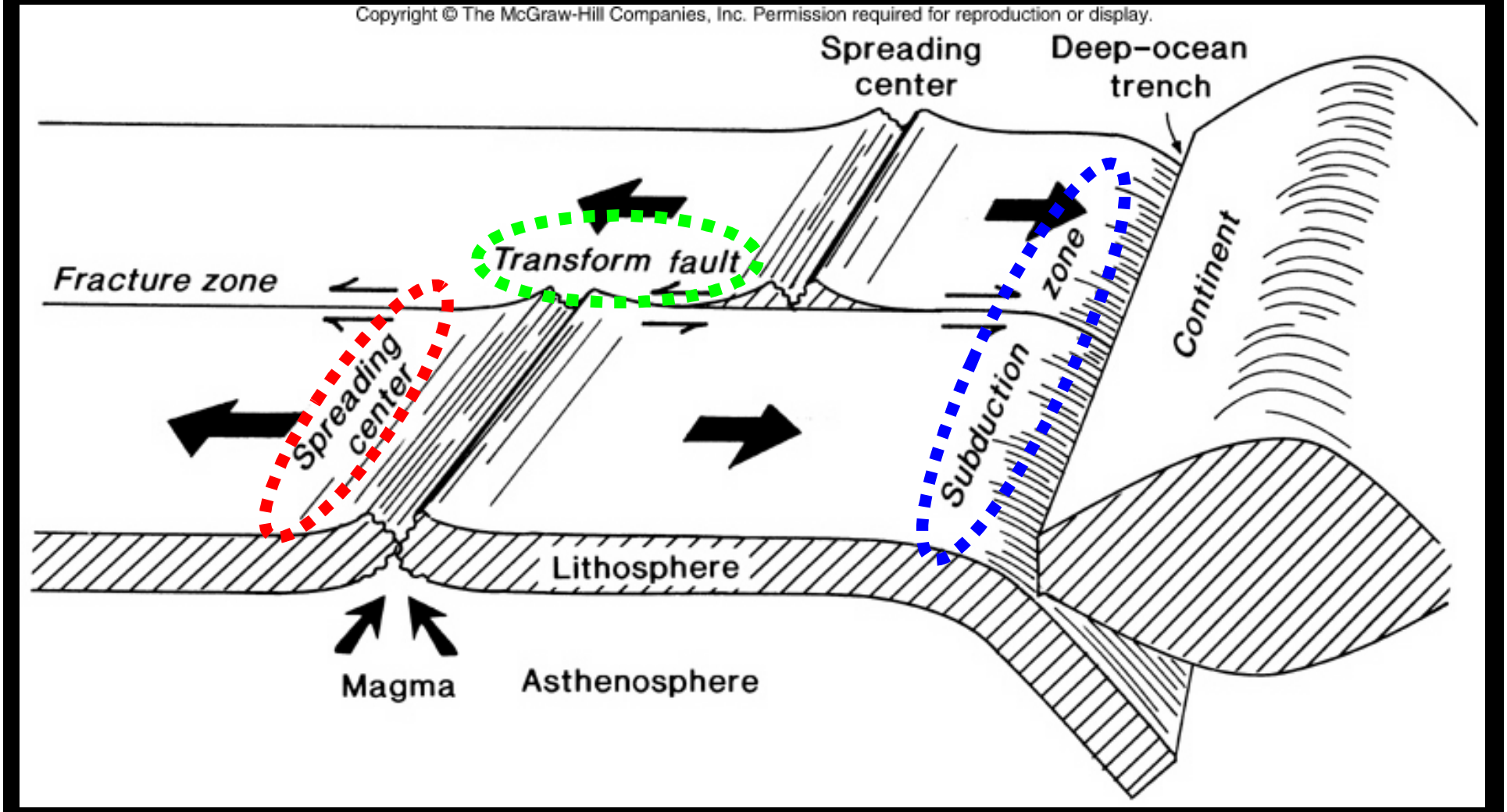
Plate tectonics is the top of the convecting mantle where the near surface layer of rock (plates) is pulled along by the cold, heavy slab sinking into the mantle along subduction zones, which are marked by deep ocean trenches.

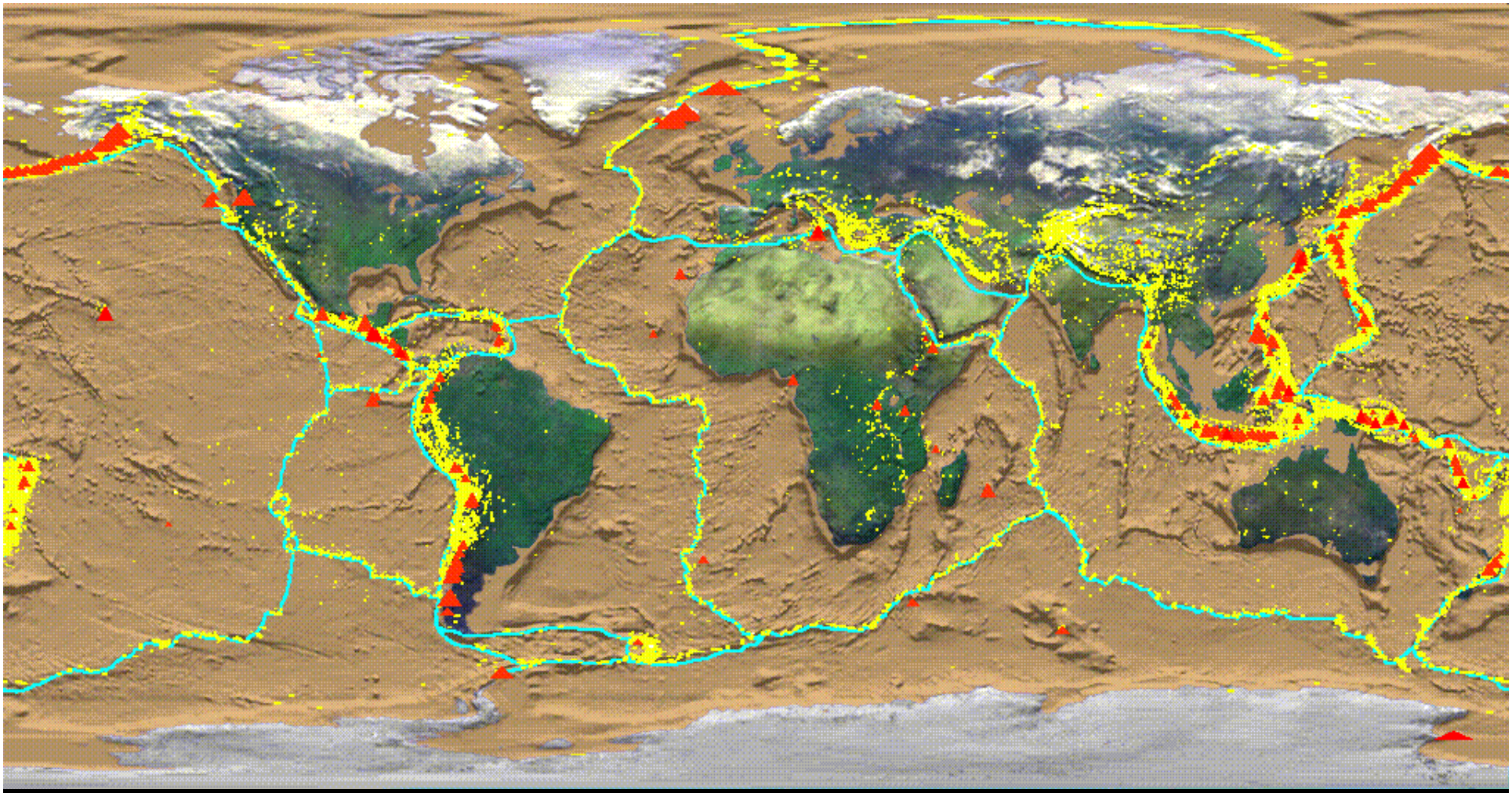
Plate Tectonics

- Crust of Earth is broken into plates separated by:
  - spreading centers = mid-ocean ridges = diverging zones
  - strike-slip faults = transform faults
  - subduction zones = collision zones = converging zones



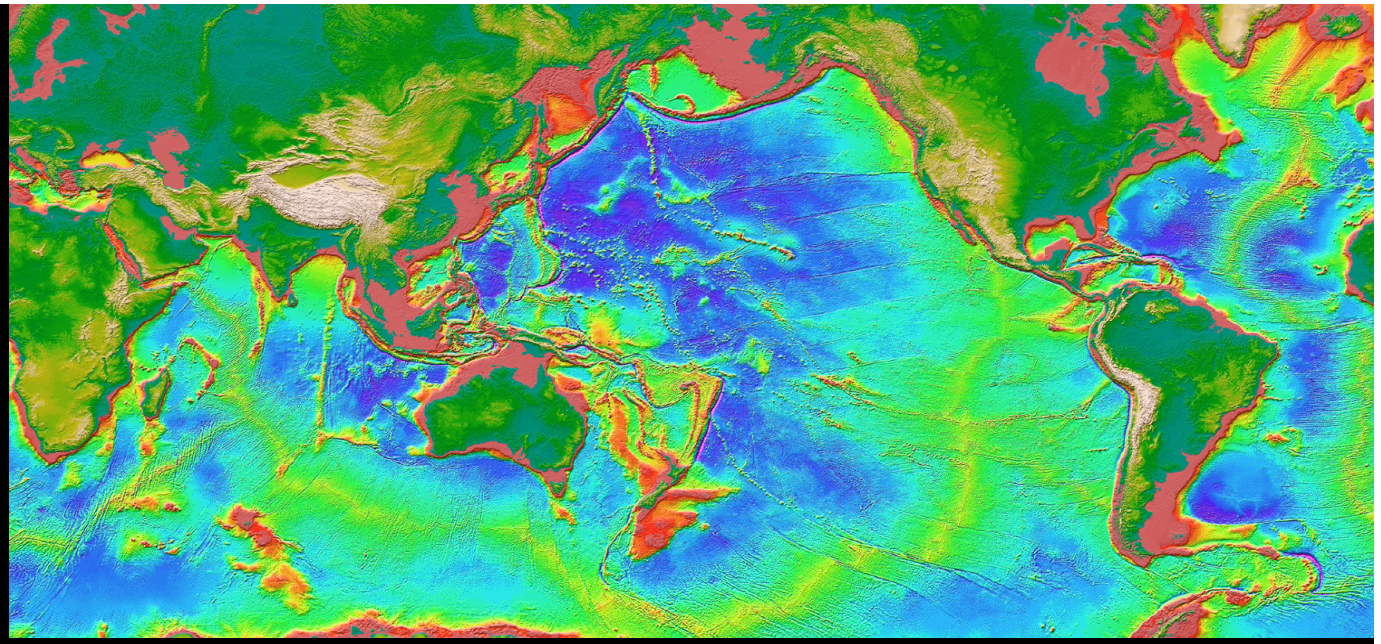
Types of plate boundaries

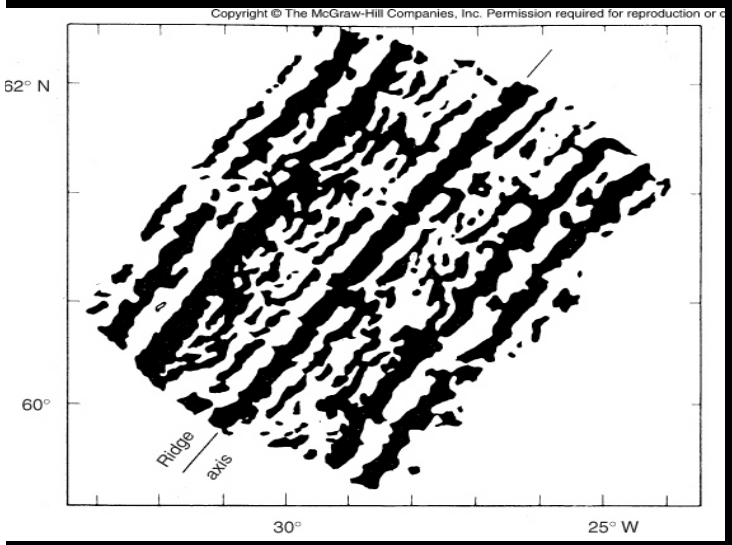




- Earthquakes, volcanoes occur mostly on plate boundaries.
- Why plate tectonics is important: tells us where events are likely to occur and what sort of events they're likely to be.

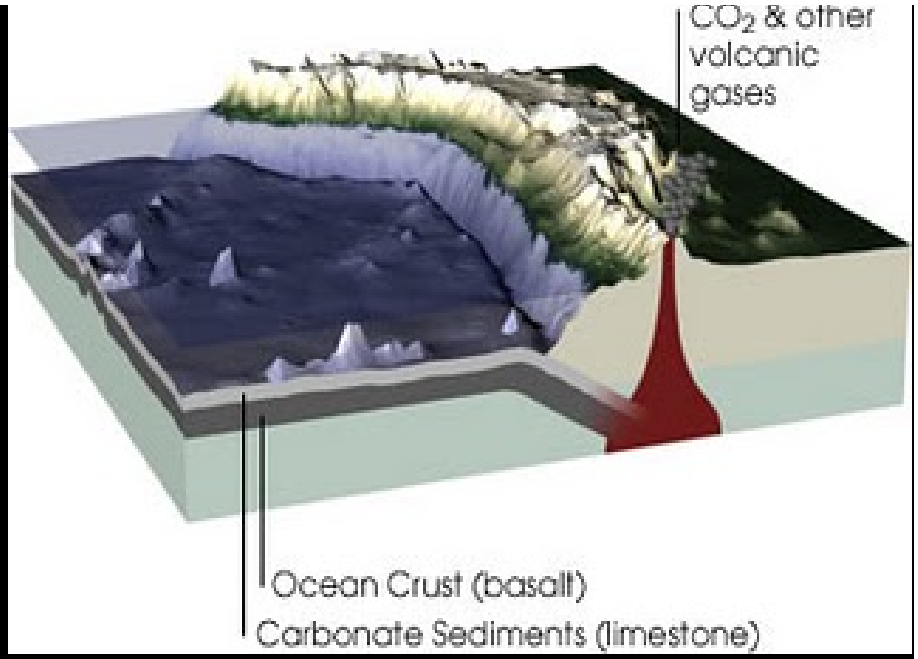
Plate Tectonics





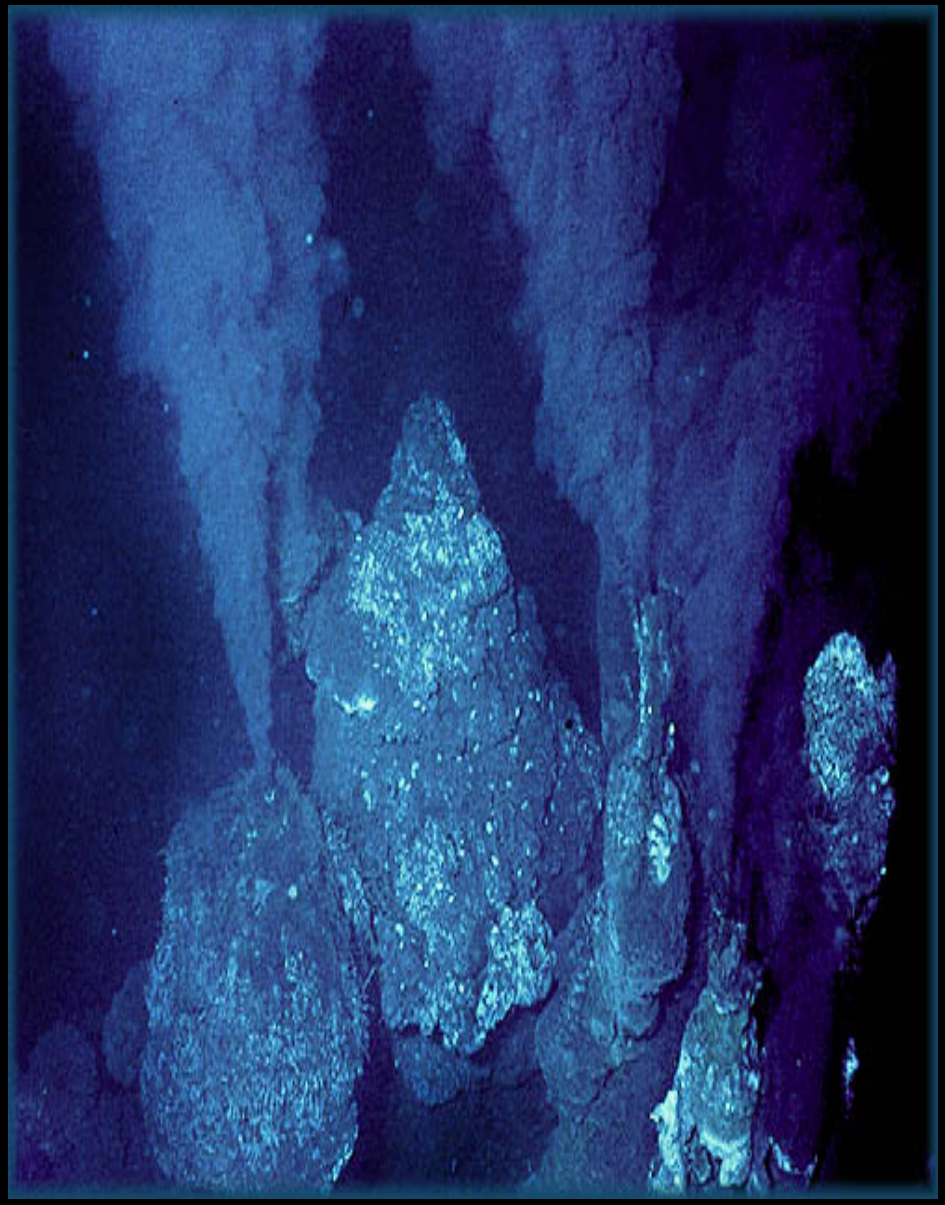
- Study of sea floor and paleo-magnetism following WWII provided evidence of sea-floor spreading and continental motions.
  - Continents are set within and ride along with tectonic plates.
- Theory of plate tectonics developed 1960s-1970s and widely accepted.
- Mantle convection still assumed to be the driving mechanism, but many loose ends.

Plate tectonics and climate



- Mountain building promotes erosion, weathering, formation of carbonate minerals on the sea floor
  - sink of atmospheric CO_2
- Arc volcanism returns CO_2 locked up on sea-floor:
  - source of atmospheric CO_2
- Seafloor carbonates (limestone) are major reservoir of CO_2
  - Mountain building keeps it from draining
  - Arc volcanism keeps it from over-filling
- **Negative, stabilizing feedback gives Earth's temperate climate**
  - Cooling reduces precipitation and weathering, weakens CO_2 sink; volcanic source replenishes CO_2 and drives GH warming
  - Warming increases precipitation and weathering eventually draws down CO_2, forces cooling

Plate tectonics and life



- Provided the energy source (through volcanic submarine vents) for the earliest forms of life on our planet.

- Black smokers at mid-ocean ridges
  - Super heated, mineral rich water; precipitate builds chimneys
  - Supports diverse biological communities
    - Archaea, tubeworms

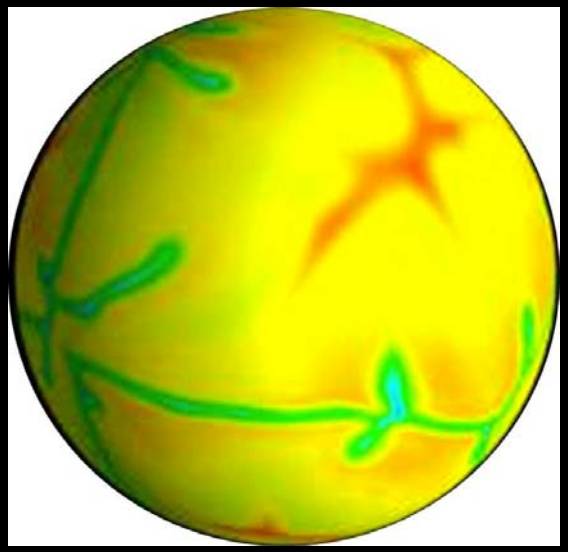
Unique Earth?

- **Why is Earth the only terrestrial planet in solar system with**
- Plate tectonics, liquid water and temperate climate, life
  - (Although Europa and Enceladus likely have liquid water also)
- Understanding why plate tectonics arises is key to under-standing how our planet works:
- ***One of the grand questions of Earth science***

Extrasolar planets

- Since the mid 1990s, thousands of planets in other stellar systems have been discovered (many of them by the Kepler mission).
- Many exoplanet searches focus on "habitability"
- Because plate tectonics stabilizes climate, and is possibly needed for early life, it is a likely ingredient for a habitable planet sustaining life and possibly even complex life.

The "Plate Generation" Problem



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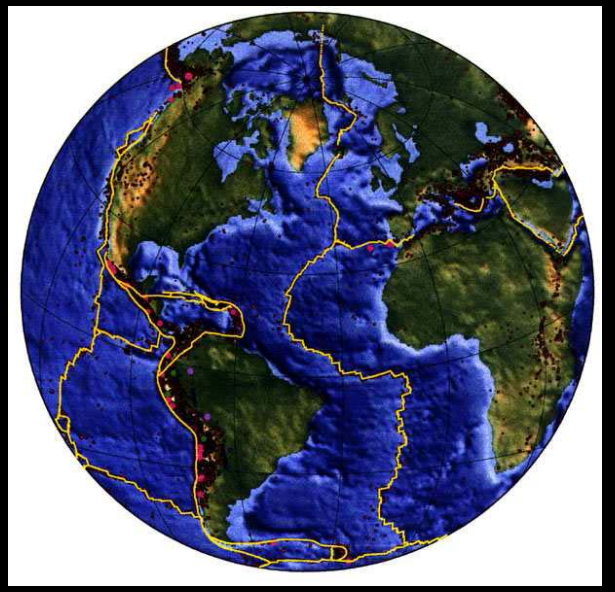
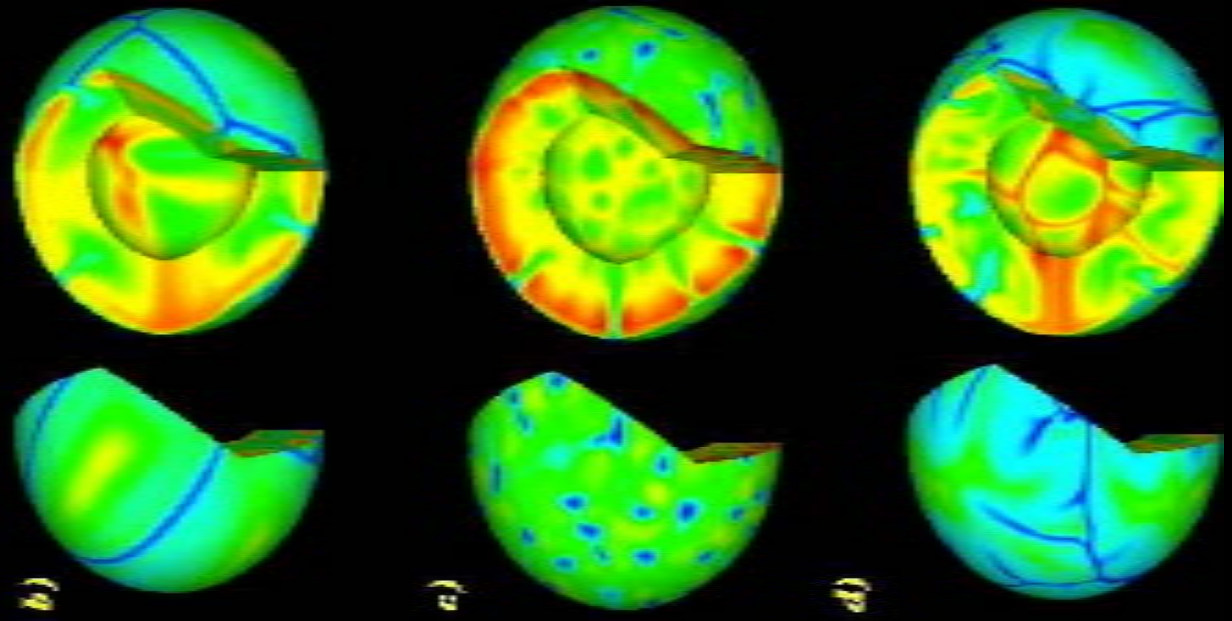
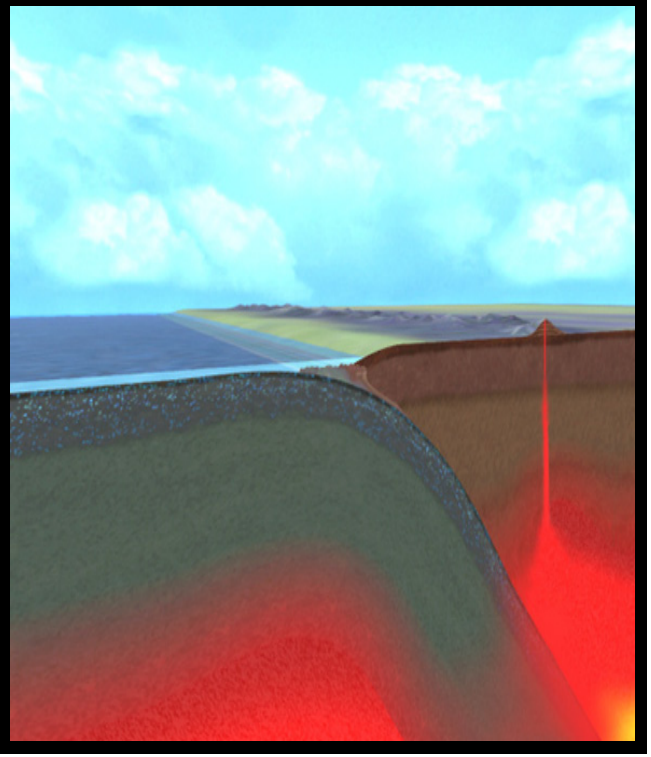


- How does plate tectonics arise from a convecting mantle?
- Why Earth, not Venus (or Mars)?
- What governs whether we expect to find plate tectonics in other stelllar systems?
- Mantle dynamicist's view: Plate tectonics is an integral part of the overall convecting system: *the plates are convection*.

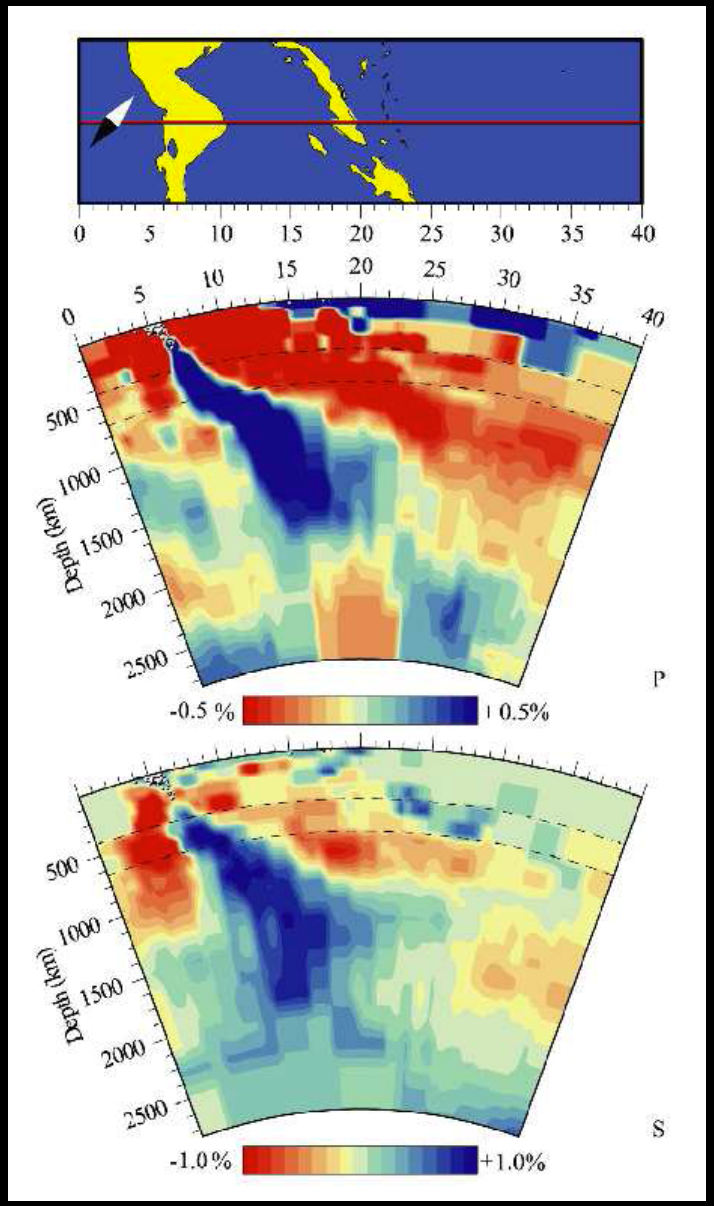
Major connection between convection and plates: *Slabs*





- **Earth-like internal heating leads to flow dominated by cold downwellings or slabs**

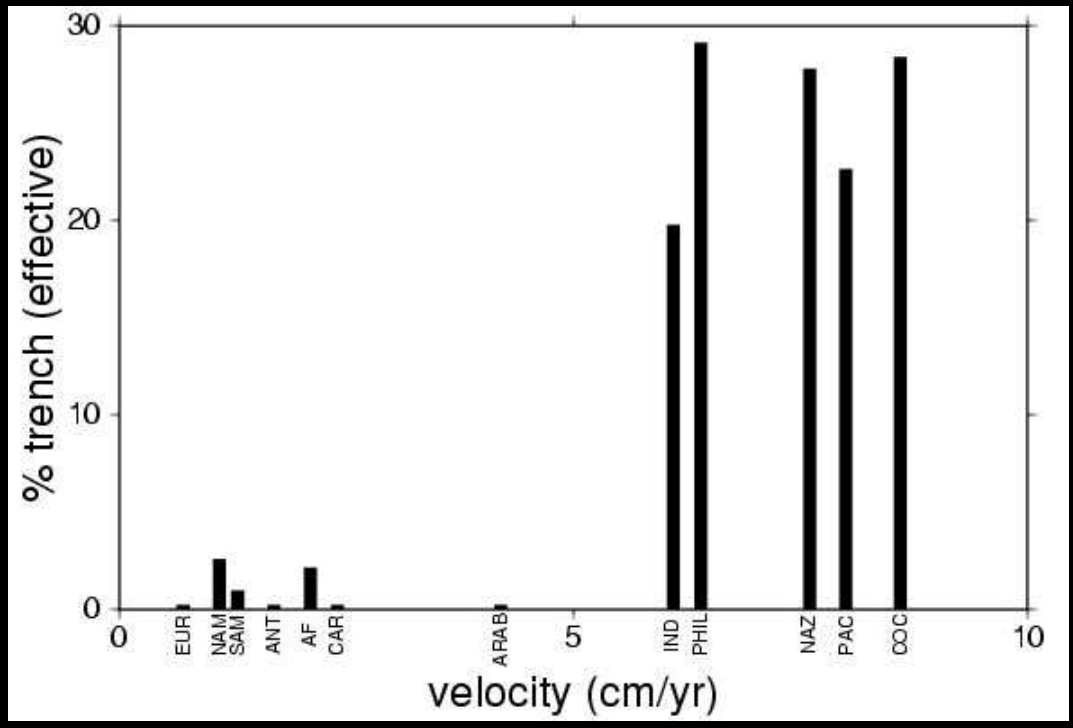
Slabs are convection, slabs drive plates



van Keken et al. (2002)

Corresponds to

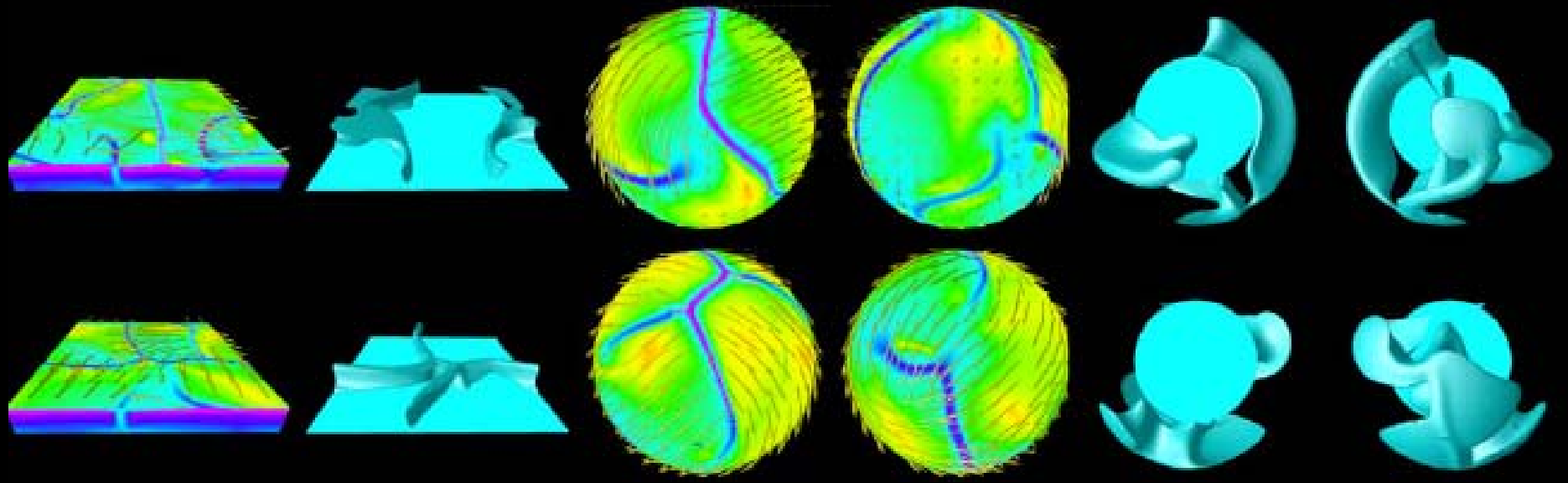
- seismic images,
- plate-force and plate velocity estimates
- mantle heat loss = cooling by slabs



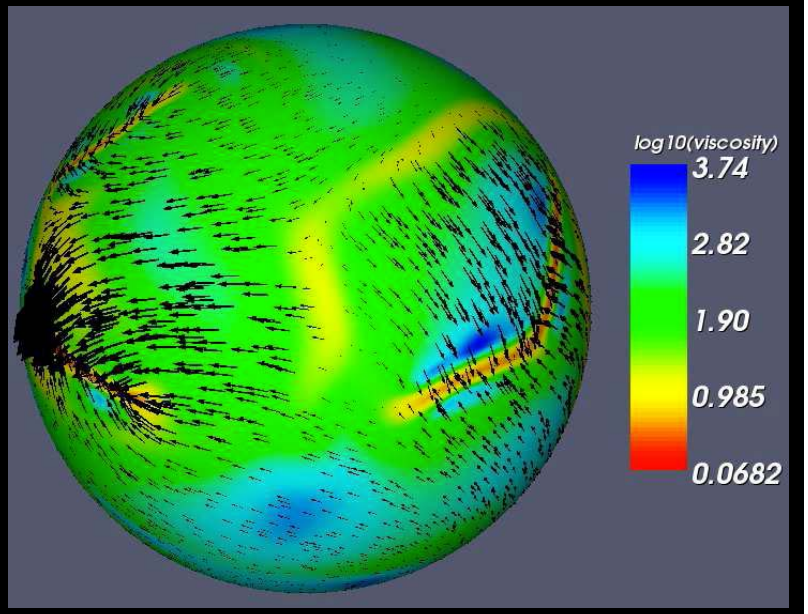
Forsyth & Uyeda (1975)

Plastic yielding models

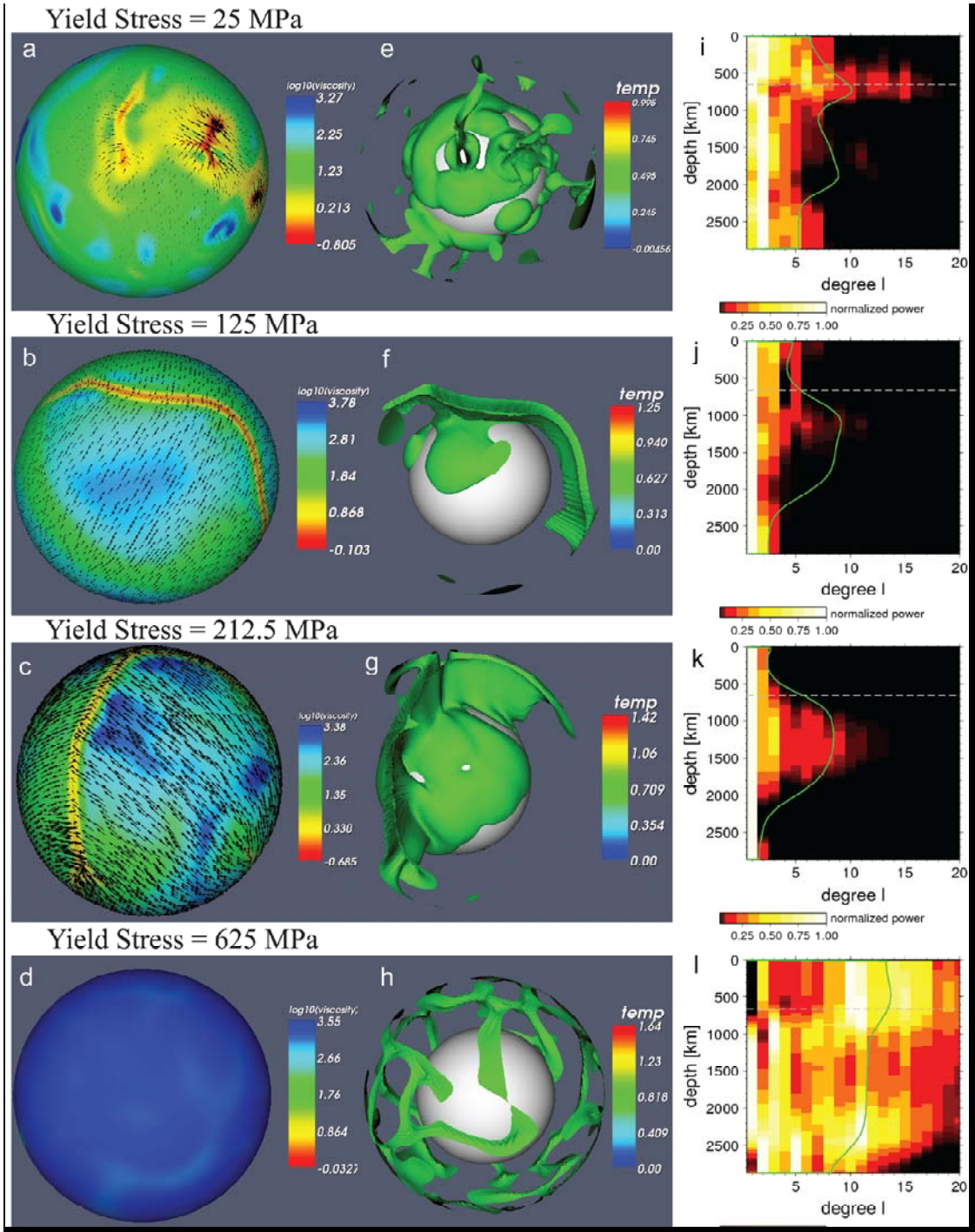
Van Heck & Tackley 2008



- Generates instantaneous nearly plate like flows
- But…plate boundaries only exist while deforming
- No dormant weak zones, sutures, to be reinherited
  - Doubtful can initiate subduction without these (Toth, Gurnis, 2000)



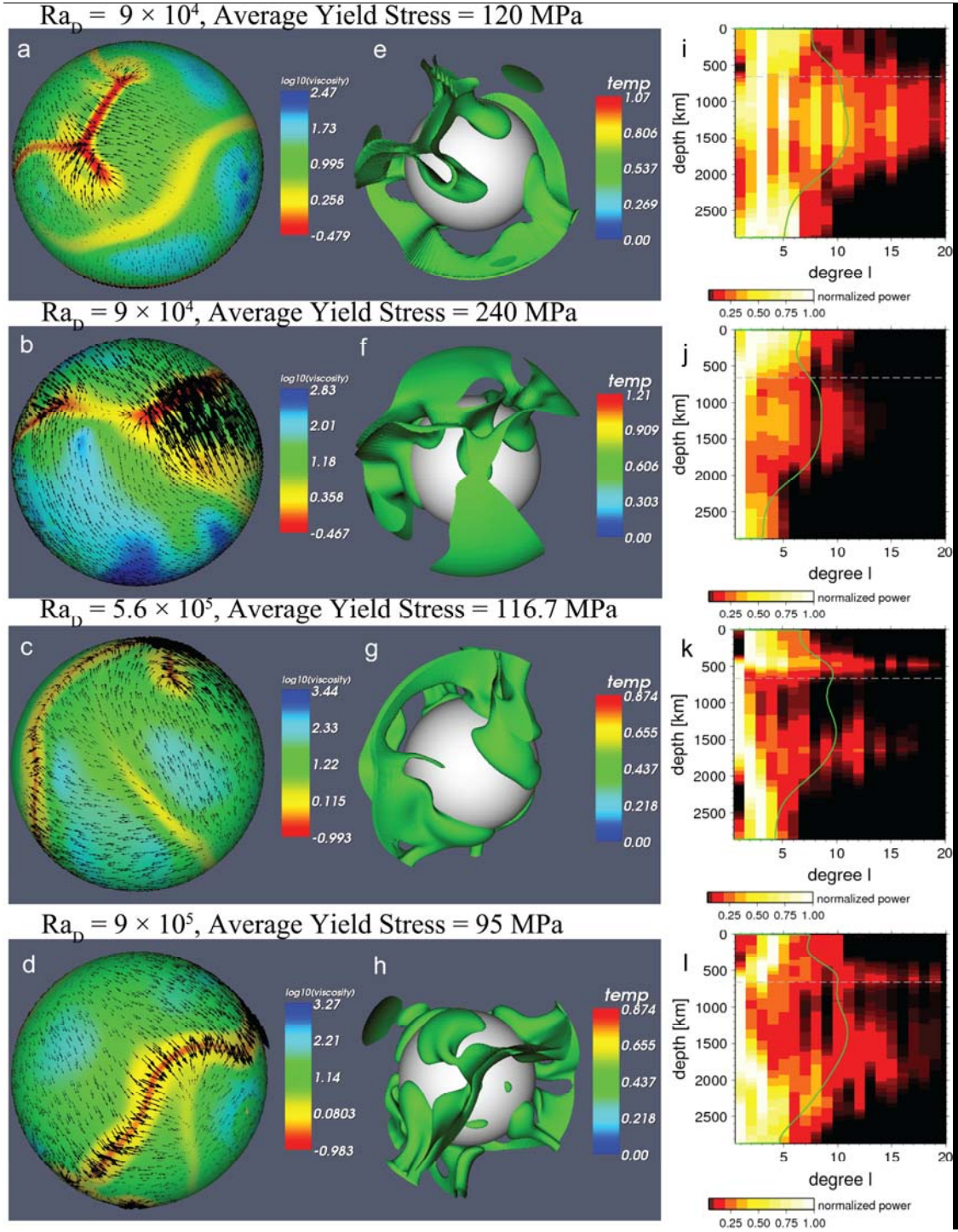
Foley & Becker, 2009



Low Ra_D, constant σ_y models. (a–d) Viscosity fields with velocity vectors, (e–h) cold (T ~ 0.5) temperature isosurfaces, and (i–l) temperature power spectra for the four regimes of convection at $Ra_D = 9 \times 10^4$, with specified σ_y. Figures a, e, and i show mobile convection; Figures b, f, and j show plate-like convection; Figures c, g, and k show episodic convection; and Figures d, h, and l show stagnant lid convection.

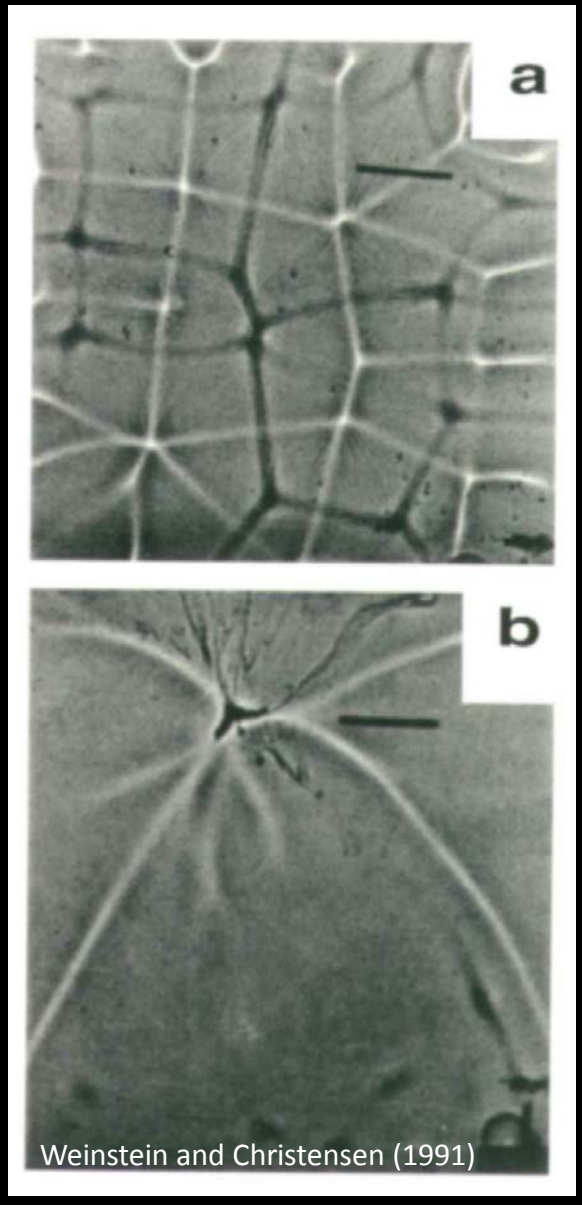
Foley and Becker, 2009

Depth-Dependent Yield Stress



(Foley and Becker, 2009)

Rheological complexity: Temperature-dependent viscosity

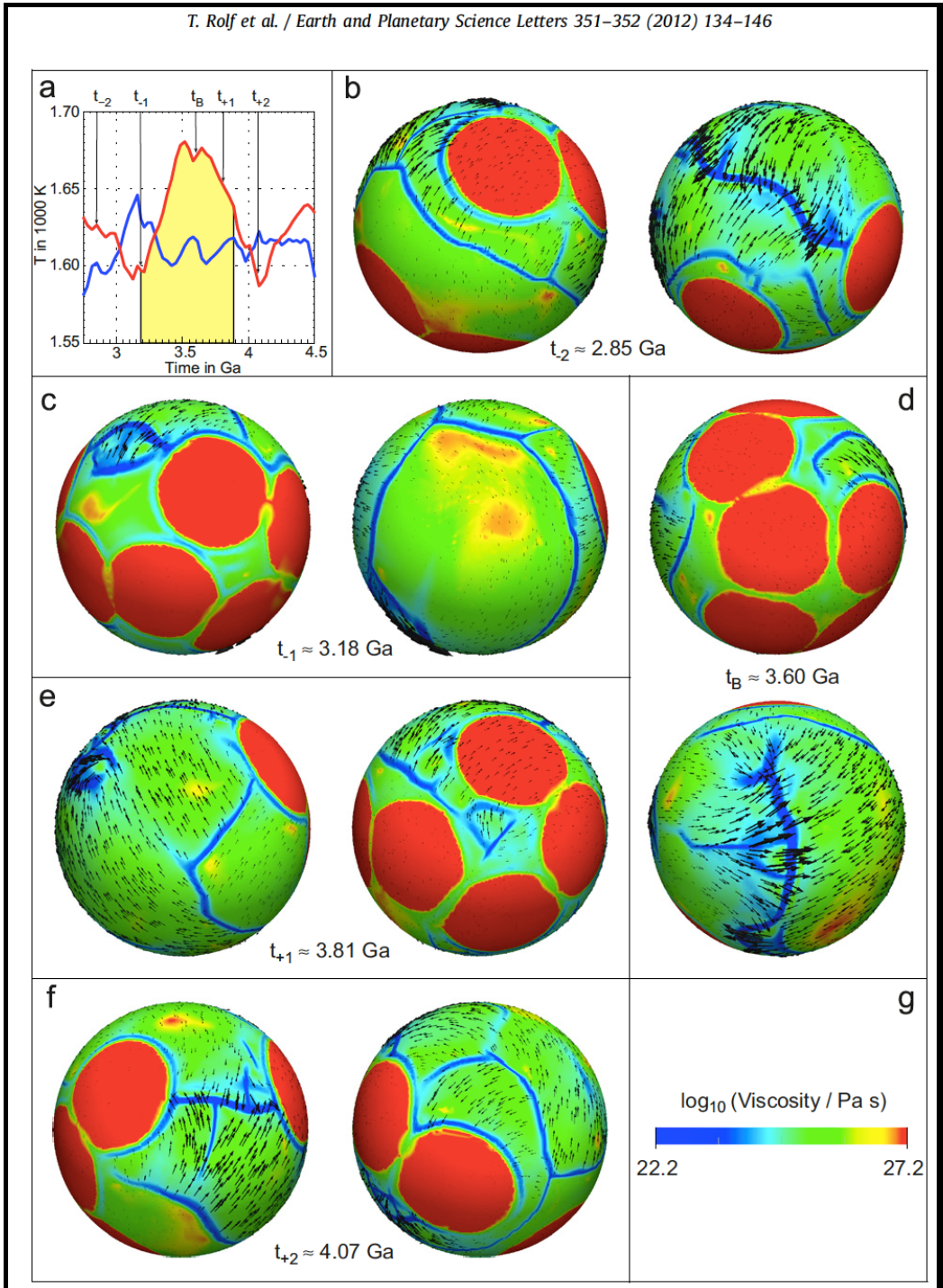


Weinstein and Christensen (1991)

- Silicate viscosity law:

$$\mu \sim e^{\frac{E_a + PV_a}{RT}}$$

- Widens convection cell (material in top must cool longer before being able to sink, so must travel horizontally further)
- Can explain large aspect ratio cells(much longer/wider than mantle is deep): Pacific plate
- But can also lock up top boundary entirely and cannot yield plate-like behavior



Mantle convection with continents & realistic plates

The figure shows the warming effect of assembling a supercontinent. The mean suboceanic temperature is compared to the mean subcontinental temperature (a) for a time period that starts before the formation of the supercontinent and lasts until continents have dispersed again.

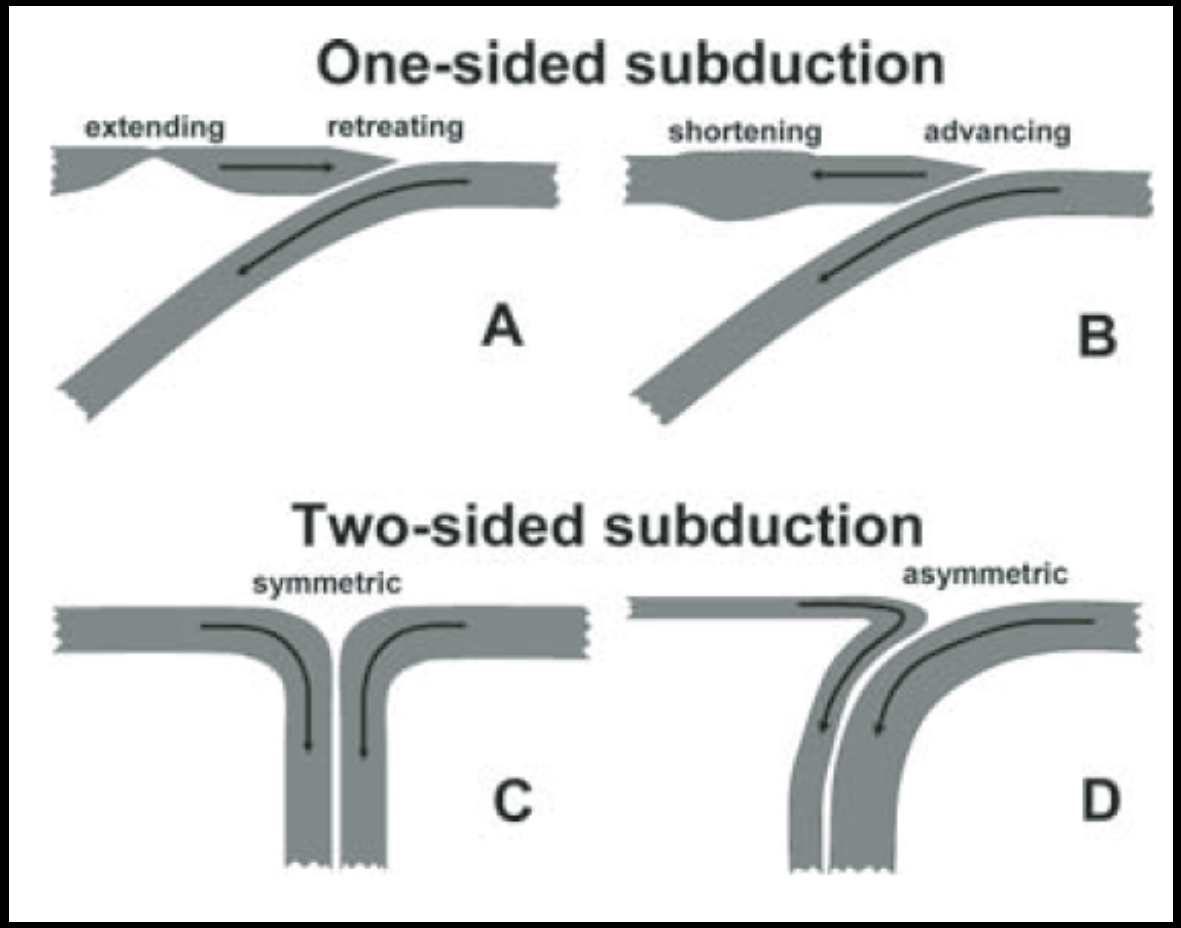
The presence of a supercontinent causes a strong time- dependence of the oceanic surface heat flow and suboceanic mantle temperature, driven by the generation of new plate boundaries.

In the presence of multiple continents the temperature below individual continents is generally lower than below a supercontinent and is more time-dependent.

The periods featuring a hot subcontinental mantle correlate with strong clustering of the continents and periods characterized by cold subcontinental mantle correlate with a more dispersed continent configuration.

Continents influence the wavelength of convection: for a given strength of the lithosphere, the presence of continents results in longer-wavelength flow components.

Why is terrestrial subduction one-sided?

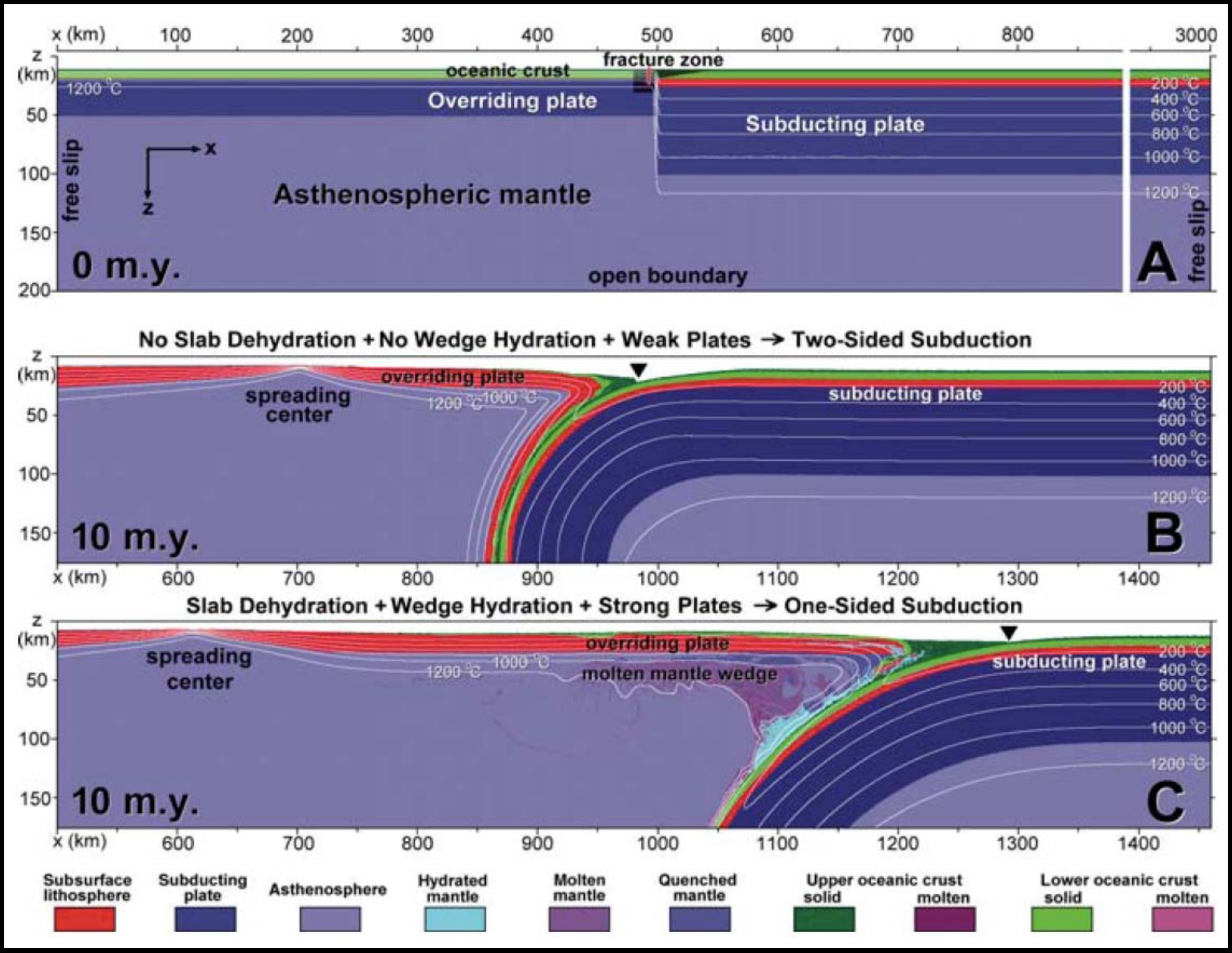


One-sided (A–B) and two-sided (C–D) subduction geometries. In the case of one-sided geometries, the overriding plate does not subduct. Depending on relative plate motion, the overriding plate can be either extending (A) or shortening (Sobolev and Babeyko, 2005) (B). In the case of two-sided geometries, both plates subduct together. Depending on the relative thicknesses (ages) of the plates, two-sided subduction can be either symmetric (Tackley, 2000) (C) or asymmetric (D) .

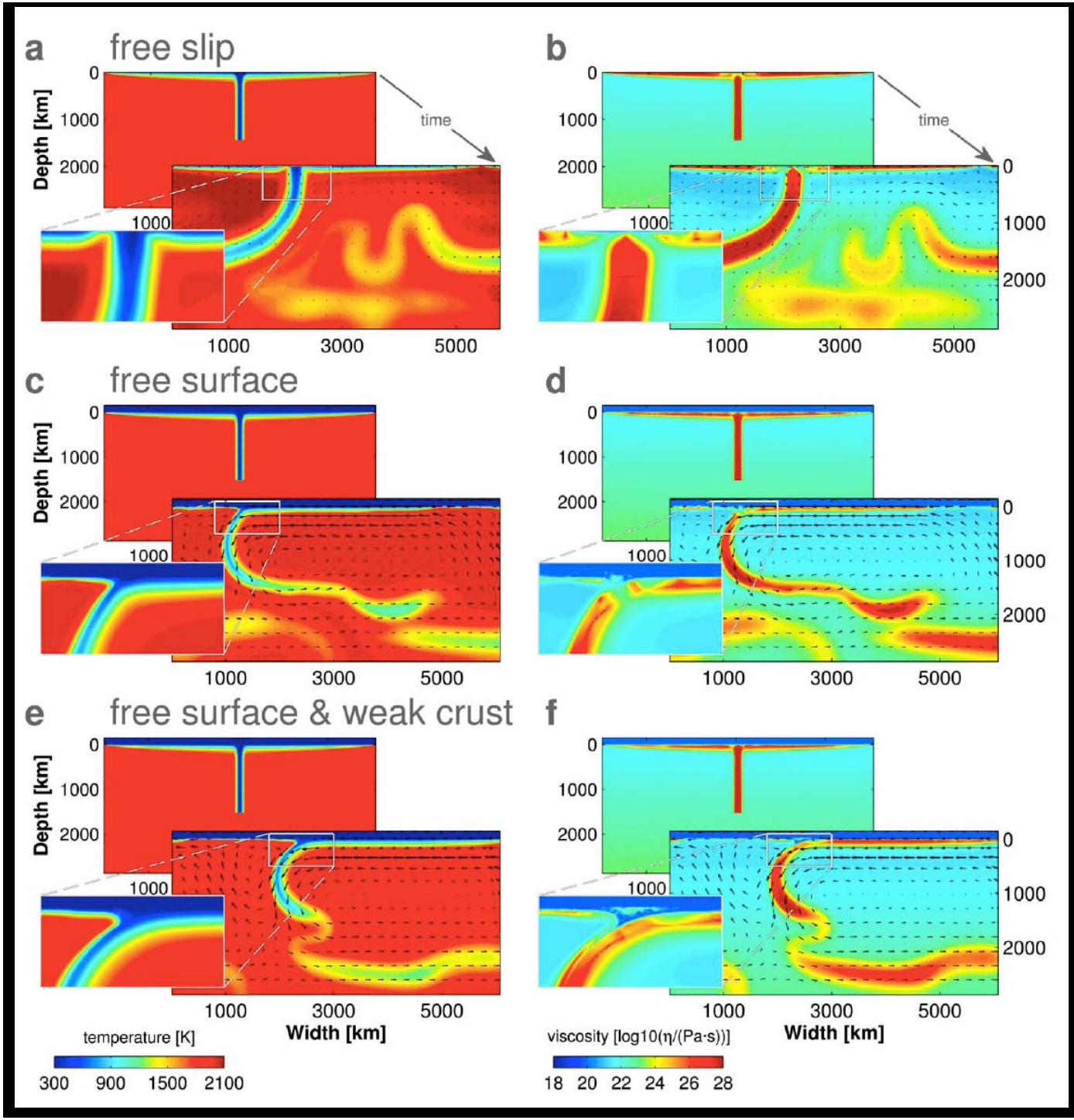
Gerya et al. (2008)

The mode of subduction depends mainly on slab strength and the amount of weak hydrated rocks present above the slab. Two-sided subduction occurs at low slab strength regardless of the extent of hydration. In contrast, steady state one-sided subduction requires a weak hydrated slab interface and high slab strength. The weak interface is maintained by the release of fluids from the subducted oceanic crust as a consequence of metamorphism. The resulting weak interplate zone localizes deformation at the interface and decouples the strong plates, facilitating asymmetric plate movement. High plate strength and the presence of water are major factors controlling the style of plate tectonics driven by self-sustaining one-sided subduction.

Gerya et al. (2008)



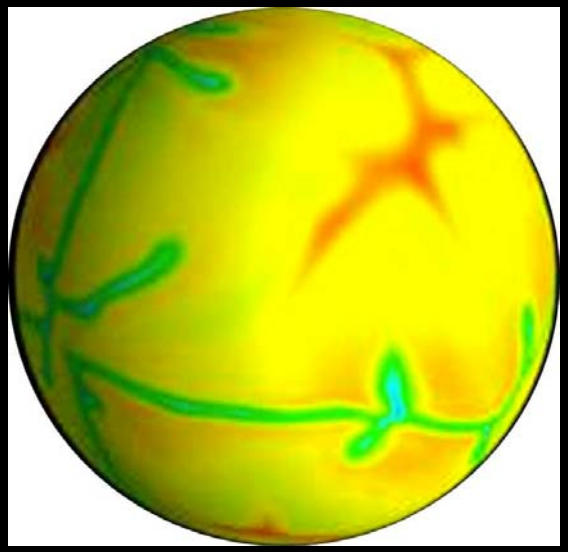
Gerya et al. (2008)



The asymmetry of subduction results from the presence of a free deformable upper surface and the presence of weak hydrated crust atop subducting slabs. A free surface, rather than the conventional free-slip surface, allows plate boundaries to change from double-sided to single-sided. A weak crustal layer further improves the behavior towards steady single-sided subduction by acting as lubricating layer between the sinking and the overriding plate. Asymmetry and stable single-sided subduction are fostered by strong plates.

Crameri et al. (2012)

The "Plate Generation" problem



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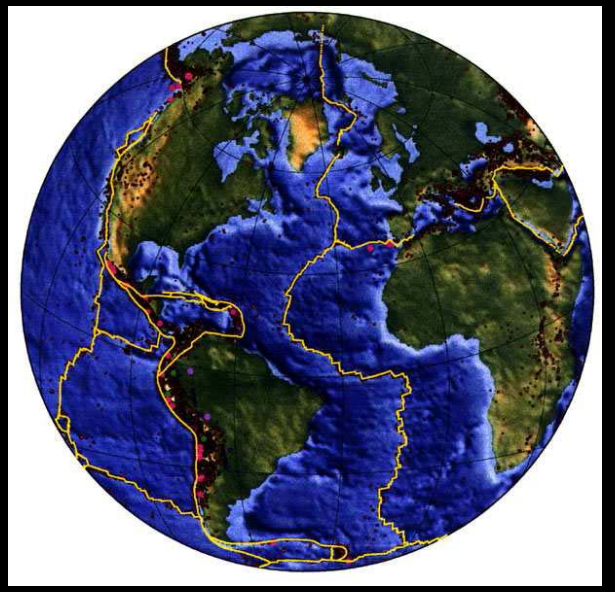
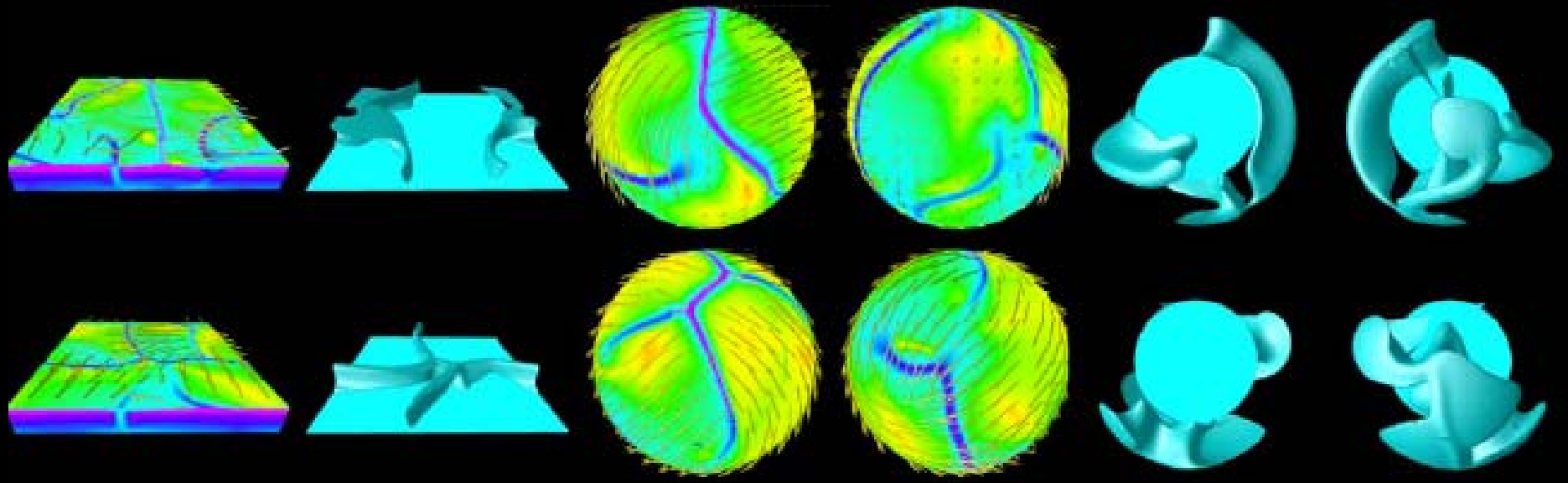


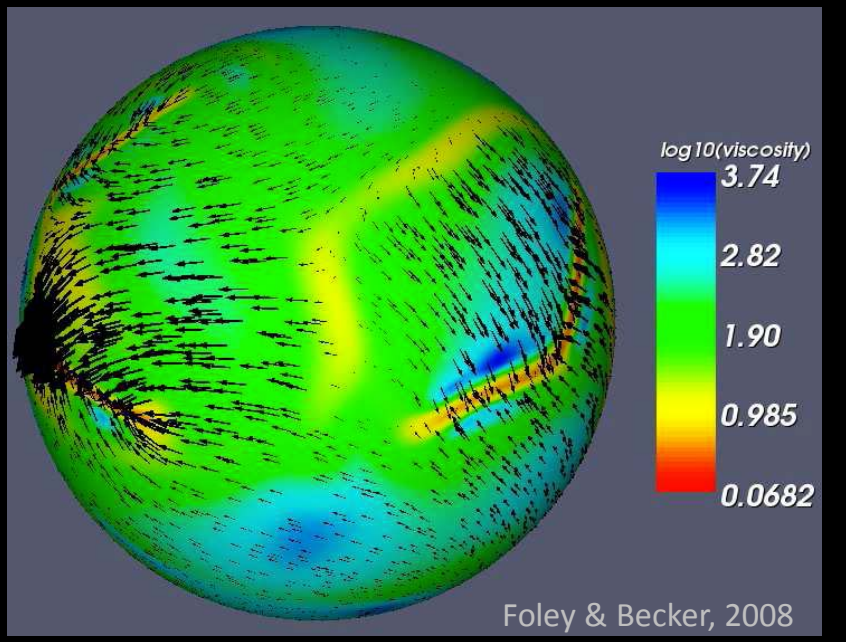
- **How does plate tectonics arise from a convecting mantle?**
- **Why Earth, not Venus (or Mars)?**
- **What governs whether we expect to find plate tectonics in other solar systems?**
- **Mantle dynamicists' view: Plate tectonics is an integral part of the overall convecting system: the plates are convection.**

Plastic yielding models

Van Heck & Tackley 2008

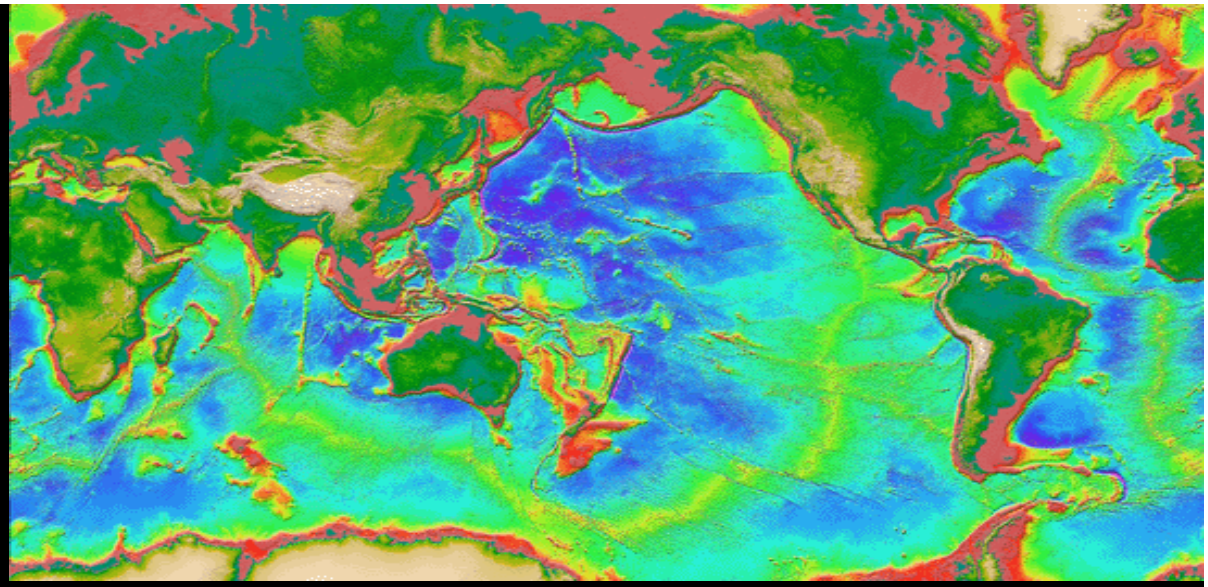


- Generates instantaneous nearly plate like flows
- But plate boundaries only exist while deforming
- Models require yield stresses much smaller than the strength of the lithopshere
- No dormant weak zones, sutures, to be reinherited
  - Doubtful can initiate subduction without these (Toth, Gurnis, 2000)



Foley & Becker, 2008

Plate Generation and Shear-Localization Mechanisms



Most terrestrial planets are stagnant lid planets

Earth has self-softening feedbacks

- deformation softens material
- weak zones focus deformation
- causes more softening, more focusing…

Allows convecting mantle to generate

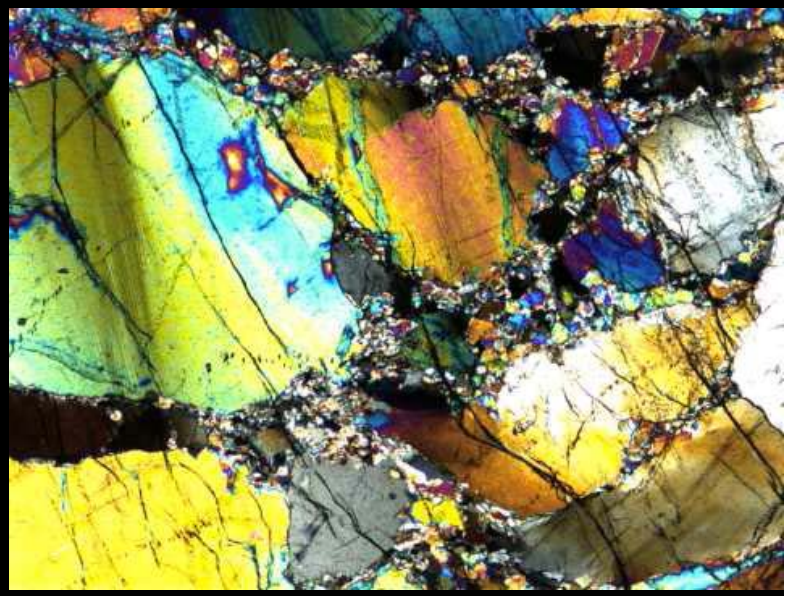
- strong broad plates,
- narrow, weak long-lasting boundaries
- localized strike-slip (toroidal) shear

Bercovici, Ricard and colleagues have developed a physically based damage theory that allows for the self-consistent generation of plates.

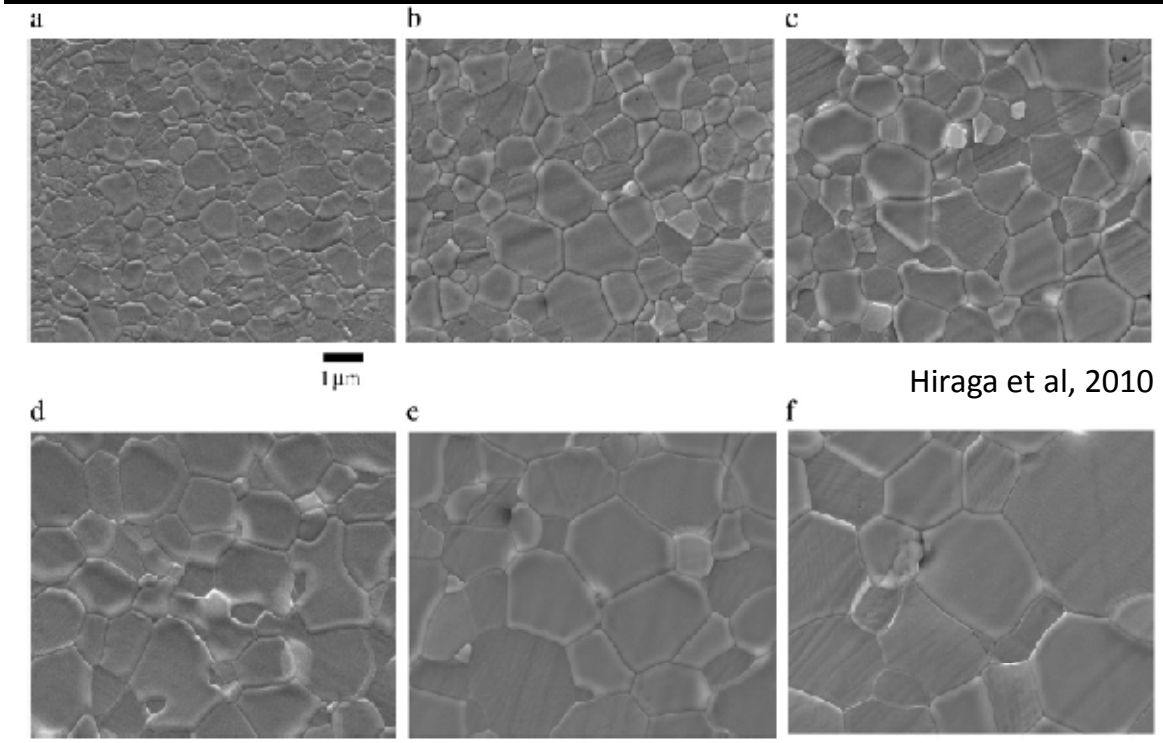
Damage occurs by deformation driven grain size reduction. Grain size reduction results in softening of the material.

Grain Damage

- Mineral grains grow if “static”
- With deformation and damage (dislocations), grain size decreases
- Rocks apparently soften as grains “shrink” ➔ positive feedback
- “Deep” lithospheric mechanism
- Evident in mylonites



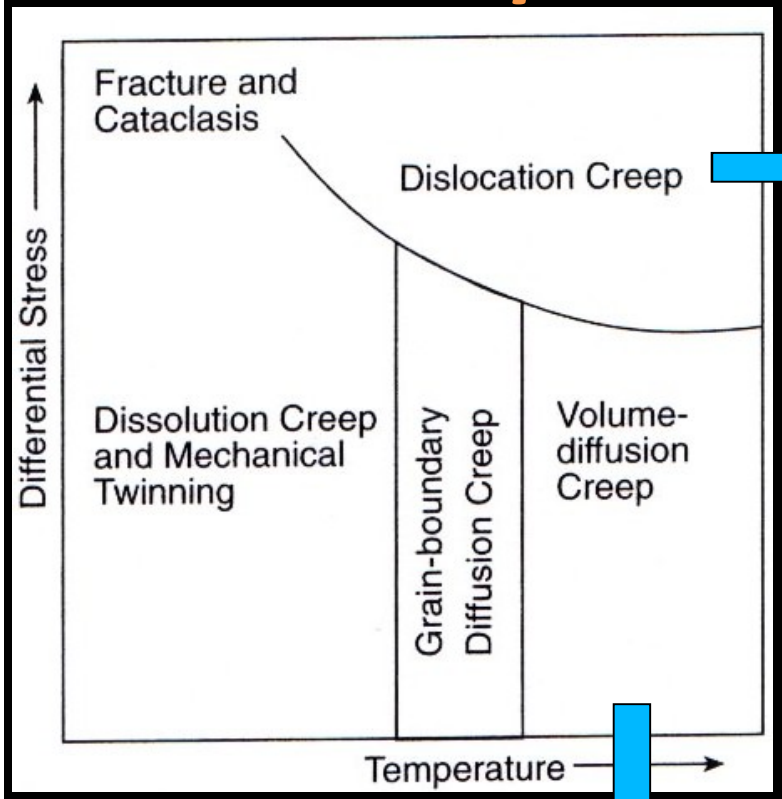
Mylonite, Ivrea Zone Italy (Jin et al., 1998)

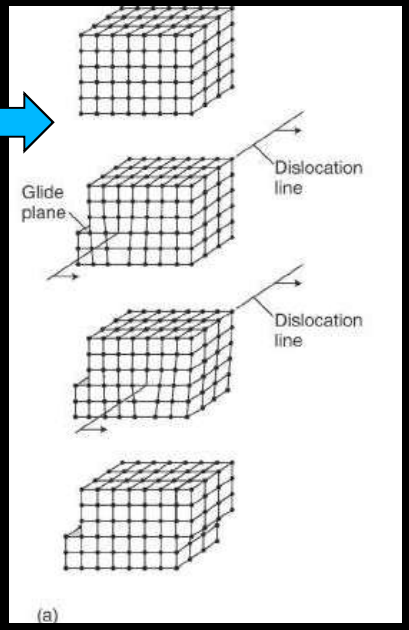


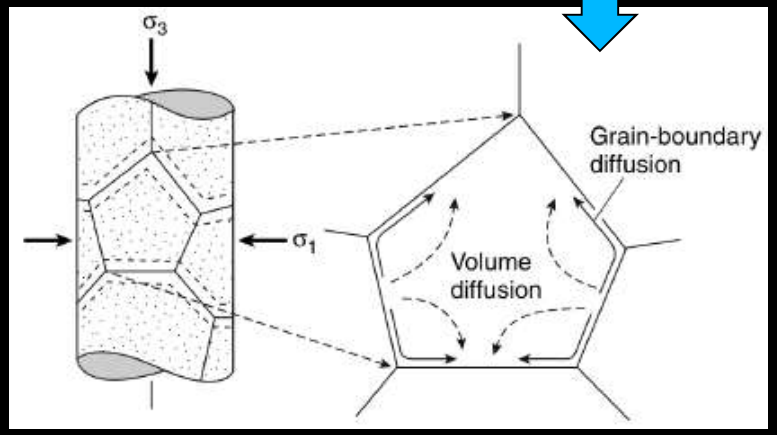
Hiraga et al, 2010

But there are some problems with this view

Rock "creep" rheology





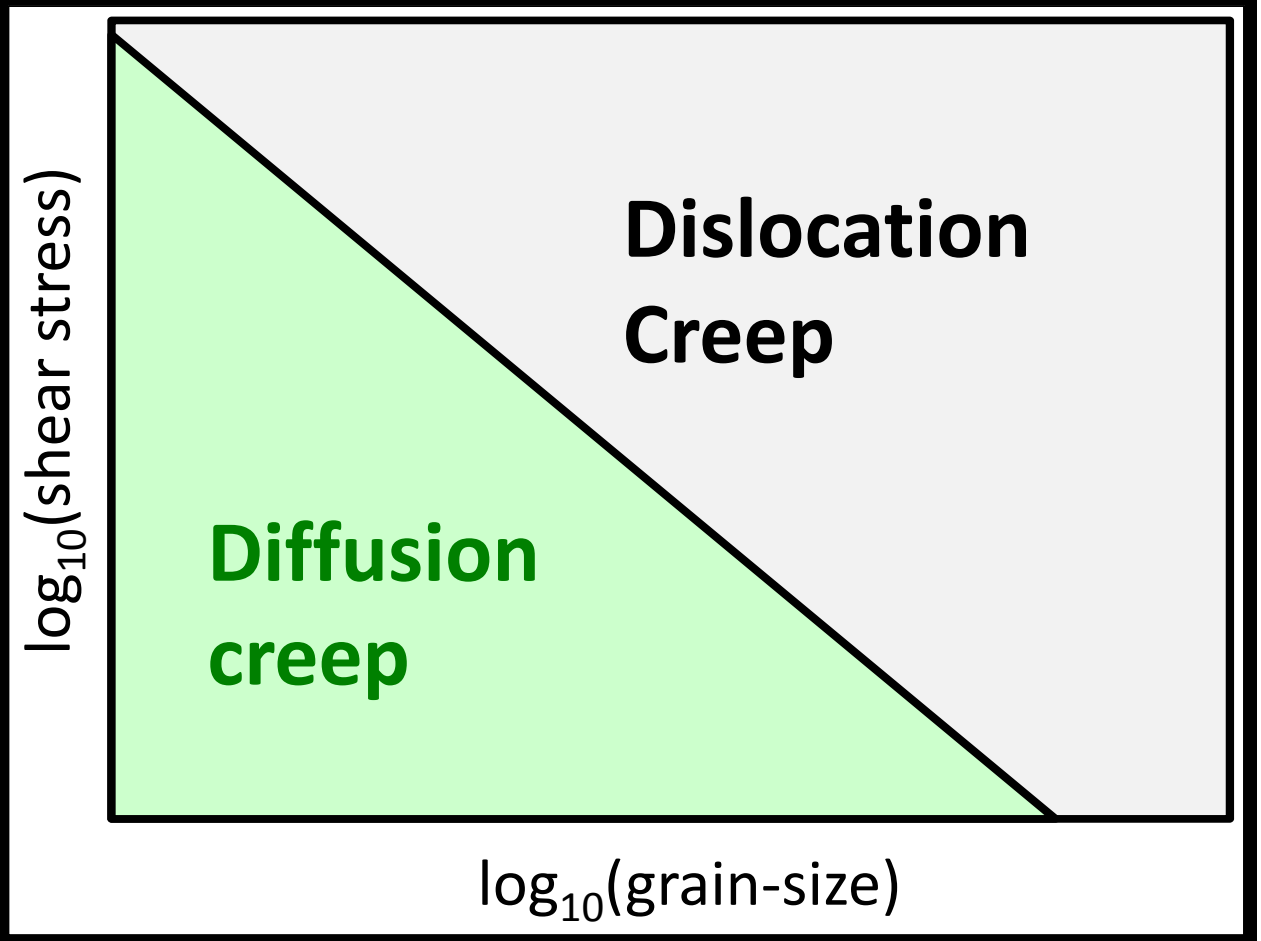


- Mantle convects in solid state (not liquid) but behaves as a fluid at long times (>1 Myr)
- At high mantle T deformation occurs…
  - At "low" stress by mass diffusion through/along mineral grains
  - At "high" stress by propagating dislocations in crystal lattice
- Both thermally activated according to Boltzmann statistics

- **Problems:**

1. **Exclusive creep mechanisms**
   - **Grain reduction only in dislocation creep (dynamic recrystallization)**
   - **Grain size weakening only in diffusion creep**
   - **Damage and weakening don't co-exist**

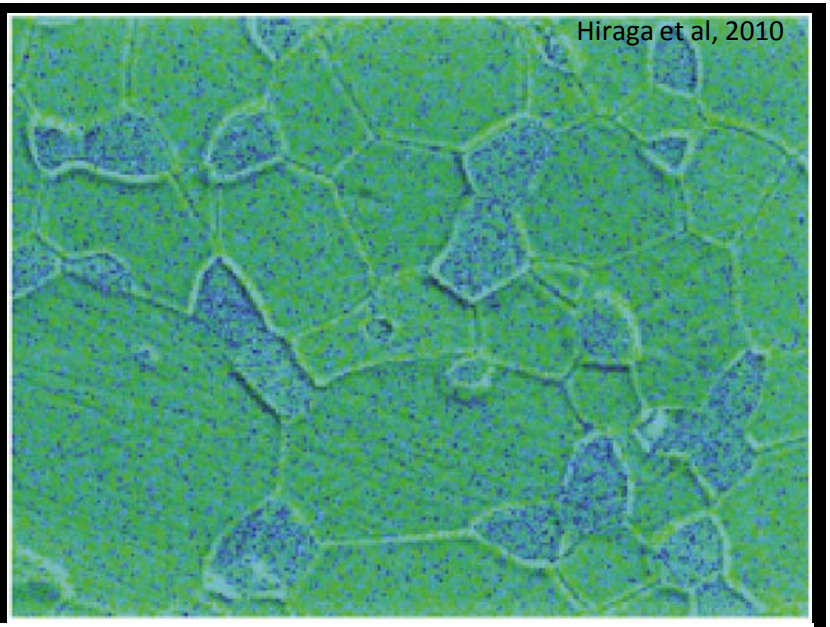
2. **Olivine grain-growth is too fast:**
   - **Loss of plate boundaries after deformation ceases within 1 Myr**

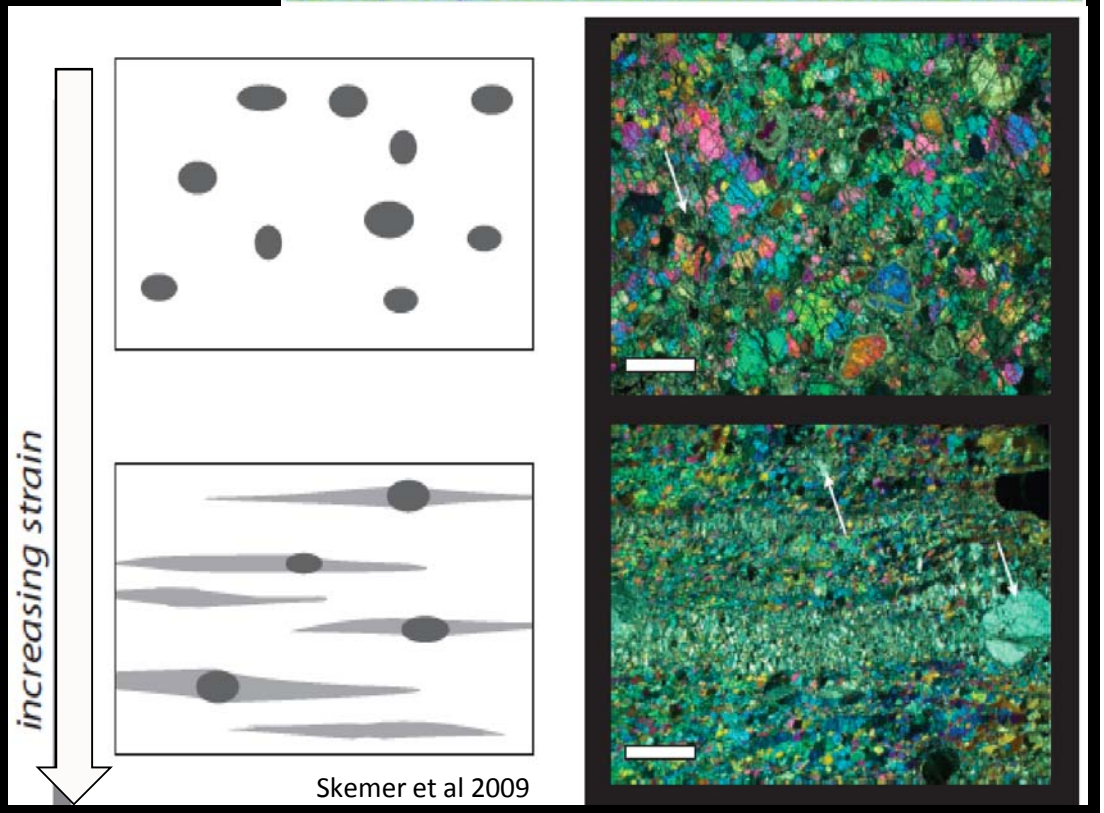


Grain-damage in rock mixtures

- Mantle rocks (peridotite) are a mixture of olivine and pyroxene
- Grain growth blocked (pinned) by interface between components
- Damage acts to "sharpen" interface
- Sharpening of interface and pinning drives grains to smaller sizes and material softens
- Damage and softening coexist

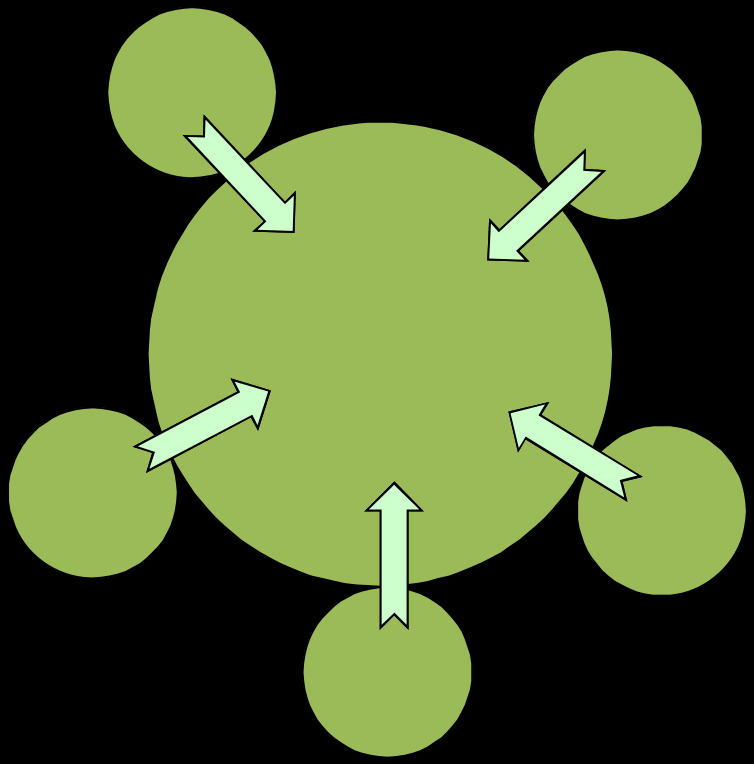
*Bercovici & Ricard 2012a,b



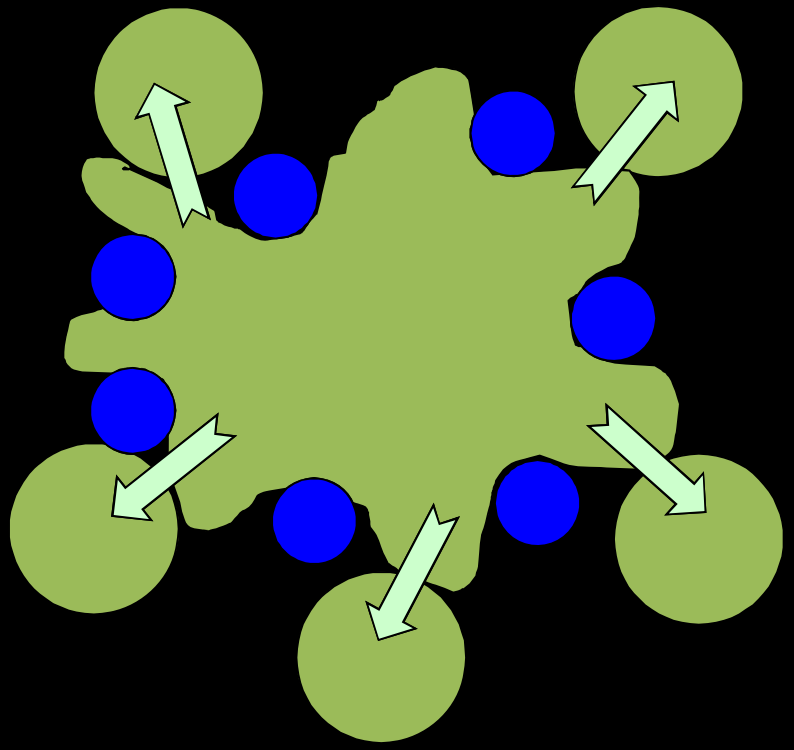


Pinning slows coarsening (grain-growth)

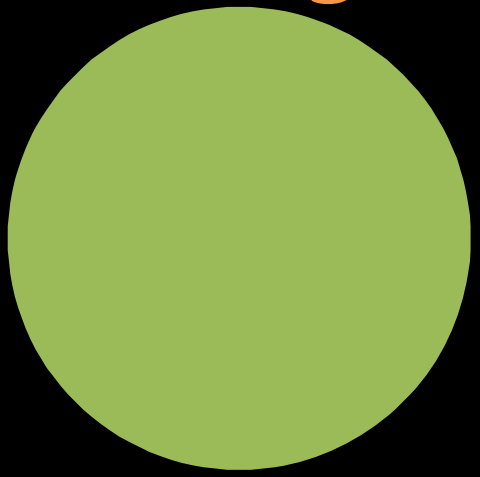
Single-phase coarsening



In 2-phase with pinning, coarsening slows or reversed

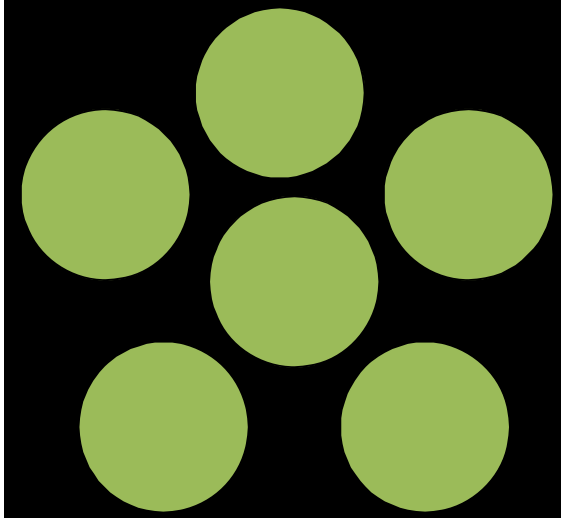


Pinning helps damage

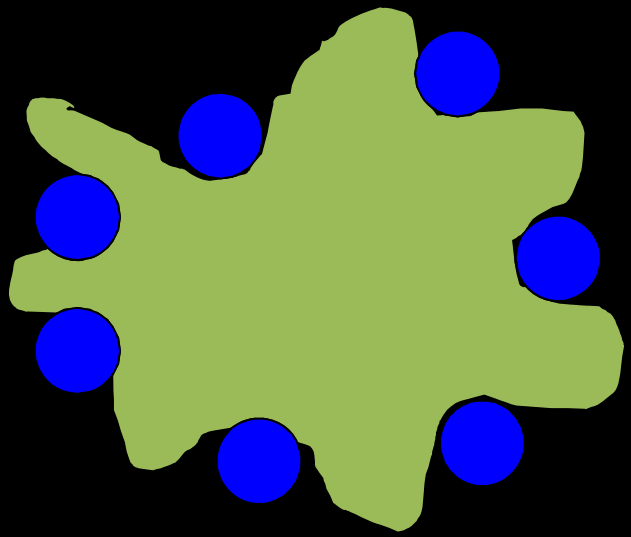


Low surface energy

Damage ➔ *work provides energy increase*

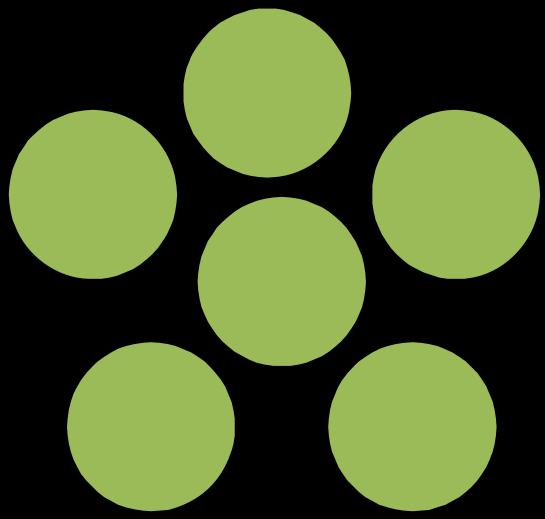


High surface energy



High surface energy

"Easier" Damage: *less energy needed*



High surface energy

Grain size reducing damage

- **Inverse grain-size (or interface roughness) A~1/R governed by**

$$\frac{\overline{D}\mathcal{A}}{Dt} = \frac{f_{\mathcal{A}}}{\gamma}\Psi - k_{\mathcal{A}}\mathcal{A}^3$$

damage healing

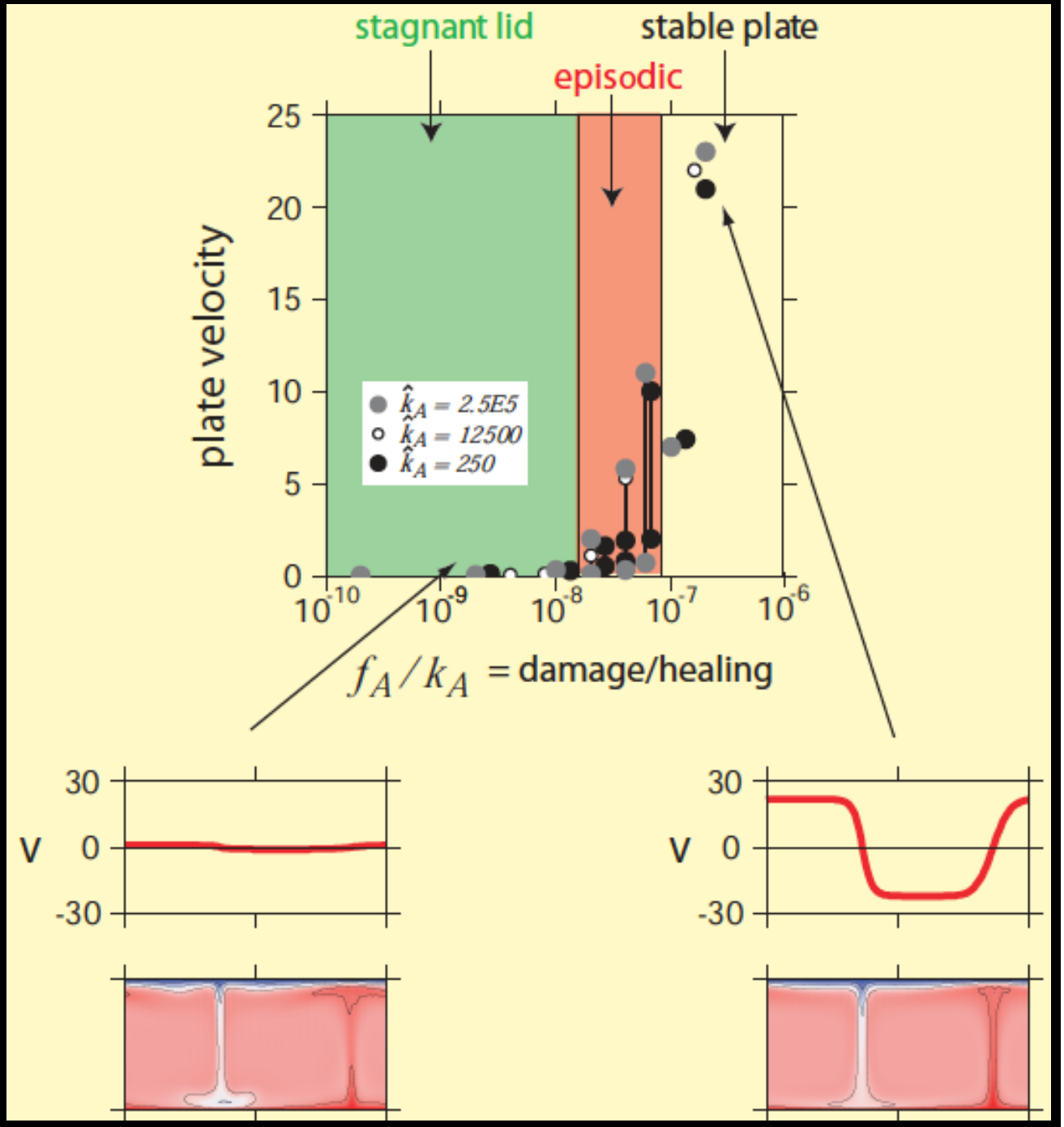
- **Viscosity decreases with A**

$$\mu_m = \mu_0(\mathcal{A}_0/\mathcal{A})^m$$

- **Where $\int_0$ can be a function of temperature**
- **Get localization, weakening and weakening history**

Convection with damage

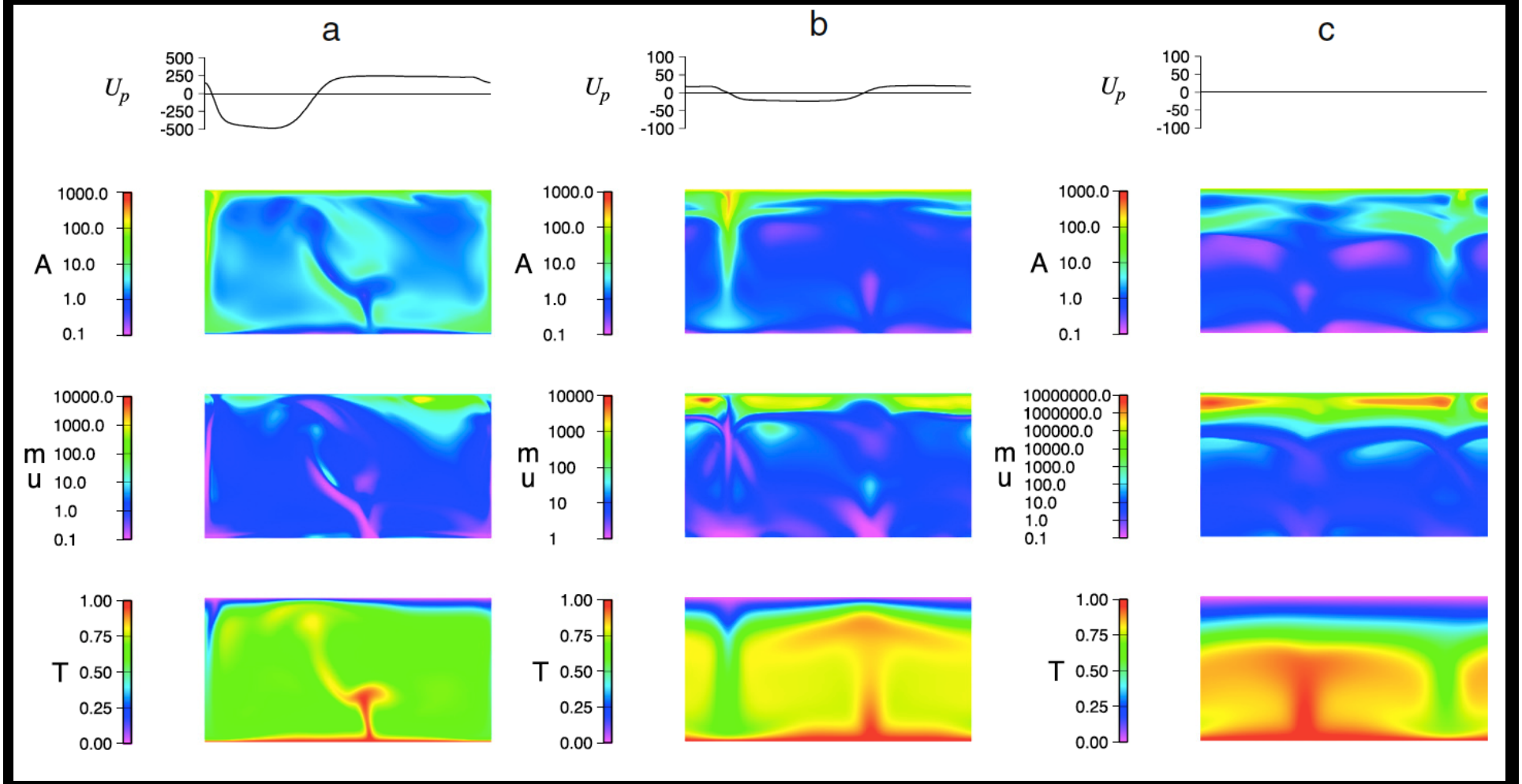
- As damage to healing ratio f_A : k_A increases
- **stagnant surface transitions to plate-like surface**



Landuyt & Bercovici 2009

Convection models with damage & healing

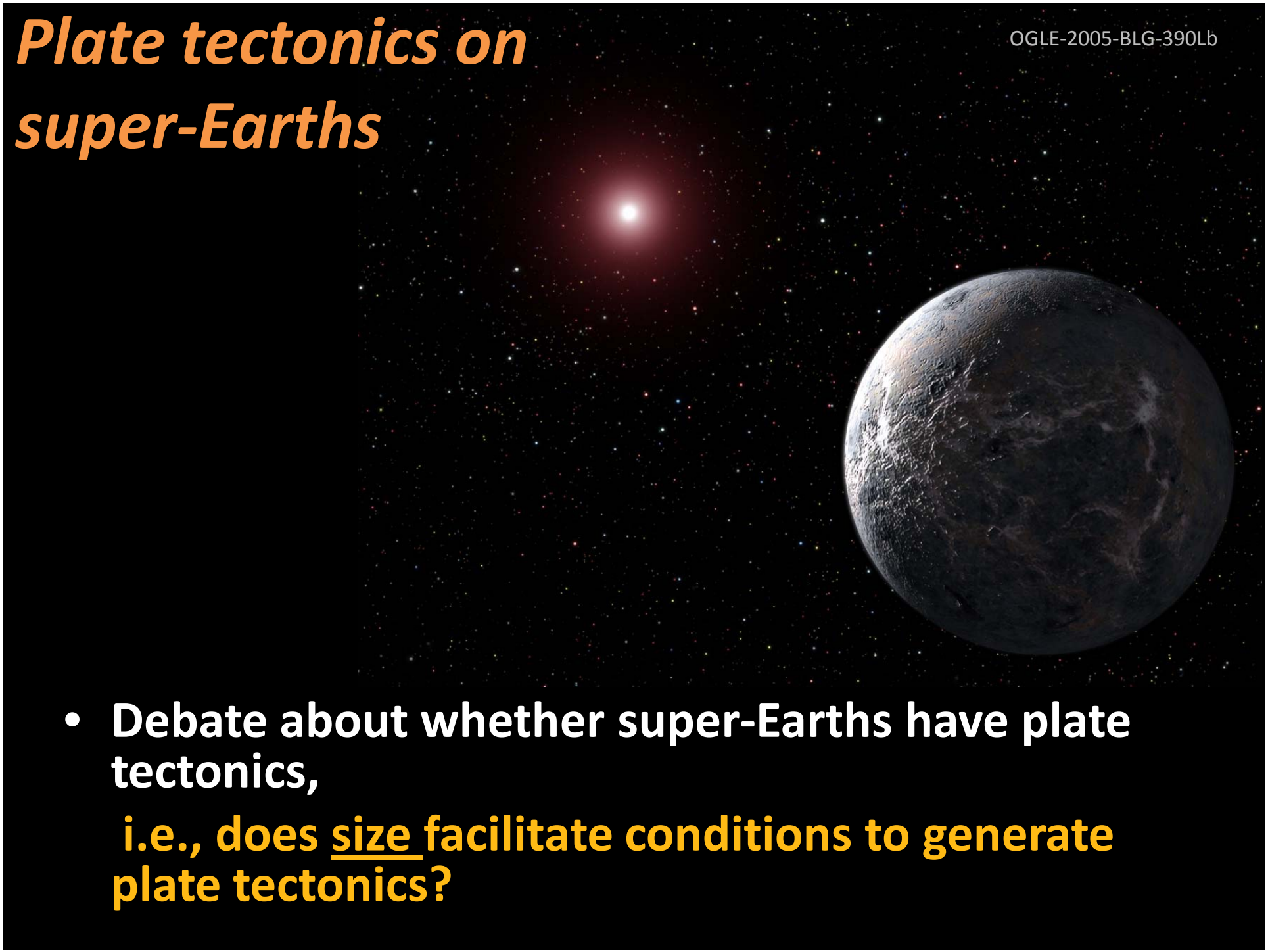
$\mu_l/\mu_m = 10^5$ | $\mu_l/\mu_m = 10^7$ | $\mu_l/\mu_m = 10^8$



- **Transition from plate-like to stagnant surface at critical lithosphere-mantle viscosity ratio μ_l/μ_m**

Foley, Bercovici, Landuyt 2012

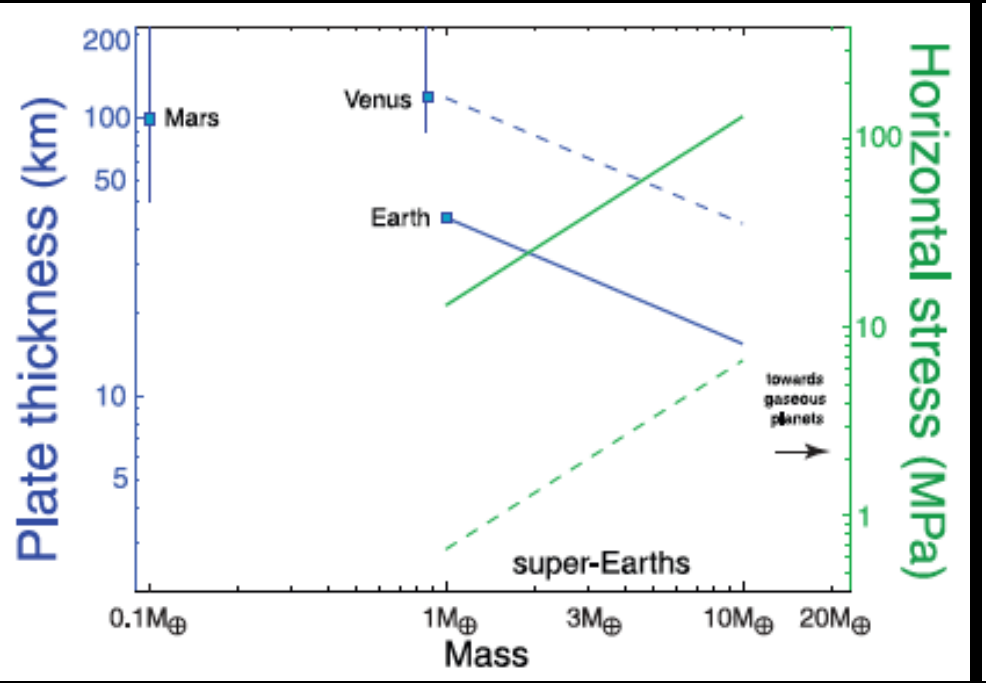
Plate tectonics on super-Earths

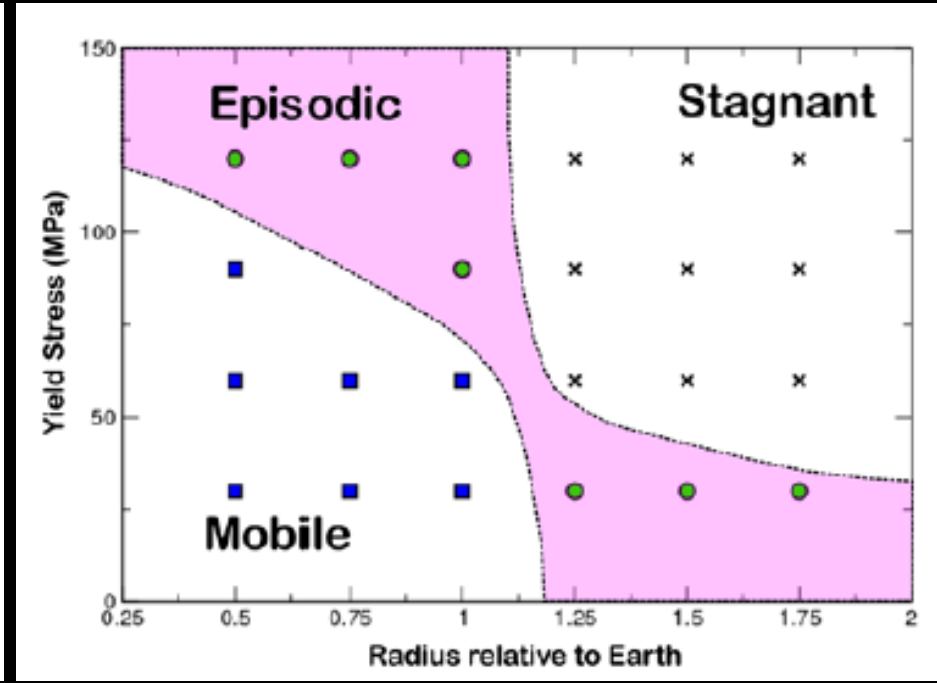


- **Debate about whether super-Earths have plate tectonics,**

  i.e., does size facilitate conditions to generate plate tectonics?

Plate Tectonics on Super-Earths





- **Valencia et al. (2007)**: Larger size, more vigorous convection: Larger stress on thinner lithosphere: **plates likely**.

- **O'Neil et al (2007)**: Larger size, hotter mantle, less lithospheric stress, but larger lithostatic P, larger yield or fault stress: **plates unlikely.**

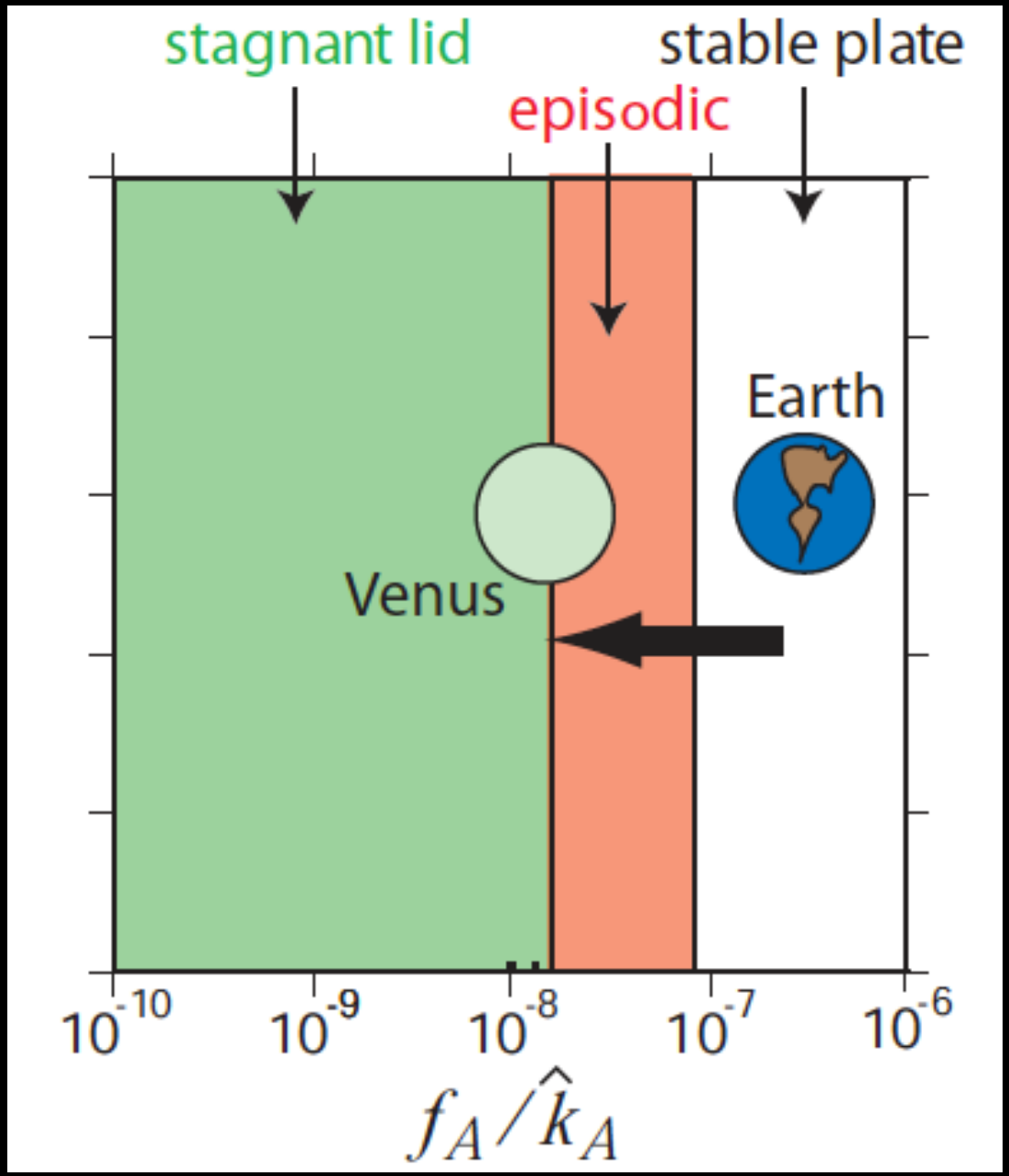
A new criterion for the onset of plate tectonics on terrestrial planets:

Damage must reduce the viscosity of shear zones in the lithosphere to a critical value equivalent to the underlying mantle viscosity (Foley et al. 2012).

Anything, e. g., surface temperature, that influences the state of damage in the lithosphere will affect whether plate tectonics can occur.

Planetary Climate and Tectonics

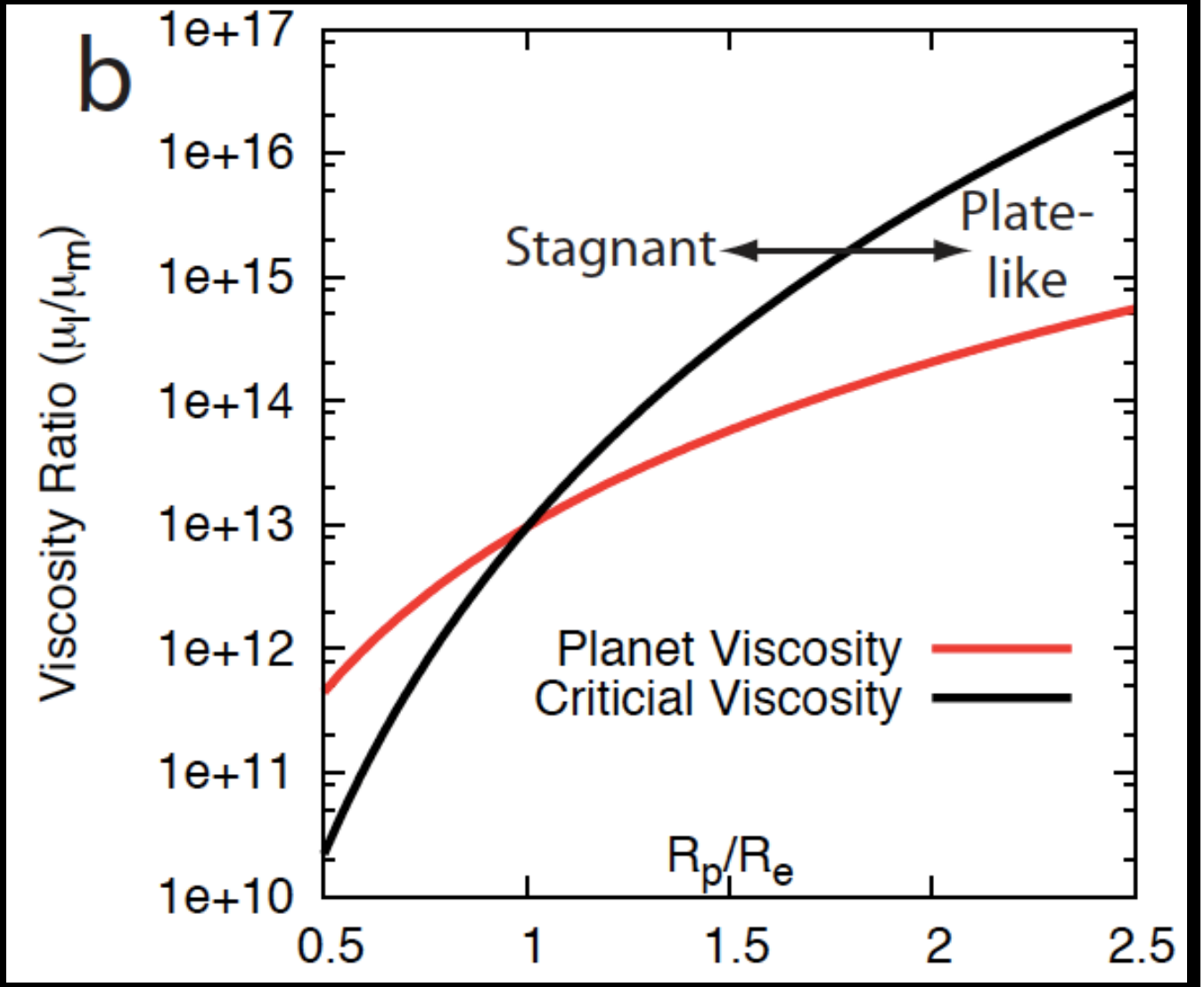
- **Higher surface T promotes healing → low damage:healing ratio →Venus**
- **Lower surface T reduces healing → high damage:healing ratio →Earth**



- Role of liquid water is to keep moderate climate through promoting carbon cycle, not necessarily through weakening.
- Plate tectonic feedback likewise stabilizes carbon cycle.

To determine if plate tectonics occurs for planets of different size:

- **Compare**
  - **critical $\lceil_I/\lceil_m$ at which plate-tectonics stops**
  - **– to**
  - **planet's $\lceil_I/\lceil_m$ (from global cooling model, $Nu \sim Ra^{\beta}$)**



- **Ratio of ratios**
  - Critical viscosity ratio
  - Planet viscosity ratio
- **< 1 stagnant lid**
- **> 1 plate-like**
- **Trend with**
  - **Planet radius**
  - **Surface T**

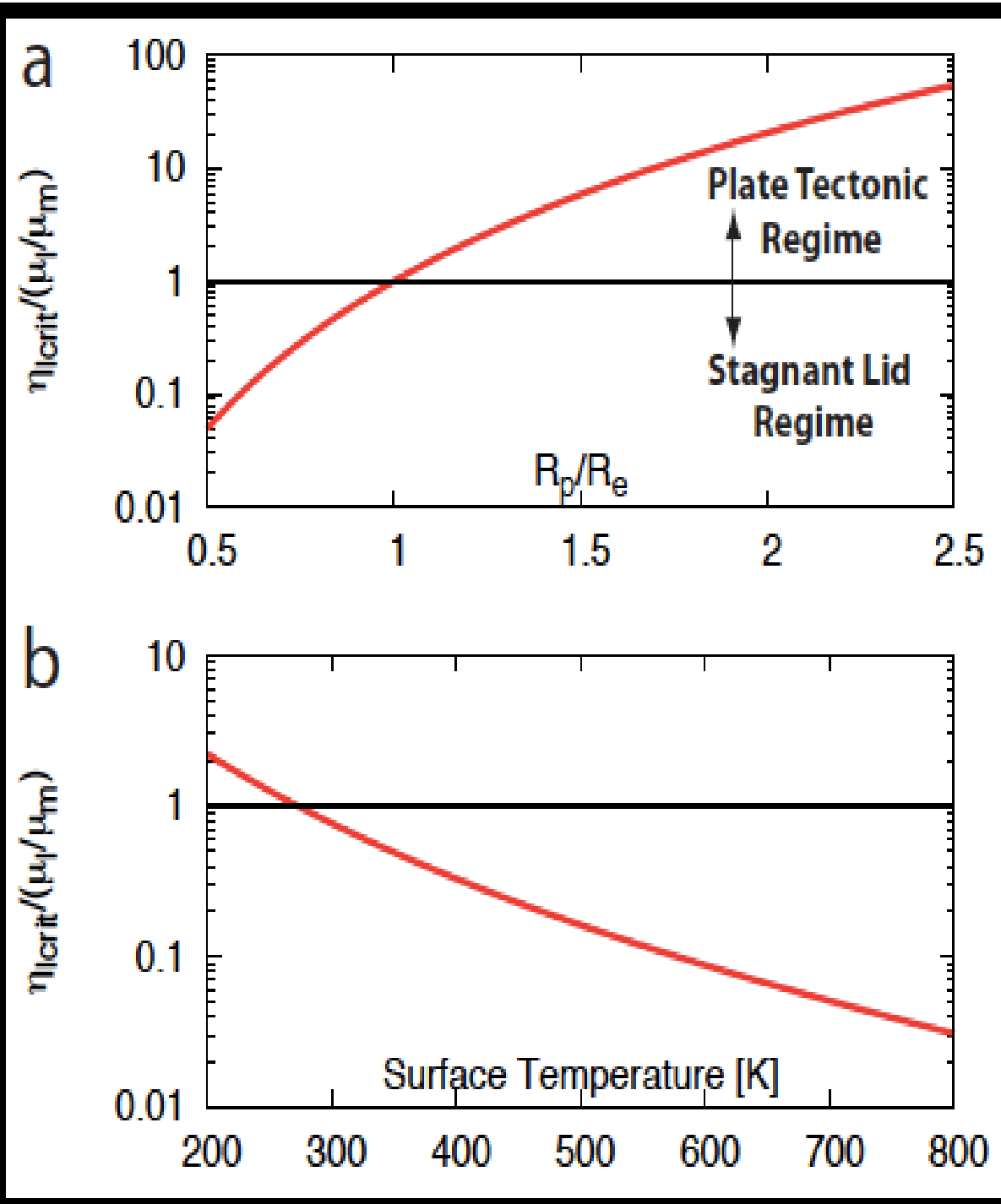
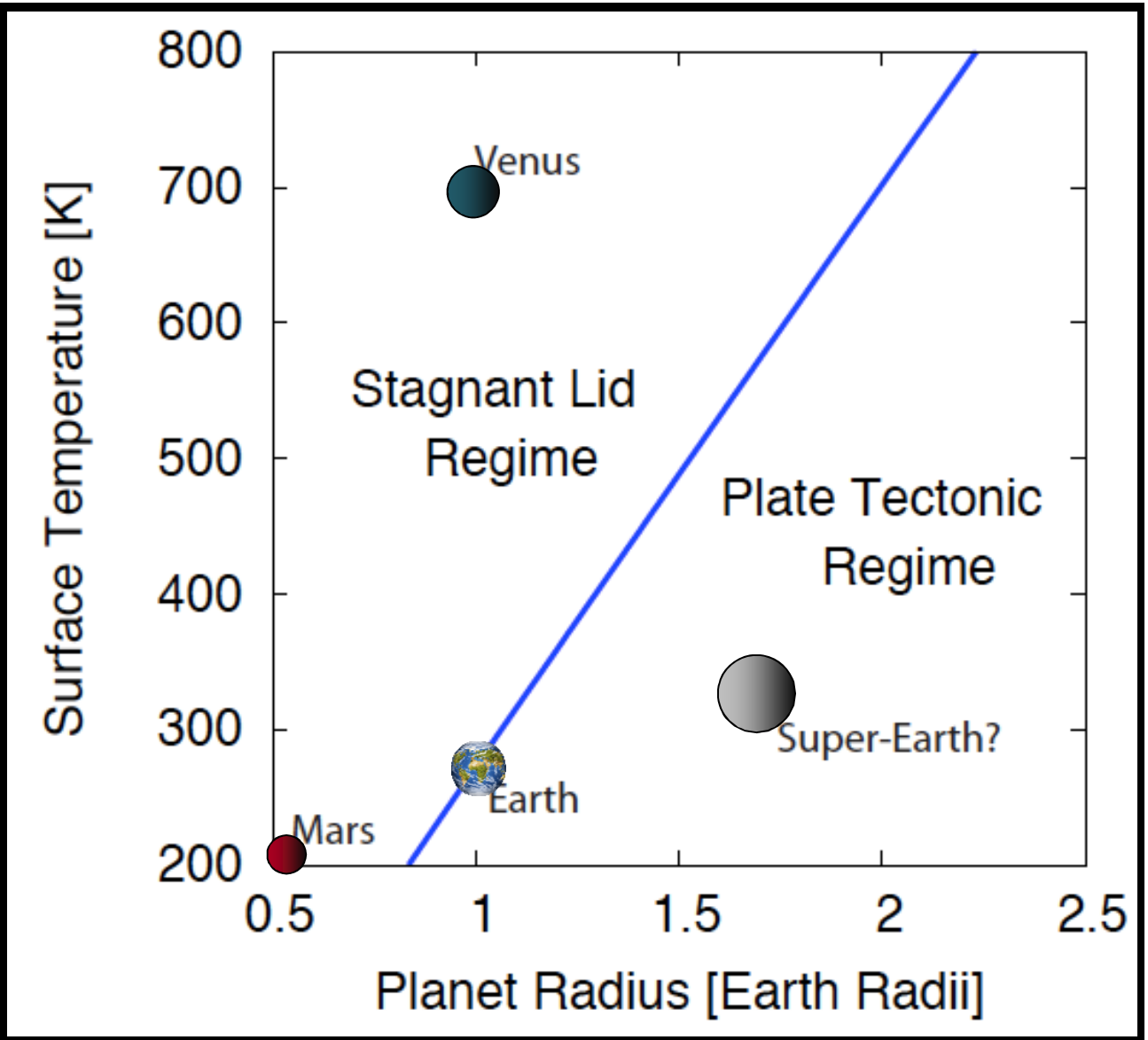


Plate generation phase diagram

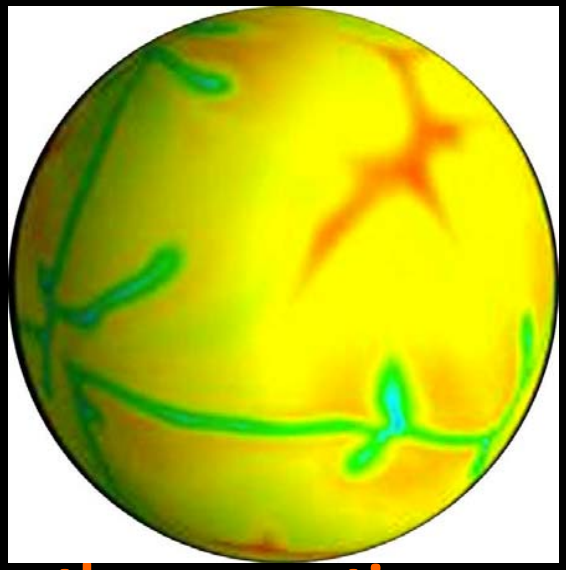
- **When**

$$\frac{\text{critical viscosity ratio}}{\text{planet viscosity ratio}} = 1$$

- **Gives equation for "phase boundary" defining when planet's surface is plate-like or stagnant**
- **Size does matter**
- **But not necessarily more so than other conditions like surface temperature**



In a nutshell…



Mantle convection and plate generation:

Grain size reduction with damage in rock mixtures

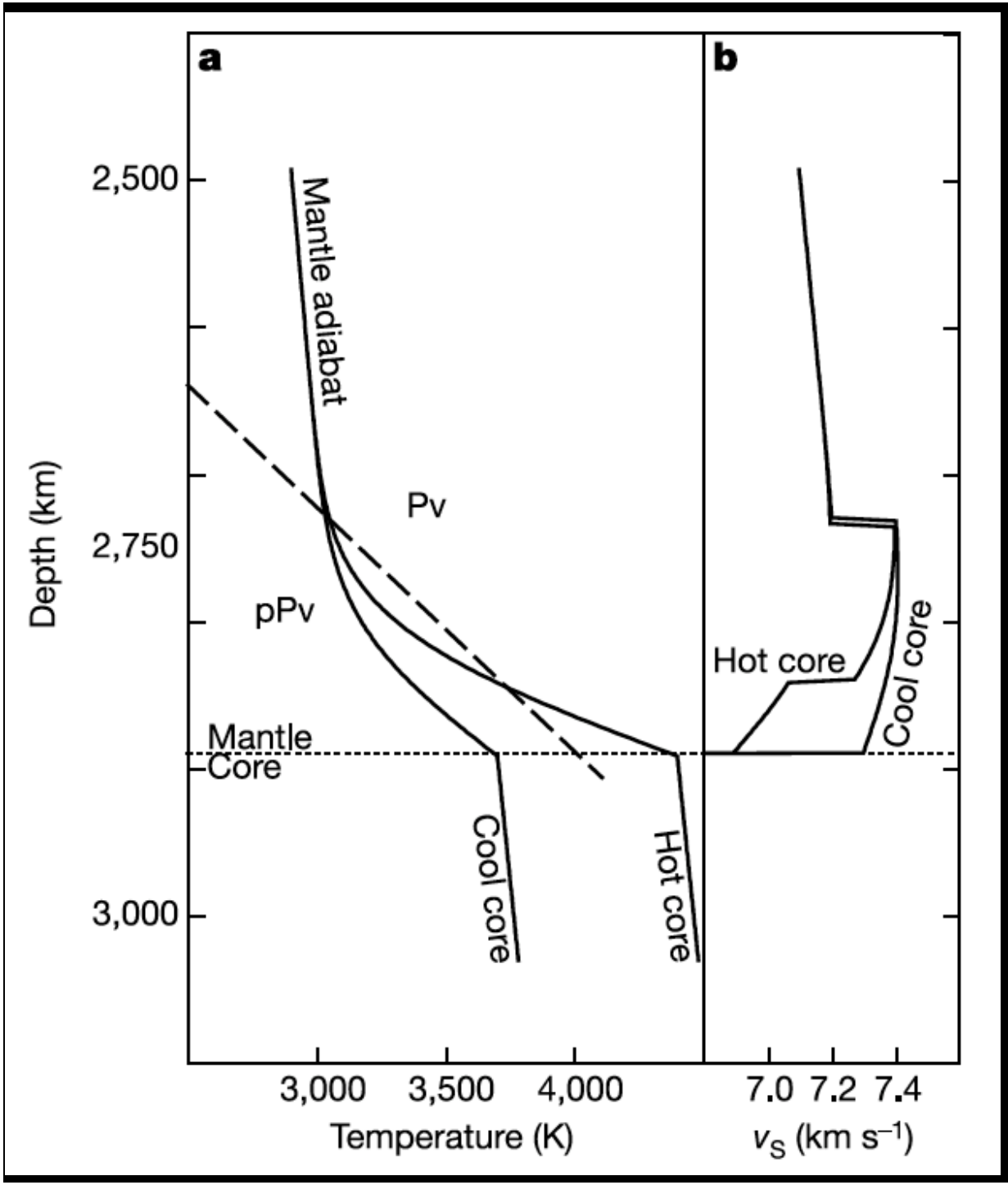
- Allows damage & grain size softening to coexist
- Focused long-lived weak zones = plate boundaries

Competition between damage and healing may explain Venus-Earth paradox

- High T promotes healing over damage; low T opposite
- Water is the agent of the carbon cycle and keeps Earth T lower

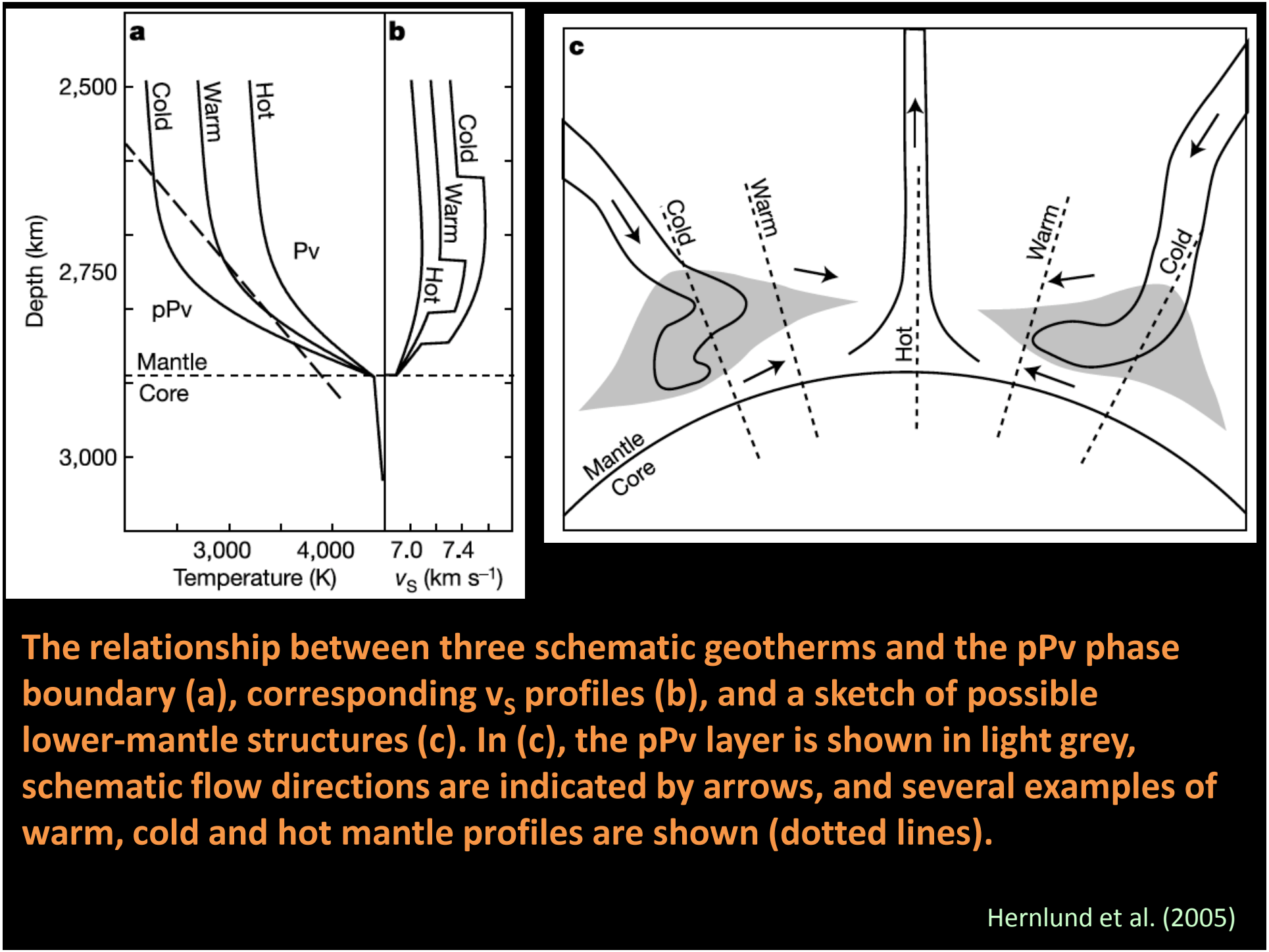
Emergence of plate tectonics on super Earths?

- Super Earth's might be more prone to plate tectonics, but size isn't everything



The relationship between the geotherm and pPv phase boundary for different core temperatures (a), and corresponding seismic shear-wave profiles (b). The geotherms (solid lines in a) are plotted following an average mantle adiabat above D" with CMB temperatures of 3,700 K (cool core) and 4,400 K (hot core) with the estimated pPv phase boundary (dashed line) superimposed.

Hernlund et al. (2005)



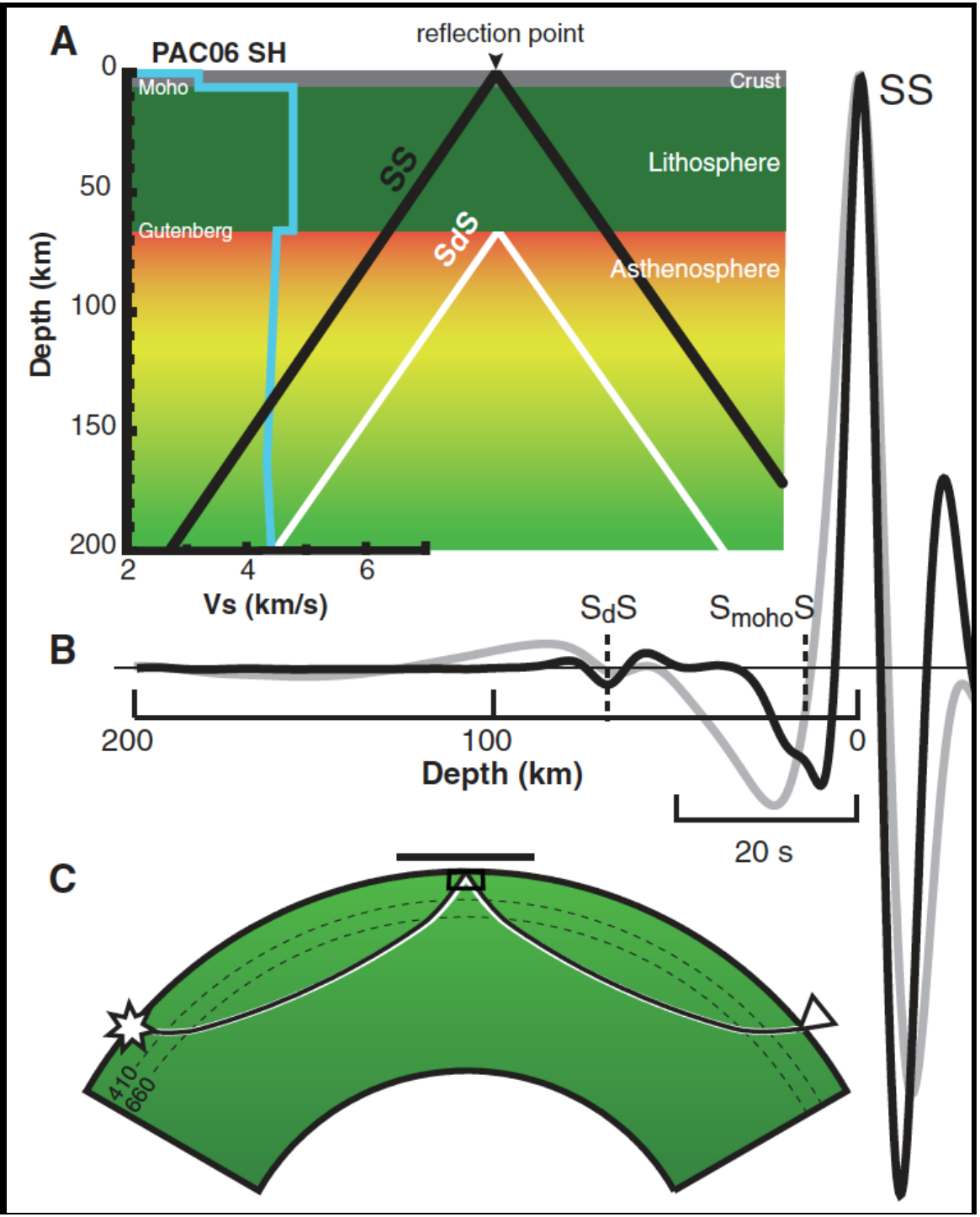
The relationship between three schematic geotherms and the pPv phase boundary (a), corresponding v_S profiles (b), and a sketch of possible lower-mantle structures (c). In (c), the pPv layer is shown in light grey, schematic flow directions are indicated by arrows, and several examples of warm, cold and hot mantle profiles are shown (dotted lines).

Hernlund et al. (2005)

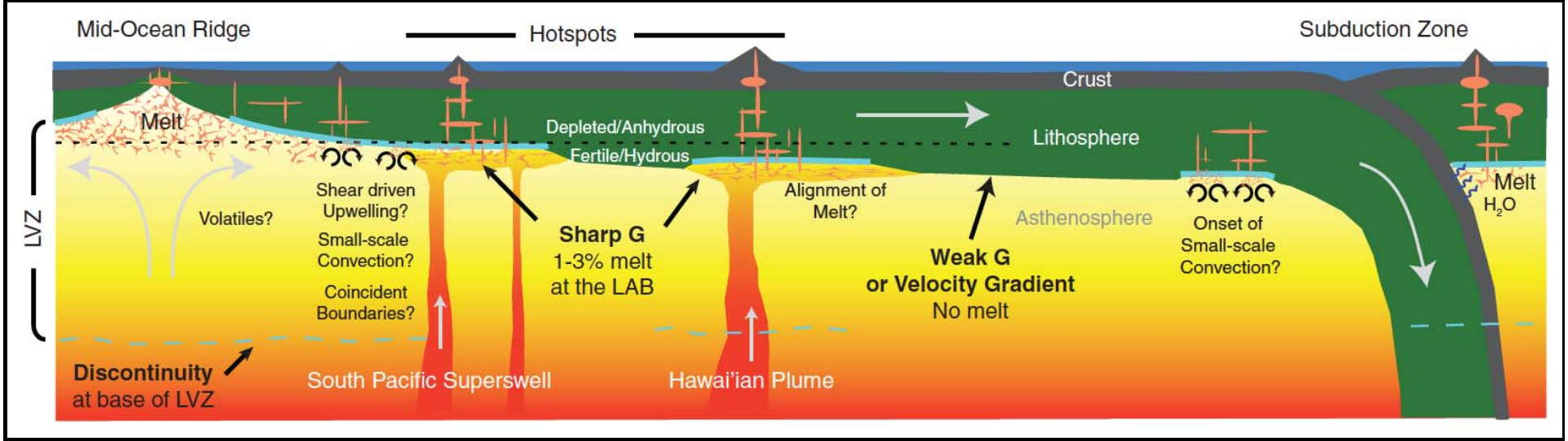
Detecting the Lithosphere-Asthenosphere Boundary (LAB)

The observed sudden drop in the seismic velocity around a depth of 50 to 100 km beneath the ocean is called the Gutenberg (G) discontinuity. Seismologists assert that G separates the high-velocity oceanic lid from the LVZ.

A small amount of melting, or water, or the size reduction of mineral grains can make mantle rocks weaker. Partial melting is most effective in producing a sharp and large velocity drop at the G discontinuity.
Schmerr (2012) uses stacked seismograms to find the SdS wave that reflects off the bottom of G. The G discontinuity occurs only intermittently beneath the Pacific.



Detecting the Lithosphere-Asthenosphere Boundary (LAB)



High-frequency SS precursors sampling below the Pacific plate intermittently detect the G as a sharp, negative velocity contrast at 40- to 75-kilometer depth. These observations lie near the depth of the LAB in regions associated with recent surface volcanism and mantle melt production and are consistent with an intermittent layer of asthenospheric partial melt residing at the lithospheric base. The G reflectivity can be regionally enhanced by dynamical processes that produce melt, including hot mantle upwellings, small-scale convection, and fluid release during subduction.

Schmerr (2012)

Future Work, Challenging Topics

Understanding the evolution of terrestrial planets from solar system and planetary formation and magma ocean and core formation.

More needs to be done to develop a physics-based theory of plate generation from mantle convection.

How does subduction initiate? When did plate tectonics start?

What is the significance of trench-parallel flow at subduction zones?

What is the nature of the lithosphere-asthenosphere boundary?

Where is there melting in the middle and deep mantle?

How do volatiles circulate through the mantle?

How does the post-perovskite phase transition affect convection in the lower mantle?

What are the long-lived "piles" at the bottom of the mantle?

Thanks to Dave Bercovici for helpful discussions and many of the slides used here.