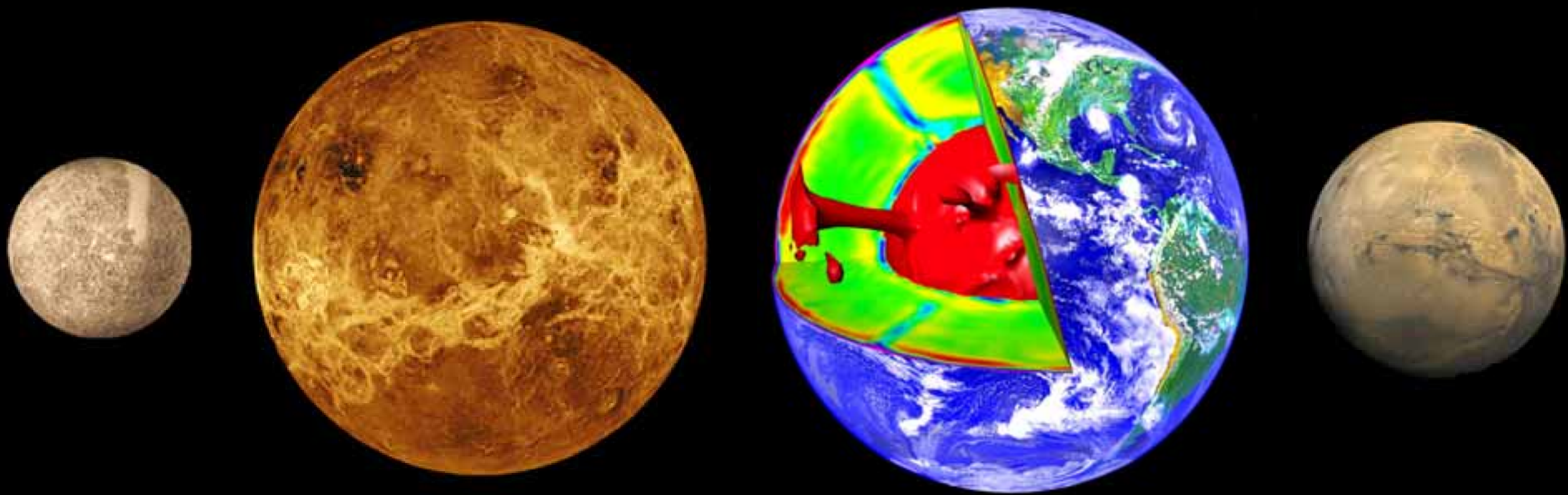
Modeling the interior dynamics of terrestrial planets

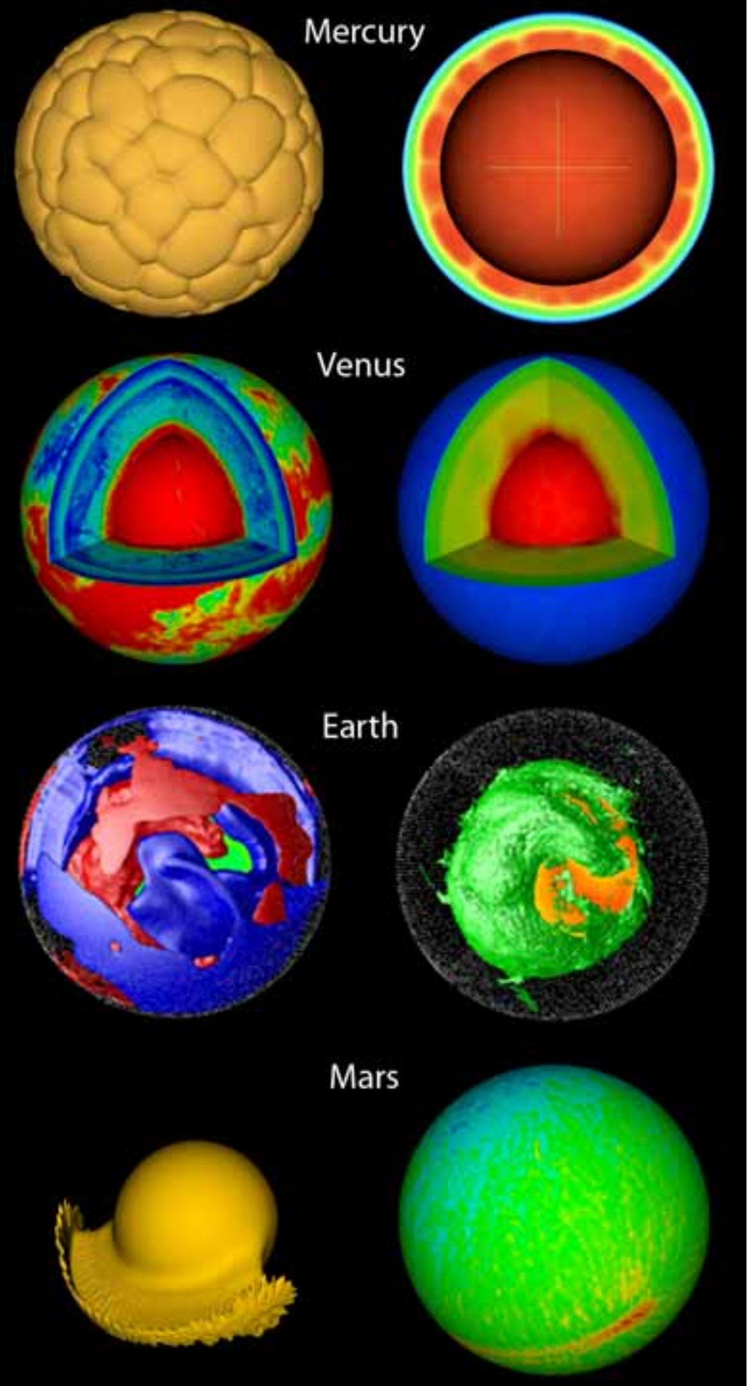
Paul J. Tackley, ETH Zürich

Fabio Crameri, Tobias Keller, Marina Armann, Hein van Heck, Tobias Rolf

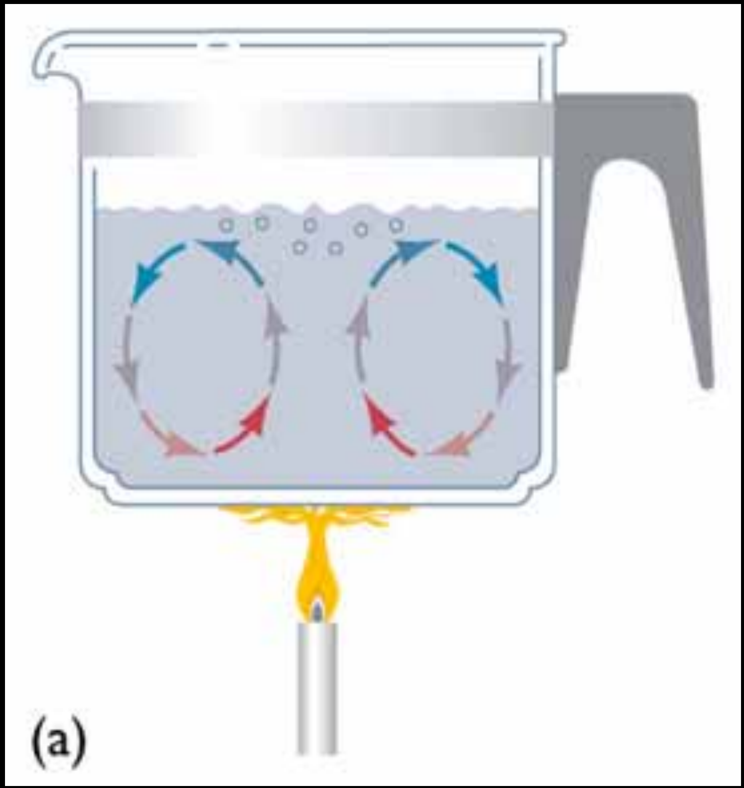


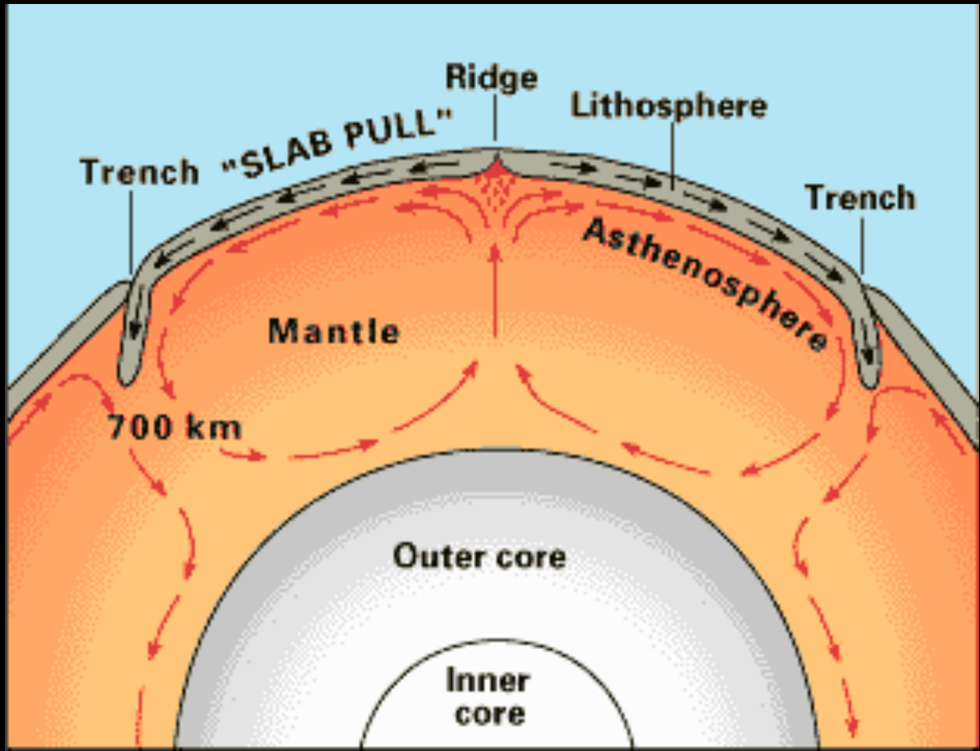
Talk Plan

- Introduction
- Tectonic modes: plates, episodic lids, rigid lids, importance of free surface
- Detailed models of Mars, Venus, and thoughts about other planets



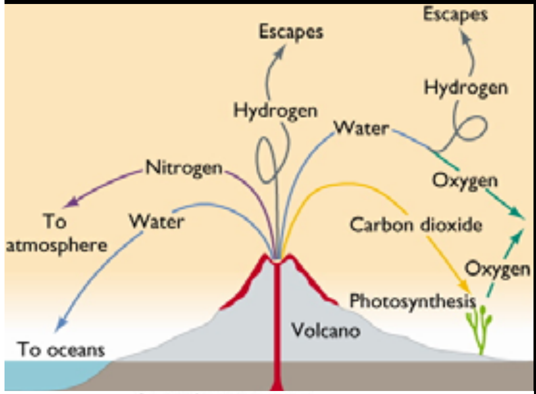
Convection is the key process
Here focus on the solid mantle

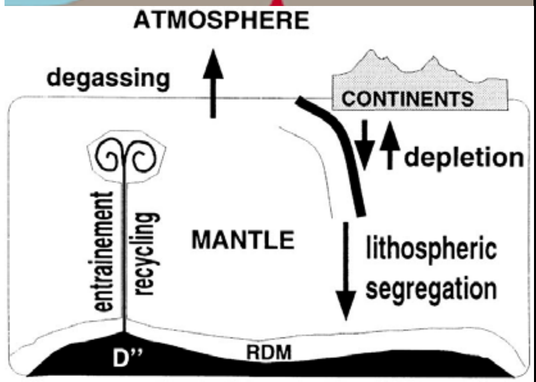


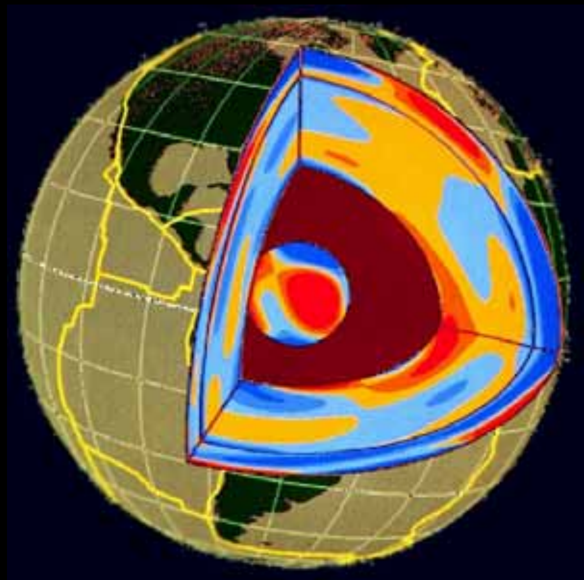


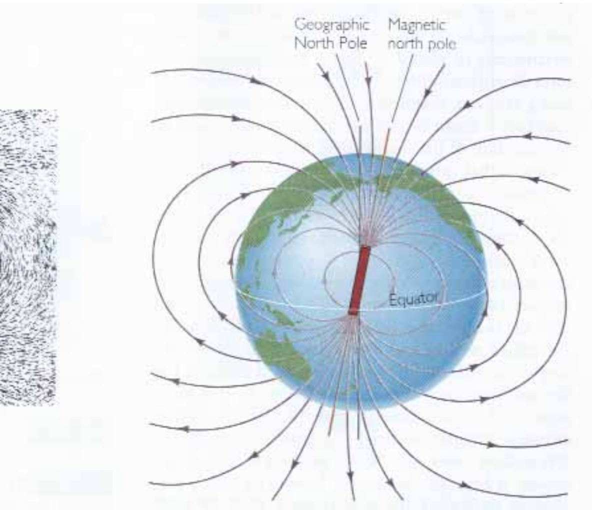
- Heat sources: radioactive heating, planetary cooling
- Earth's oceanic plates are part of this convection

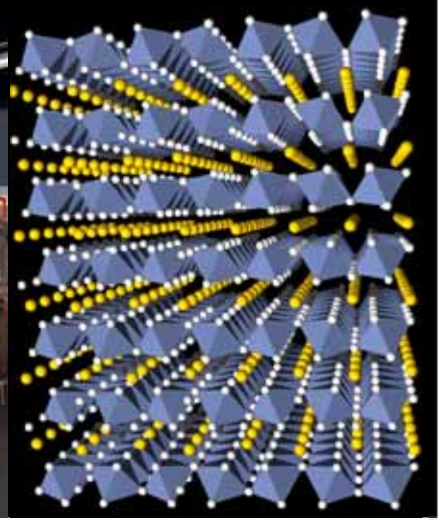
Interdisciplinary approach to Earth&planetary dynamics











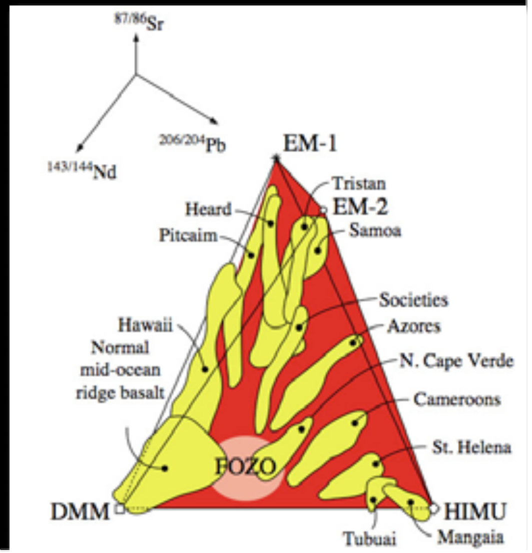
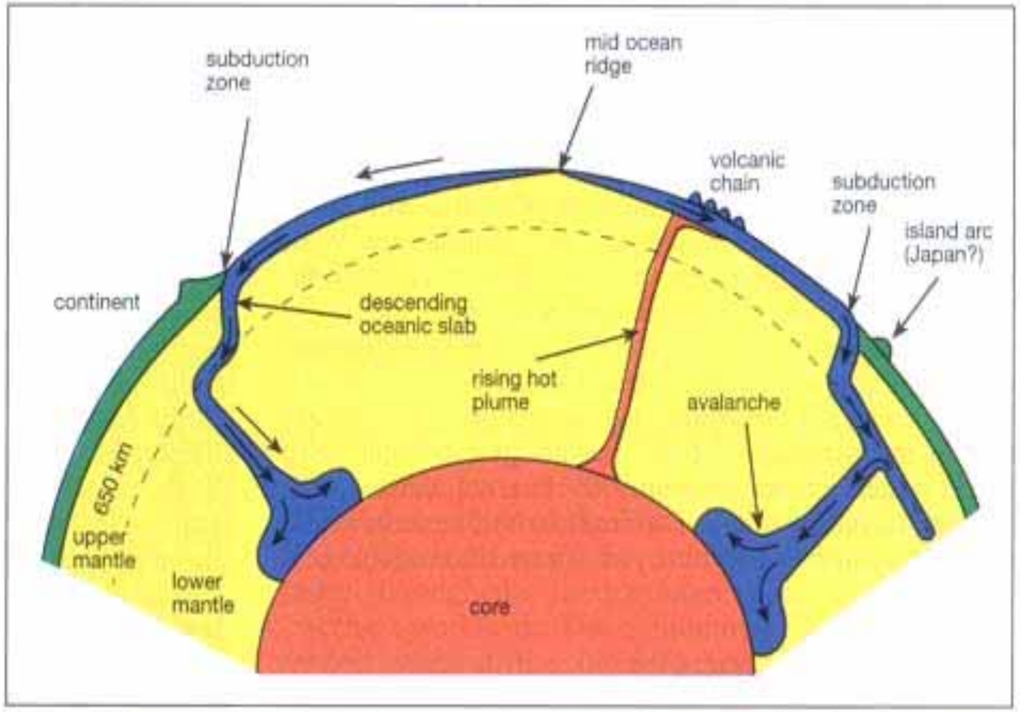


Figure 16 Three-dimensional projection of $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$, $^{206}Pb/^{204}Pb$ isotope arrays of a large

Dynamical lengthscales

Global

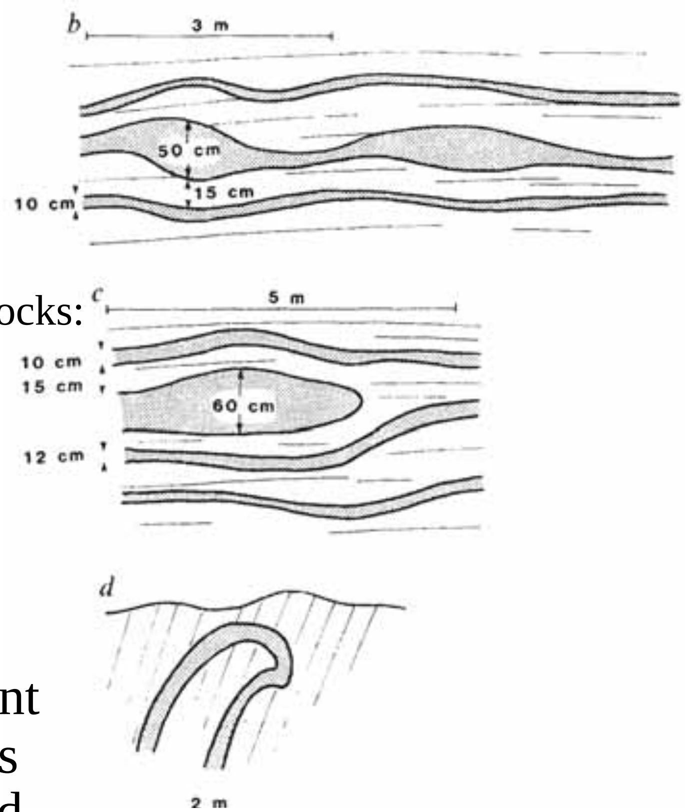


1 Schematic diagram showing the processes that occur in the mantle. The lithosphere – the outermost layer of the Earth – is made up of tectonic plates that move relative to one another. Where two plates converge, the heavy oceanic plates (blue) sink into the mantle in a process known as subduction, which cools the mantle below. Continental plates (green), which are lighter, do not subduct – at the boundaries between these plates earthquakes and volcanoes occur, and mountain ranges are formed. Hot material rises from the base of the mantle in the form of "plumes", causing volcanoes to form.

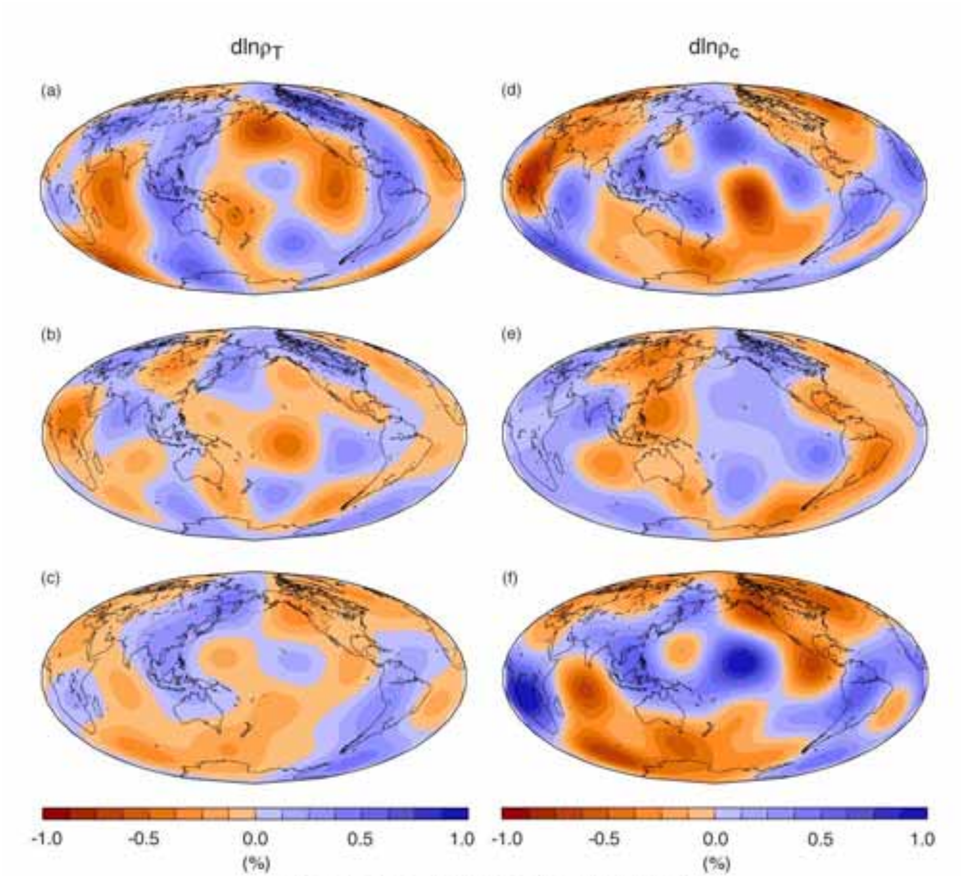
'Human' scale

Compositional lengthscales

Outcrops of mantle rocks: ~cm

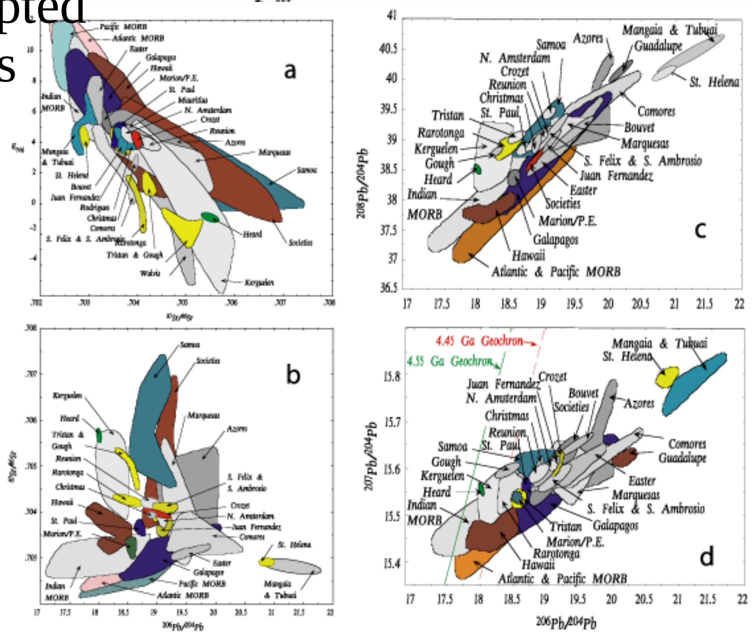


Global (mantle interior)



Deschamps, Trampert, Tackley (2005)

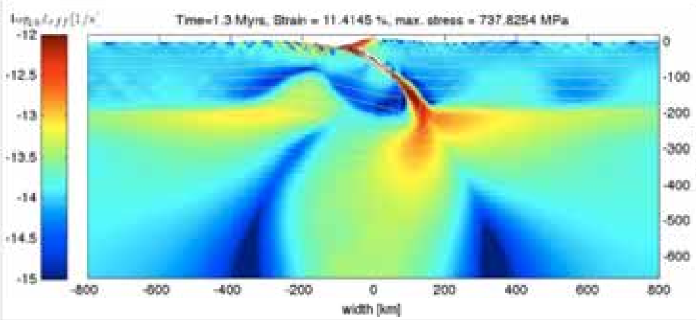
Trace element variations in erupted basalts

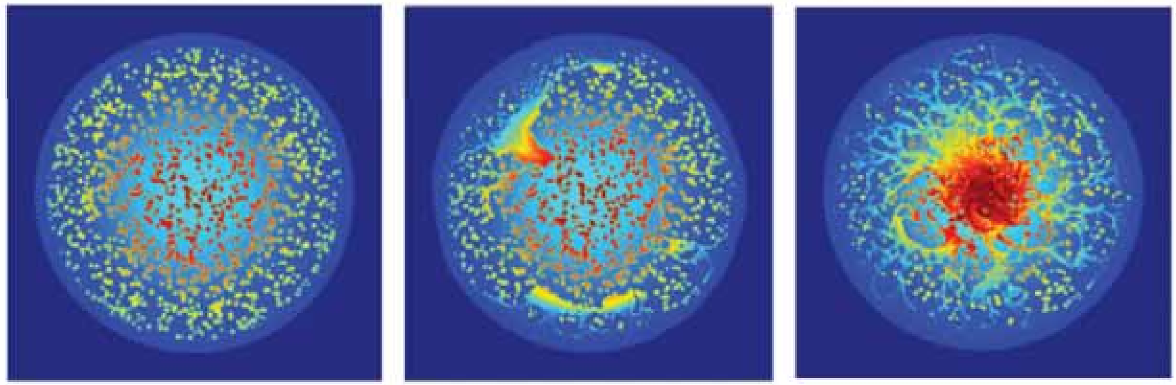


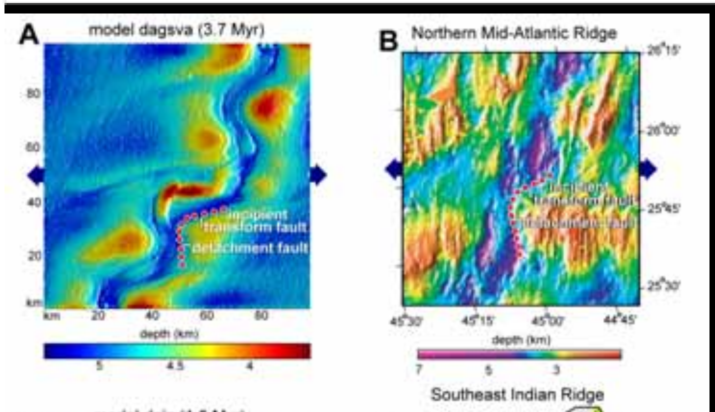
Challenges

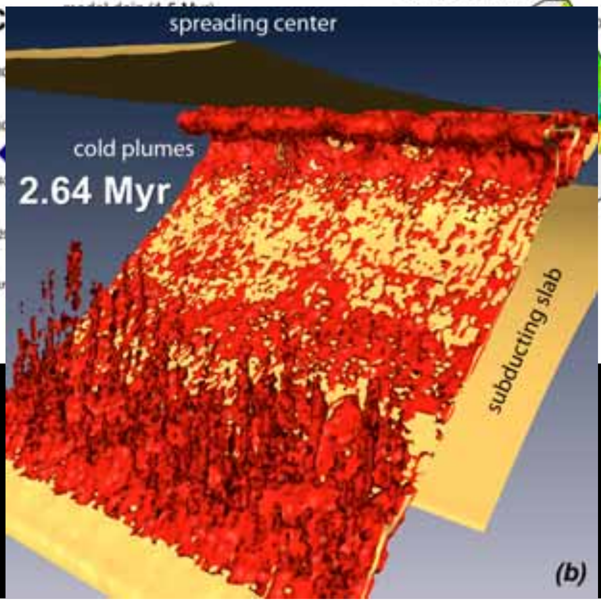
- Rheology
  - Large temperature-dependence (~40+ orders of magnitude)
  - Nonlinear
  - Brittle failure & plasticity
  - Elasticity
- Multi-scale problem
  - Length: mm to 1000s km
  - Time: seconds to billions of years
- Resolution: no limit to what is needed!

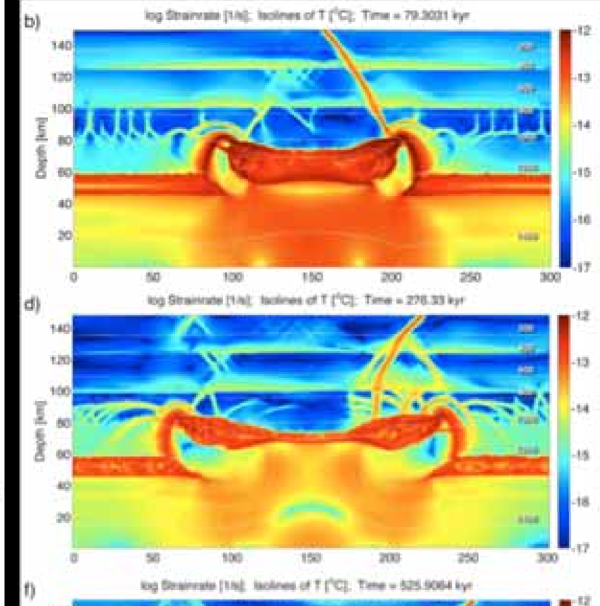
Group activities

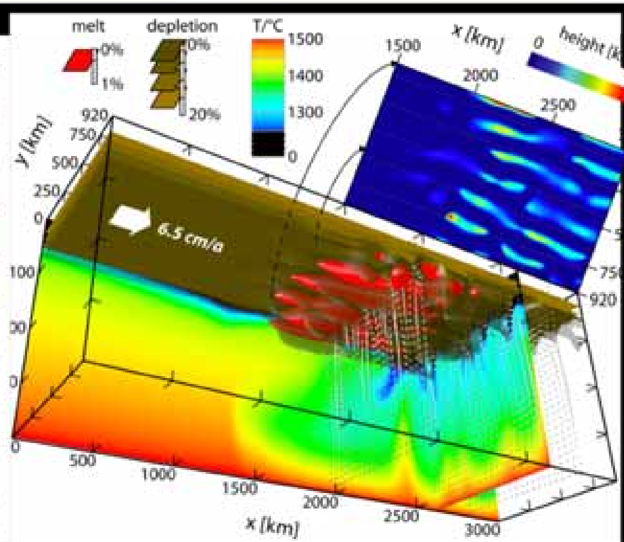


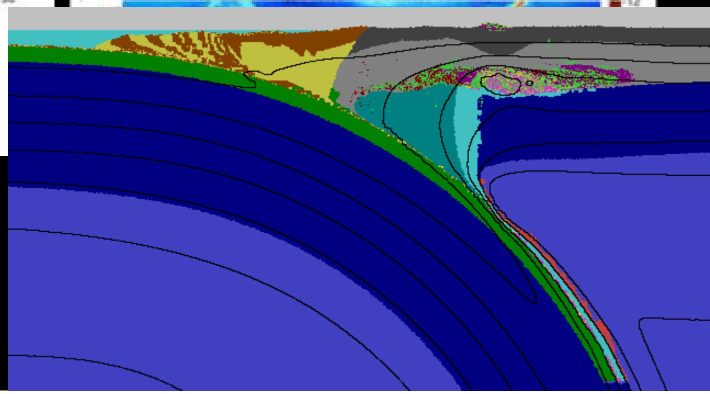


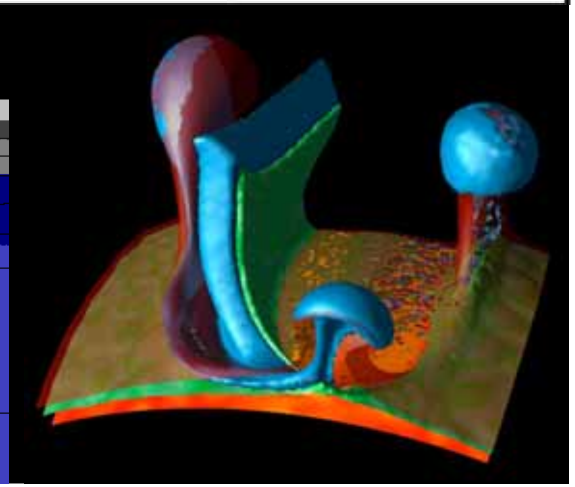






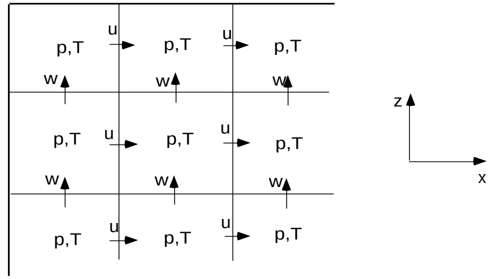


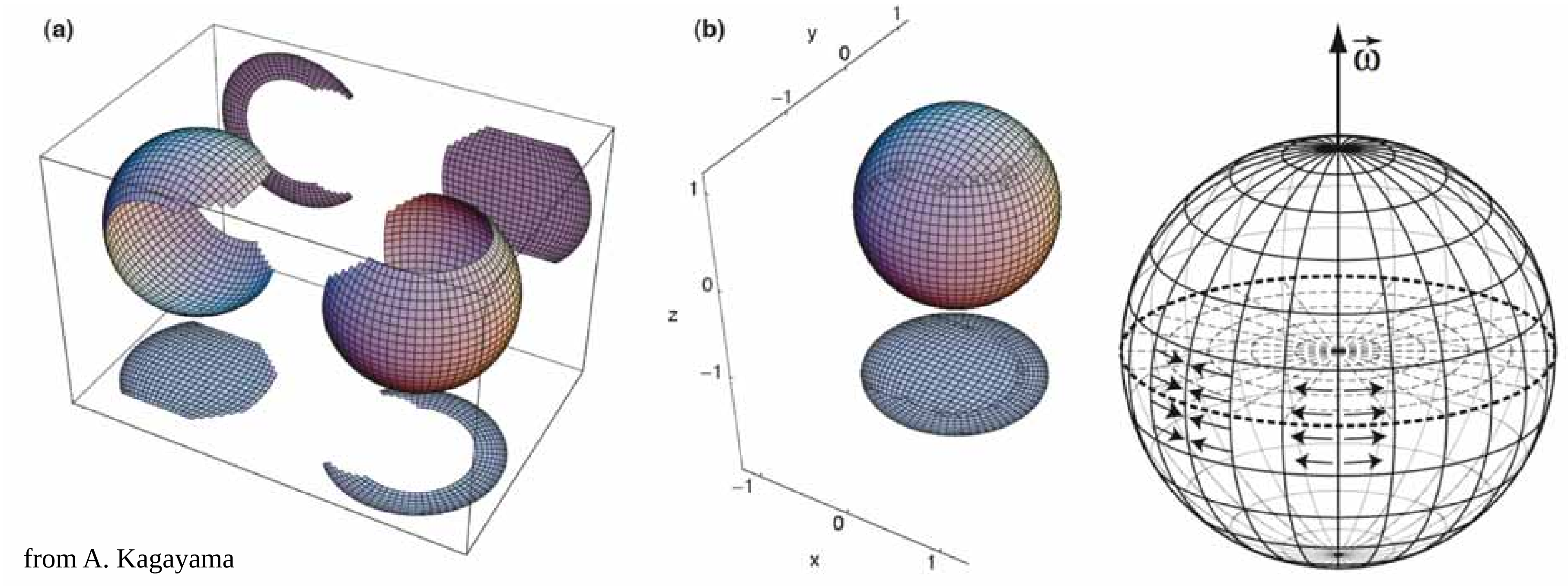


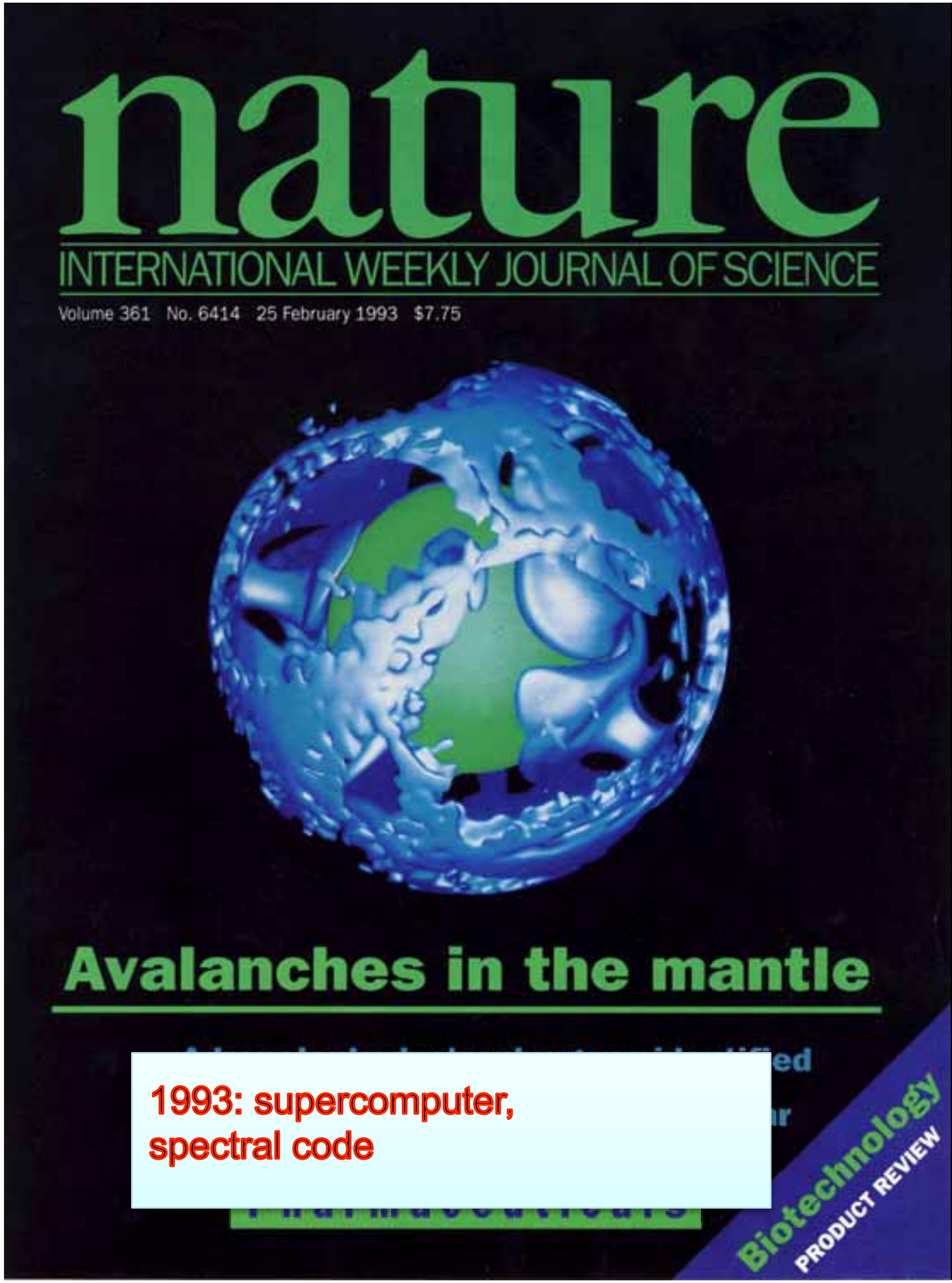


Numerical Method

- StagYY: 3D spherical finite volume multigrid solver using the yin-yang grid (Tackley, PEPI 2008) or 2D spherical annulus (Hernlund and Tackley, PEPI 2008)
- Tracers track composition ("particle in cell")
- MPI parallelized (up to 4096 cores)
- Robust to large viscosity variations: can use "laboratory" rheology

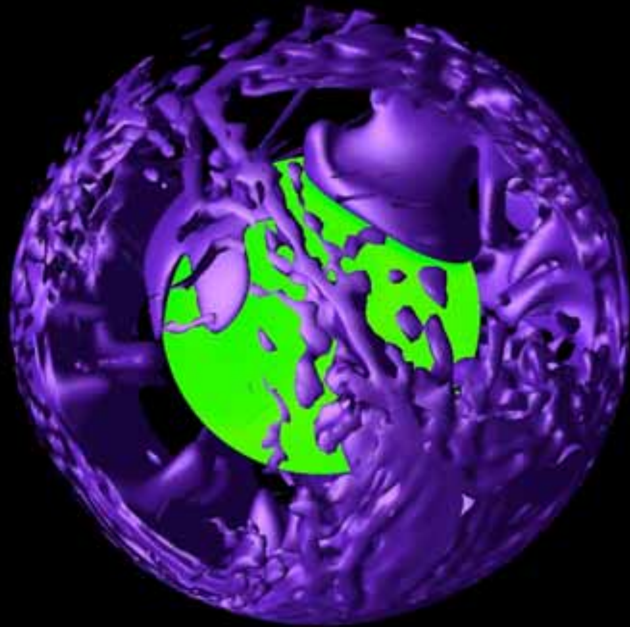






1993: supercomputer,
spectral code

15 years of progress



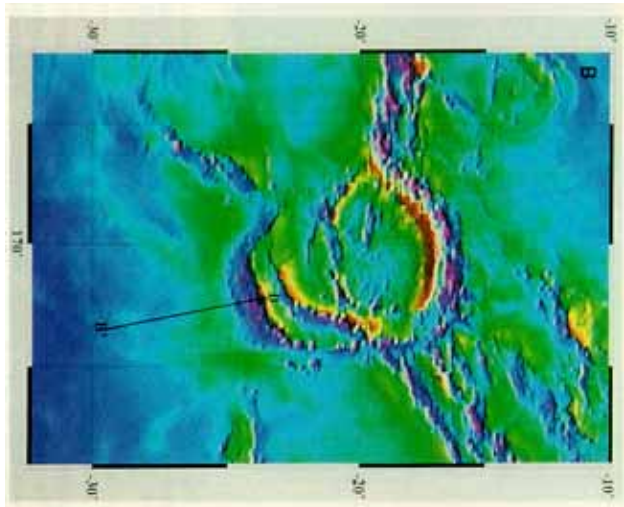
2008: laptop,
multigrid code

Plate tectonics: Earth unusual ?

- Mars: stagnant lid
  - Had plate tectonics early?
  - Subduction explains Tharsis region? (An Yin’s hypothesis)
- Venus: stagnant lid
  - Plate tectonics->rigid lid?
  - Episodic overturn?

Venus: Episodic or transition behavior?

- Main reason: uniform surface age of ~600 million years => global resurfacing
  - Subduction-like features?
- Possible mechanisms
  - Episodic plate tectonics
  - Cessation of plate tectonics
  - Single lithosphere overturn event
  - Random resurfacing
  - Something completely different (e.g., widespread volcanism from some internal instability)



Early Earth had different type of plate tectonics?

- Reasons:
  - Oceanic crust too thick=> slab buoyant
  - Inherent scaling of plate-mantle dynamics
- Some possibilities:
  - Sub-crustal subduction
  - Distributed plate boundaries
  - No plate tectonics (rigid lid)

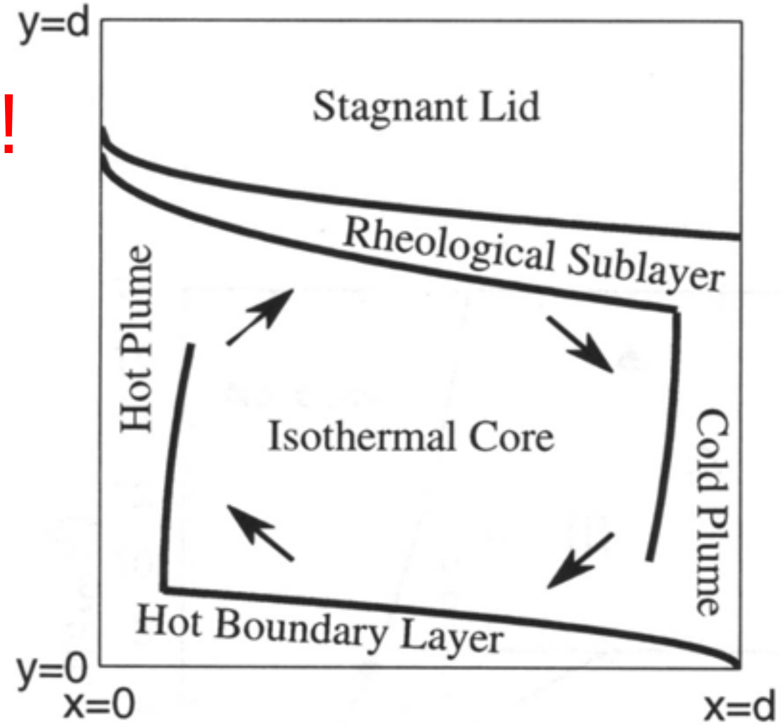
We don’t understand plate tectonics at a fundamental level

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

Simplest case: T-dependent viscosity

- 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
- =>**$1.3x10^{48}$** variation
- => RIGID/STAGNANT LID!

Only small $_{\Delta}$T participates in convection: enough to give Dh factor ~10



Strength of rocks

- Increases with confining pressure (depth) then saturates

Low T: Effect of P

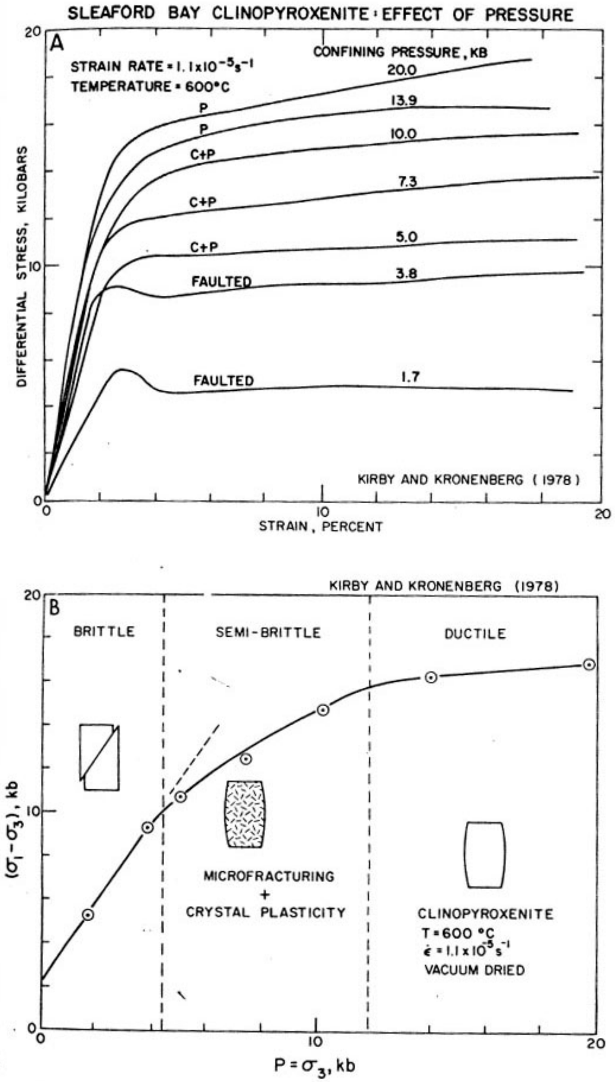
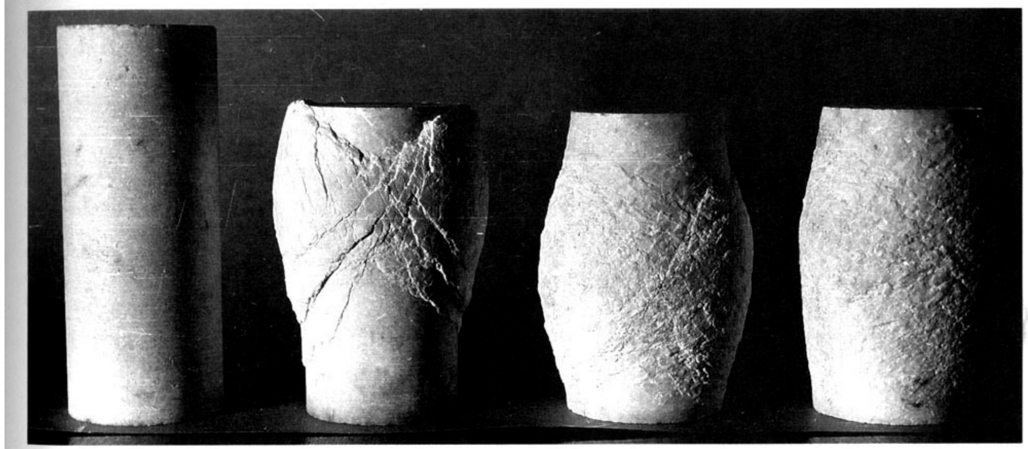


Fig. 6. Effect of confining pressure on the strength of Sleaford Bay clinopyroxenite tested in triaxial compression (S. H. Kirby and A. K. Kronenberg, unpublished data, 1978): (*a*) stress-strain curves, (*b*) ultimate strength or stress at 10% strain as a function of confining pressure.

Low-T deformation: Effect of P

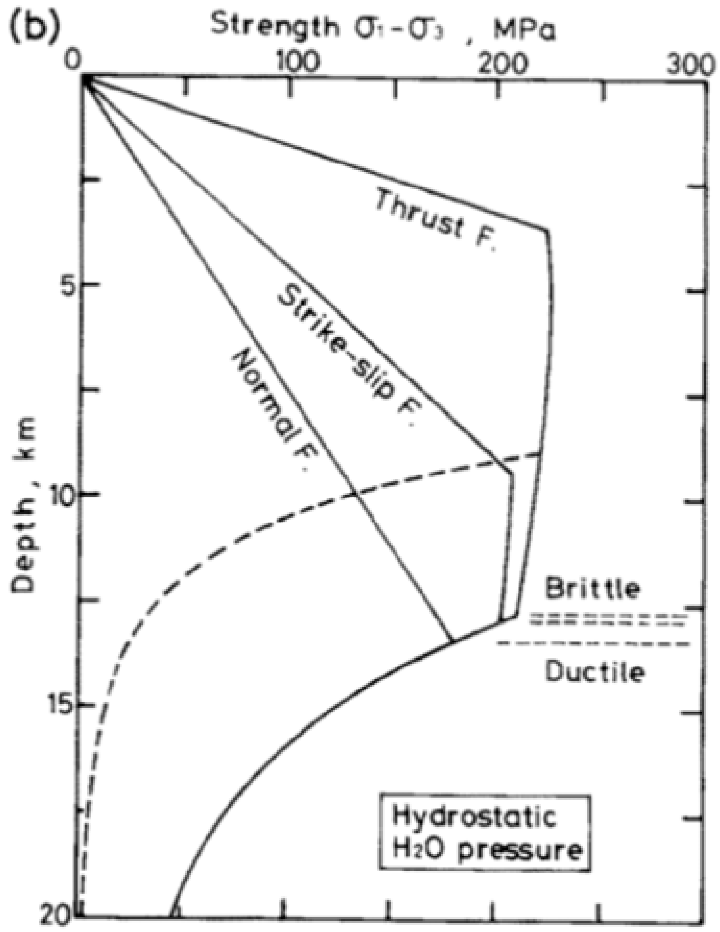


Undeformed | Low confining pressure | Intermediate confining pressure | High confining pressure

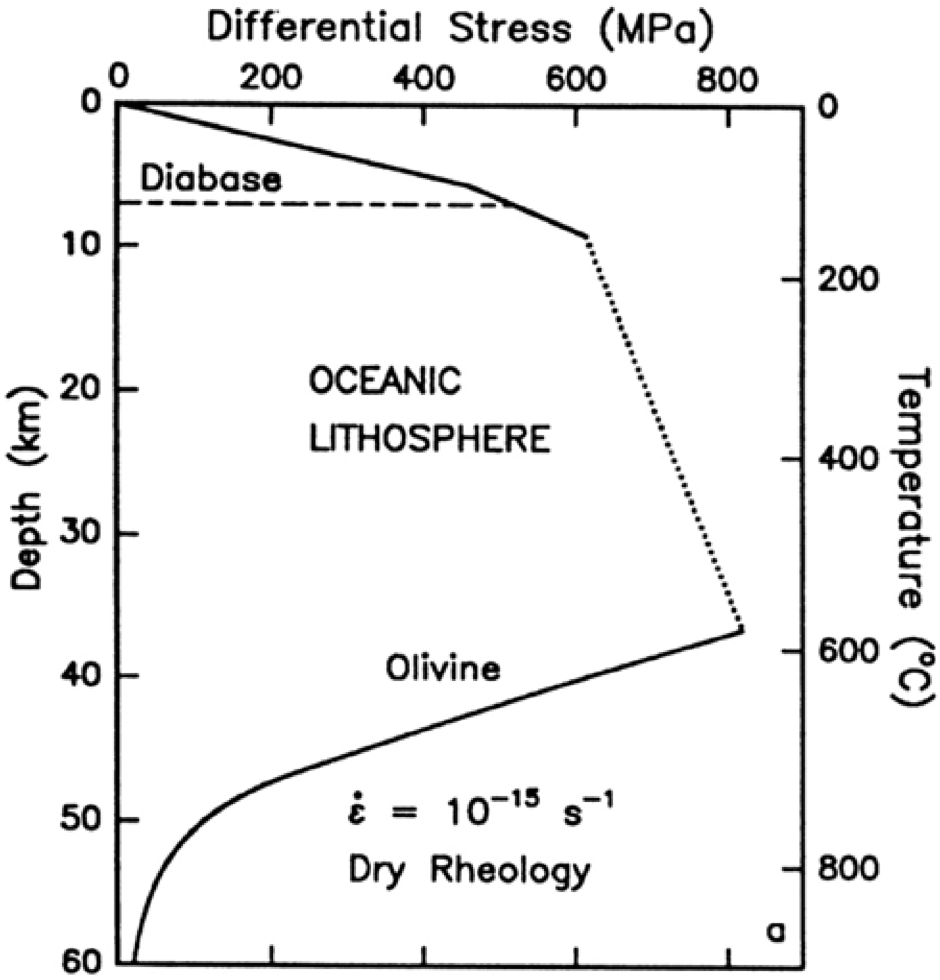
FIGURE 15.6
A marble cylinder deformed in the laboratory by applying thousands of pounds of load from above. Each sample was deformed in an environment

Strength profile of lithosphere

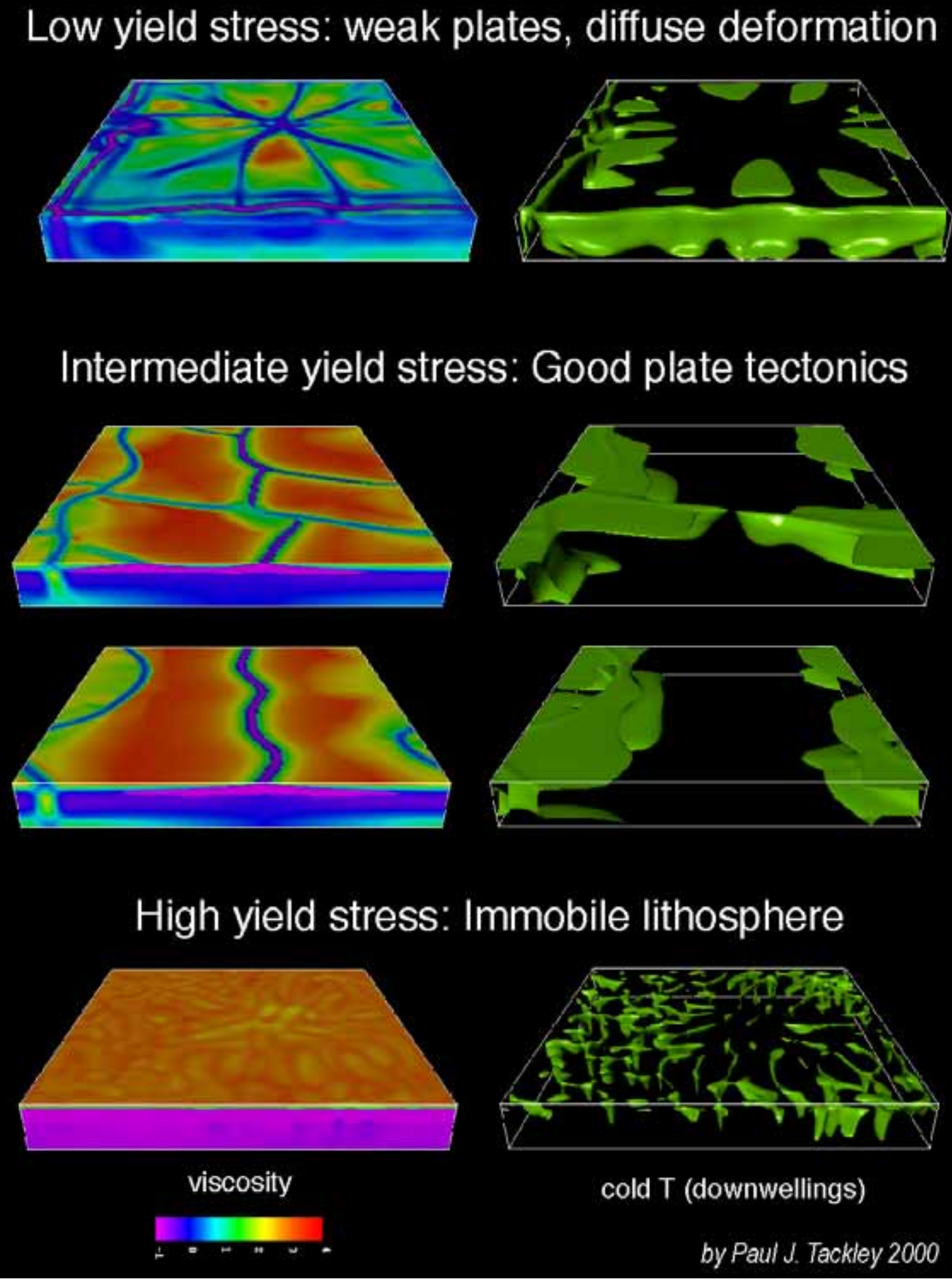
Continental (granite): Shimada 1993



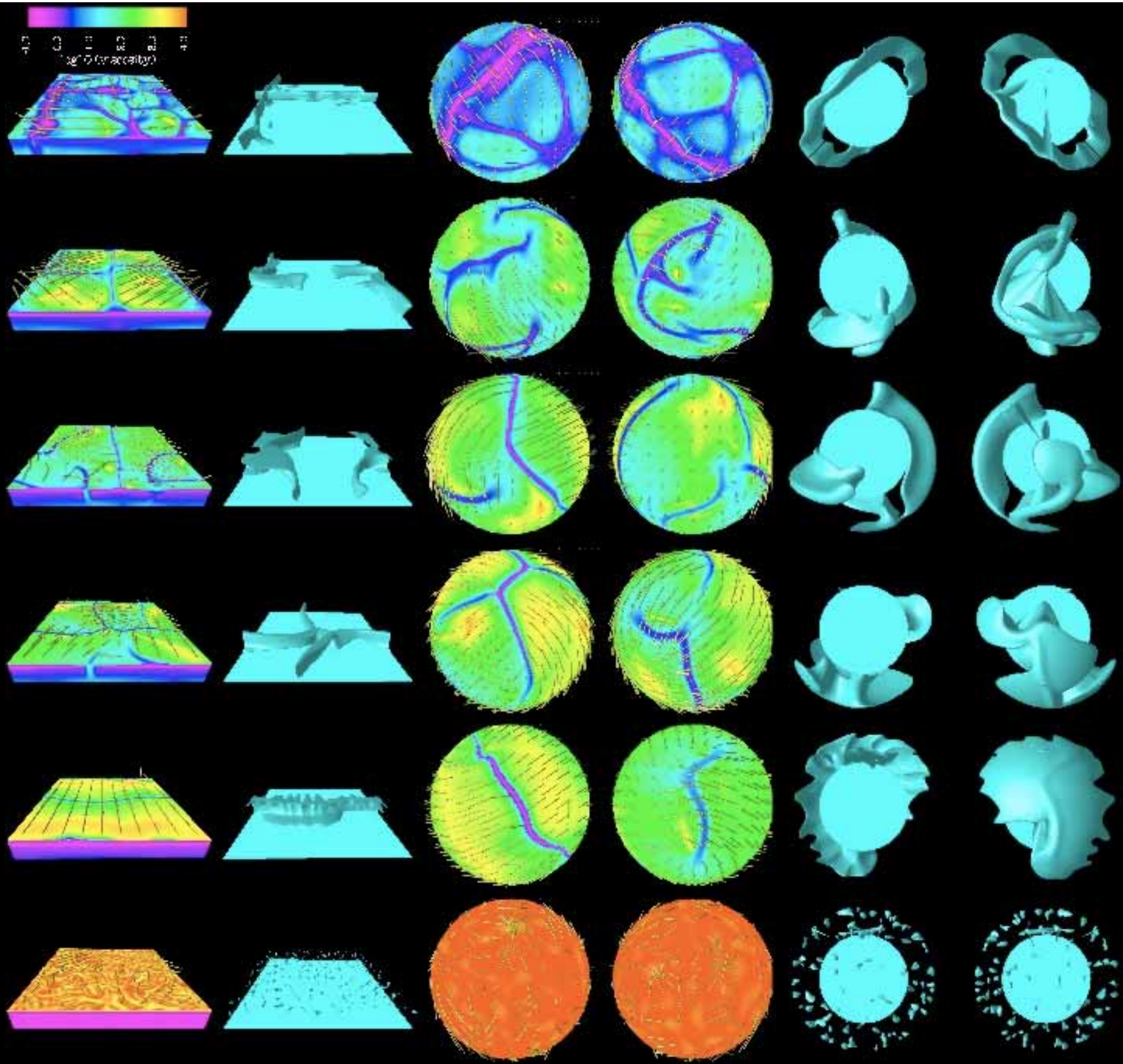
Oceanic: Kohlstedt 1995

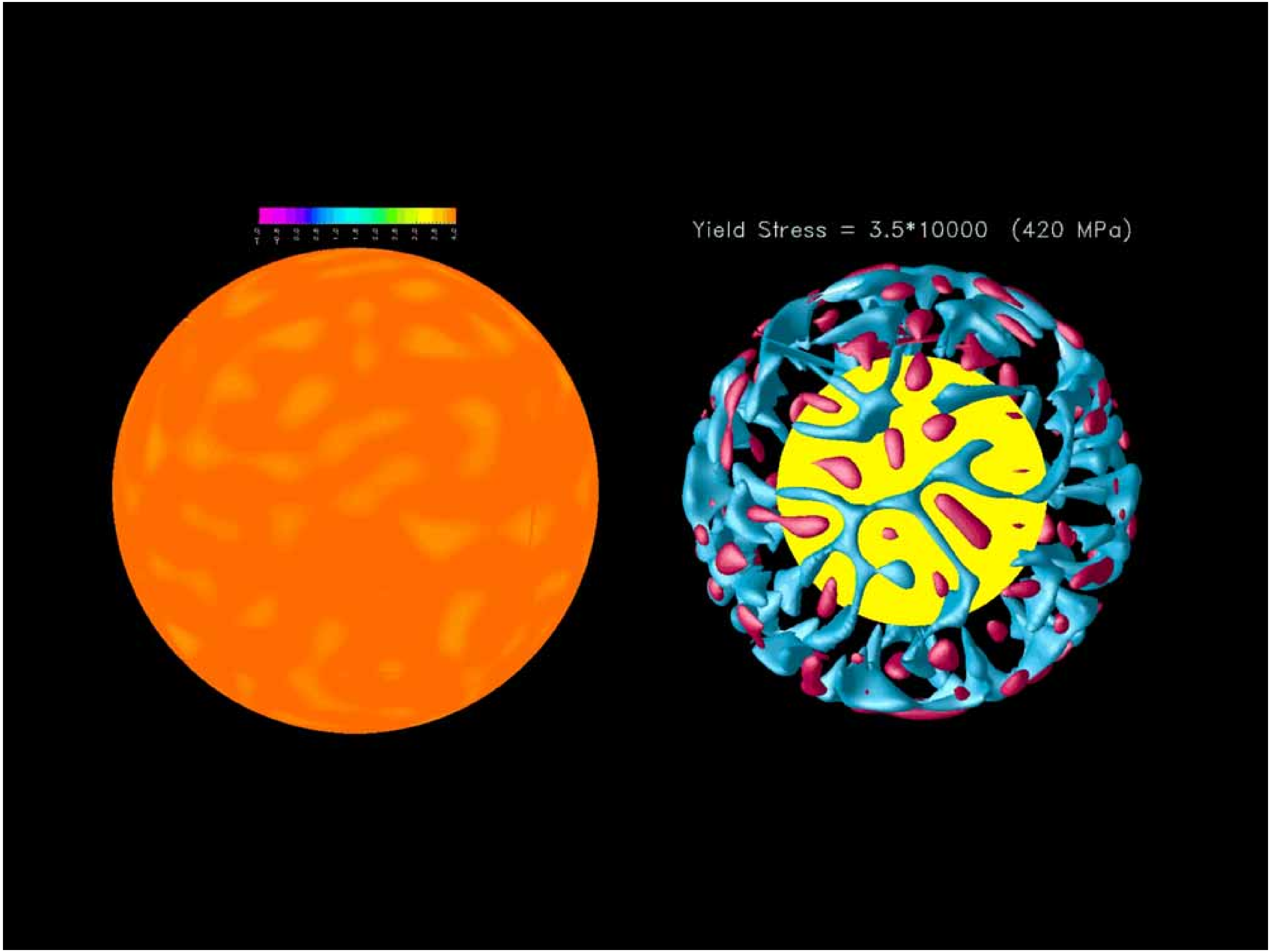


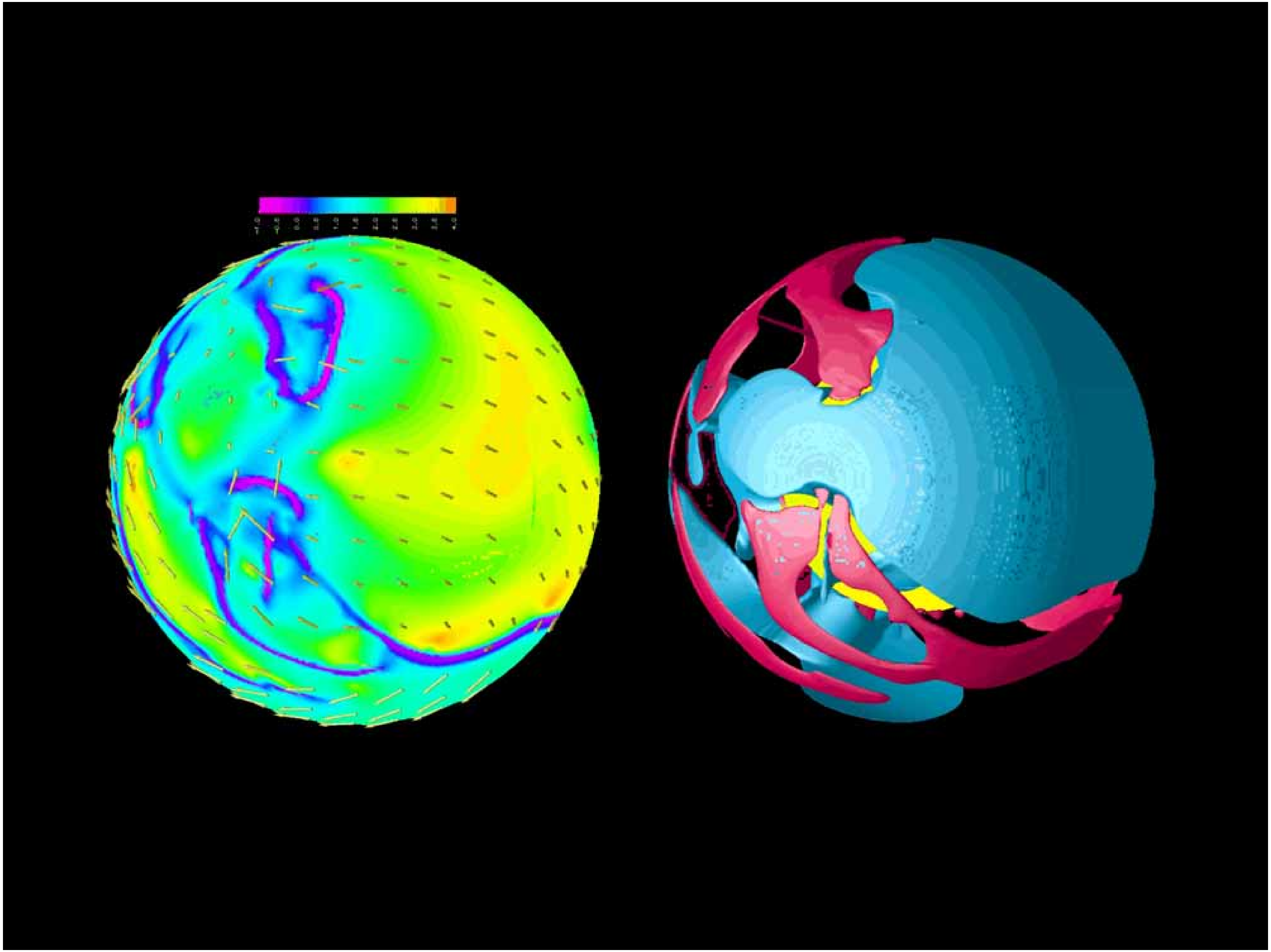
- Varying yield strength, including asthenosph.

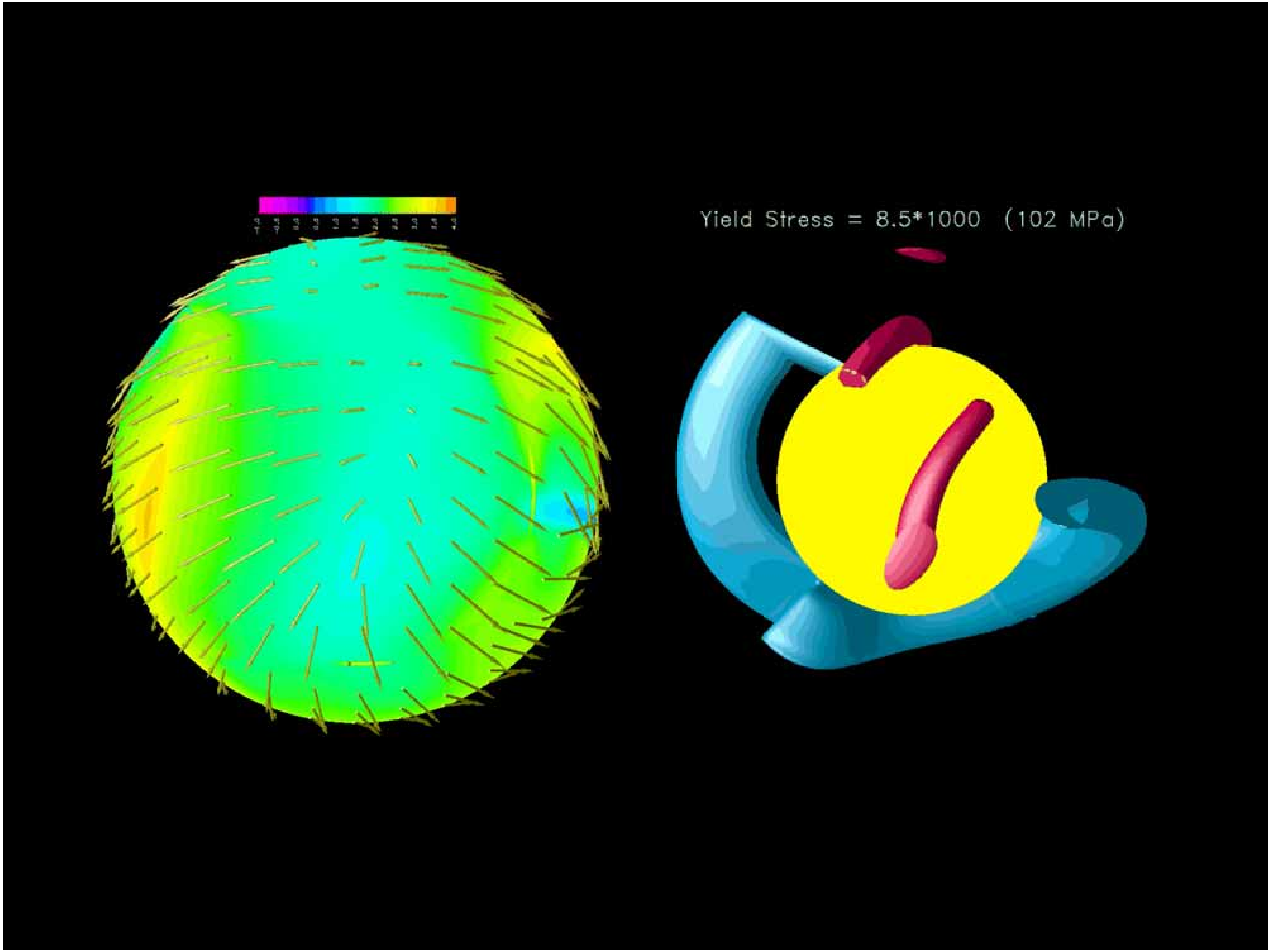


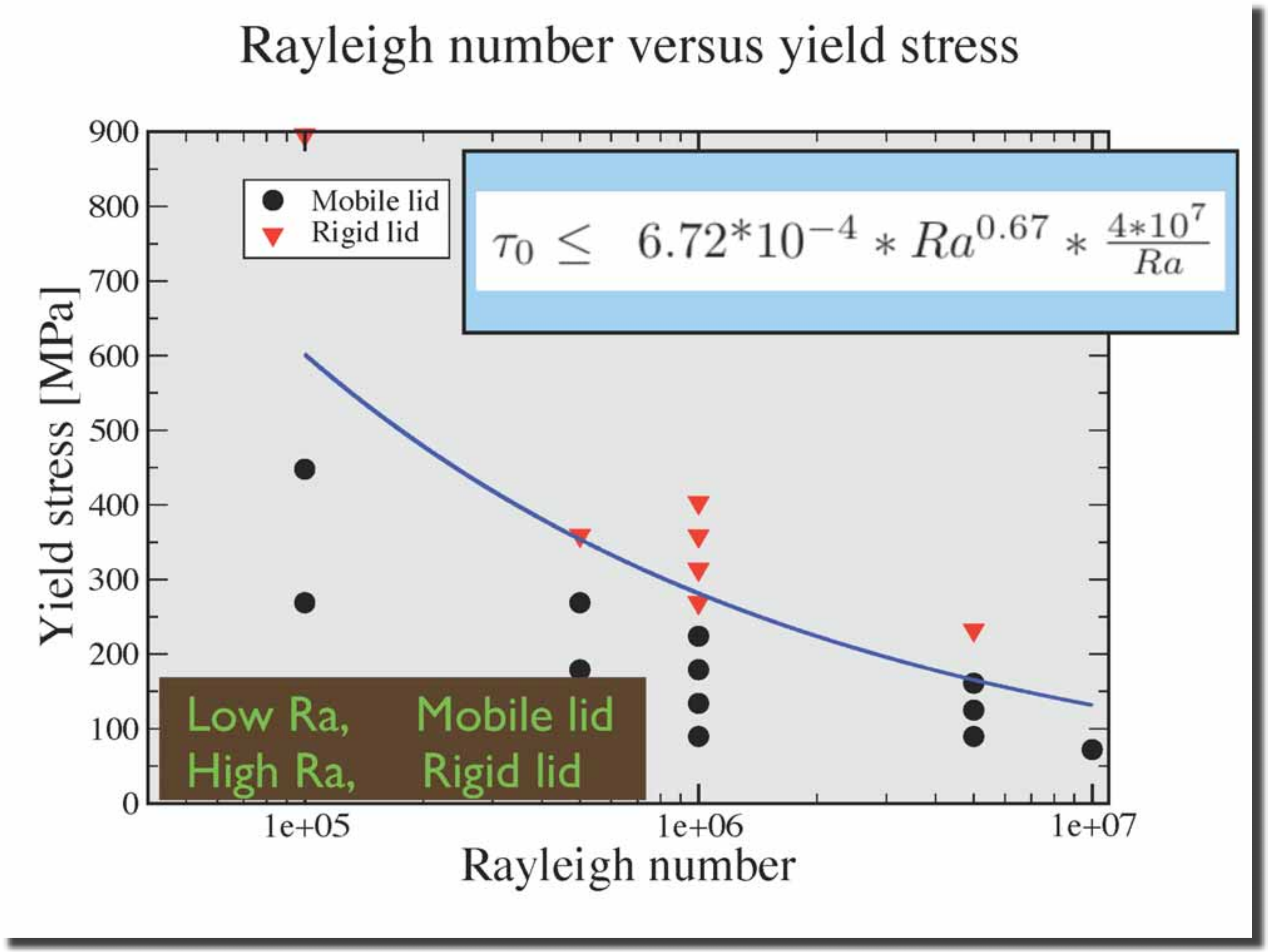
Spherical:
van Heck
& me,
GRL 2008




Yield Stress = 3.5*10000 (420 MPa)



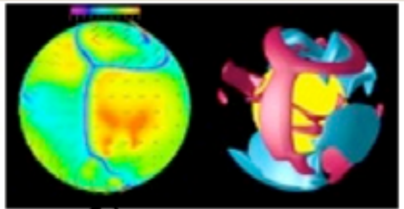

Yield Stress = 8.5*1000 (102 MPa)



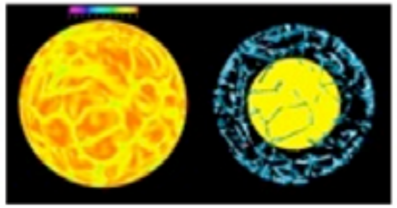
Rayleigh number versus yield stress
Mobile lid
Rigid lid
$\tau_0 \leq 6.72*10^{-4} * Ra^{0.67} * \frac{4*10^7}{Ra}$
Yield stress [MPa]
0
100
200
300
400
500
600
700
800
900
1e+05
1e+06
1e+07
Rayleigh number
Low Ra, Mobile lid
High Ra, Rigid lid

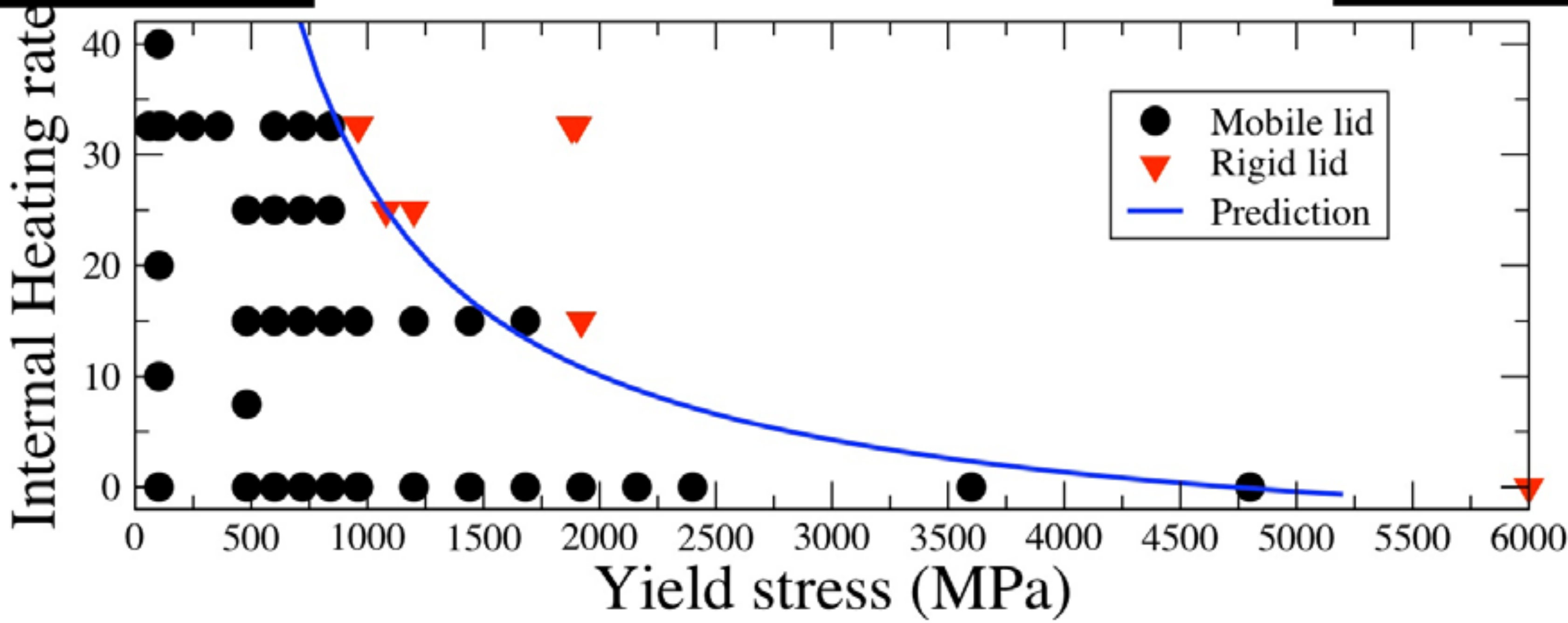
Internal heating rate

Strength of the lithosphere vs convective stresses



Yield stress versus internal heating rate



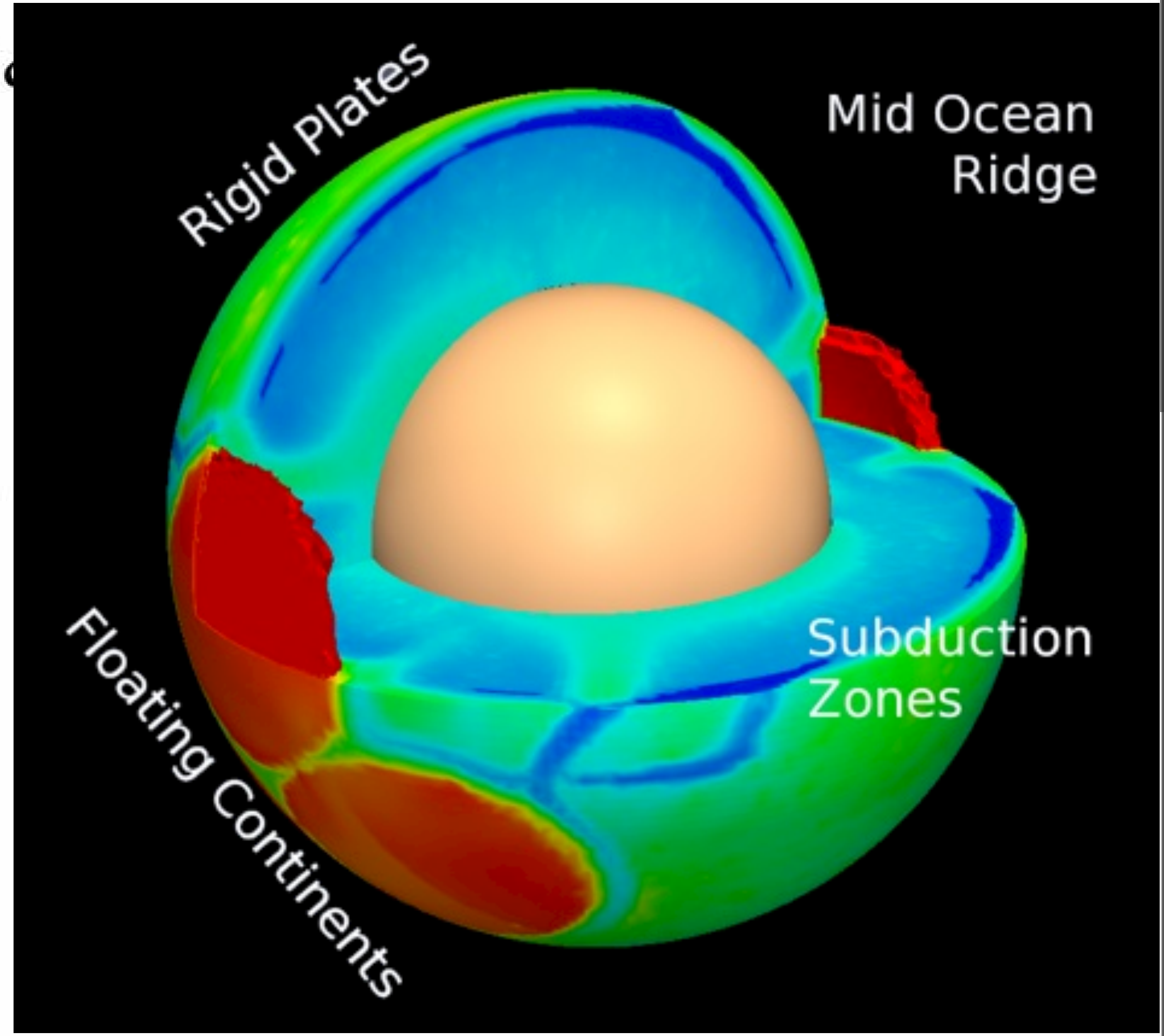


Implications for terrestrial planet evolution

- Plate tectonics favoured at
  - higher mantle viscosity (lower Ra)
  - Lower internal heating
- Transitions stagnant->episodic->plates as Earth cooled?

Influence of continents on self-consistent plate tectonics?

Tobias Rolf

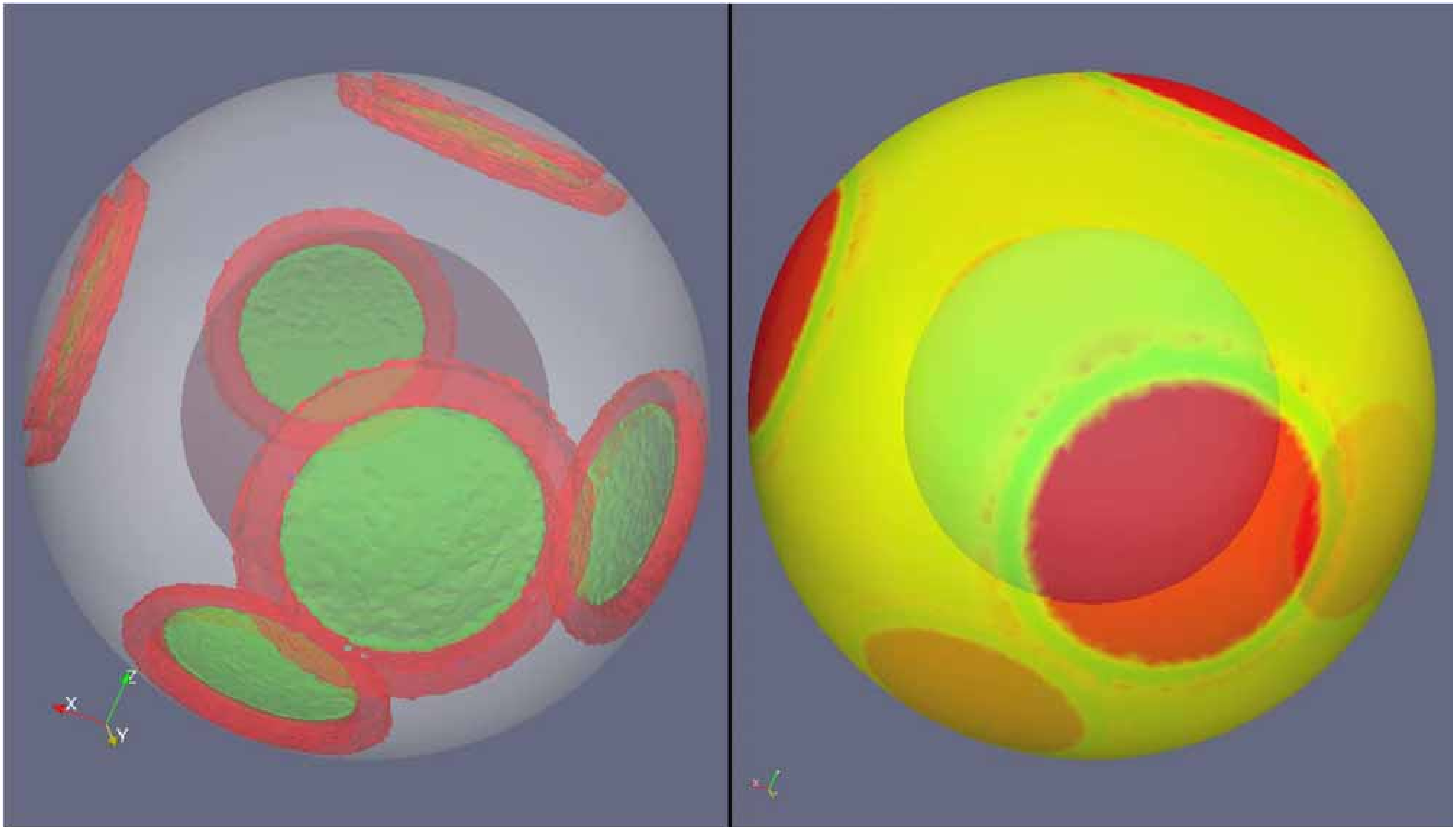


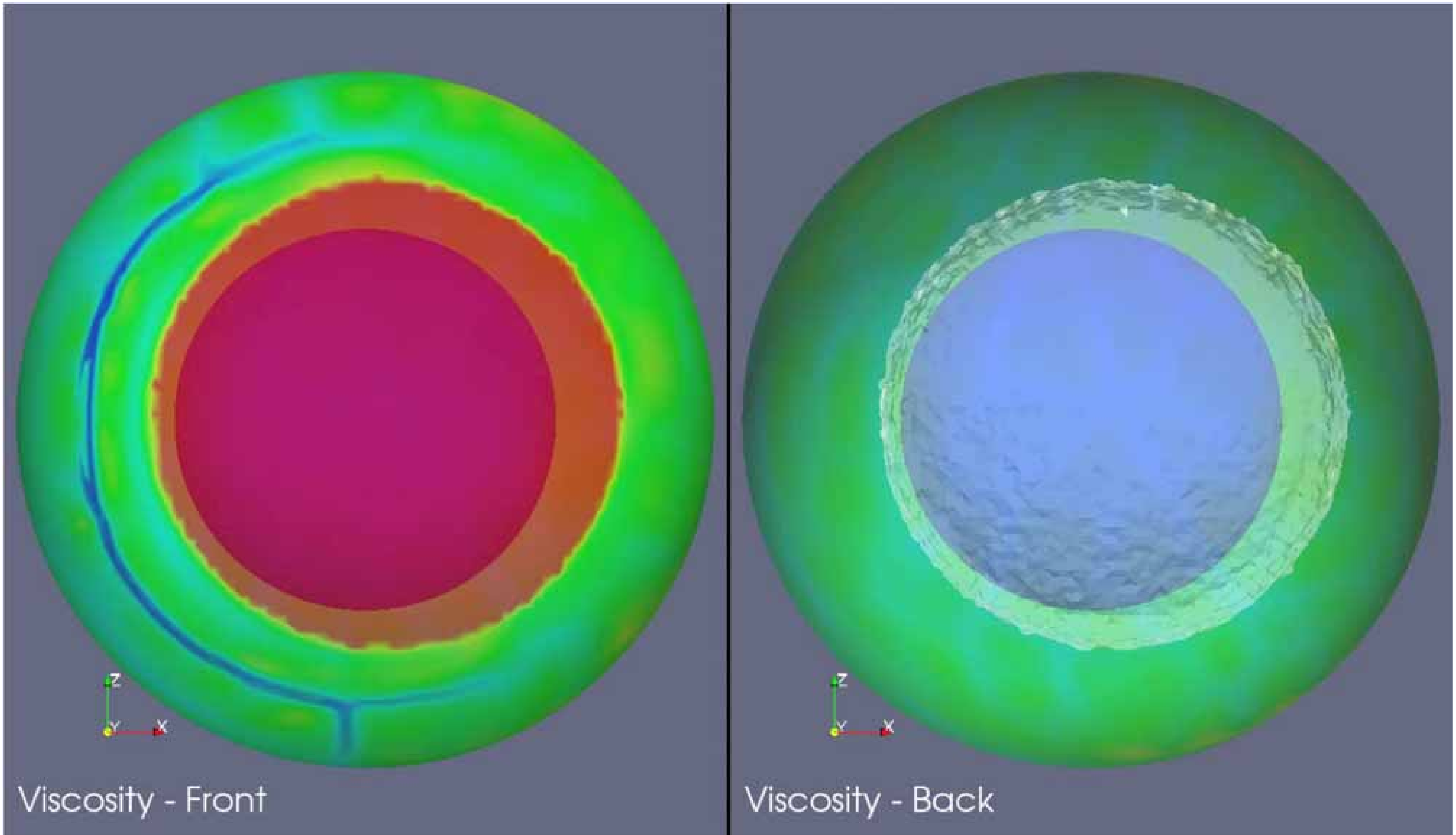
CRYSTAL2PLATE

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

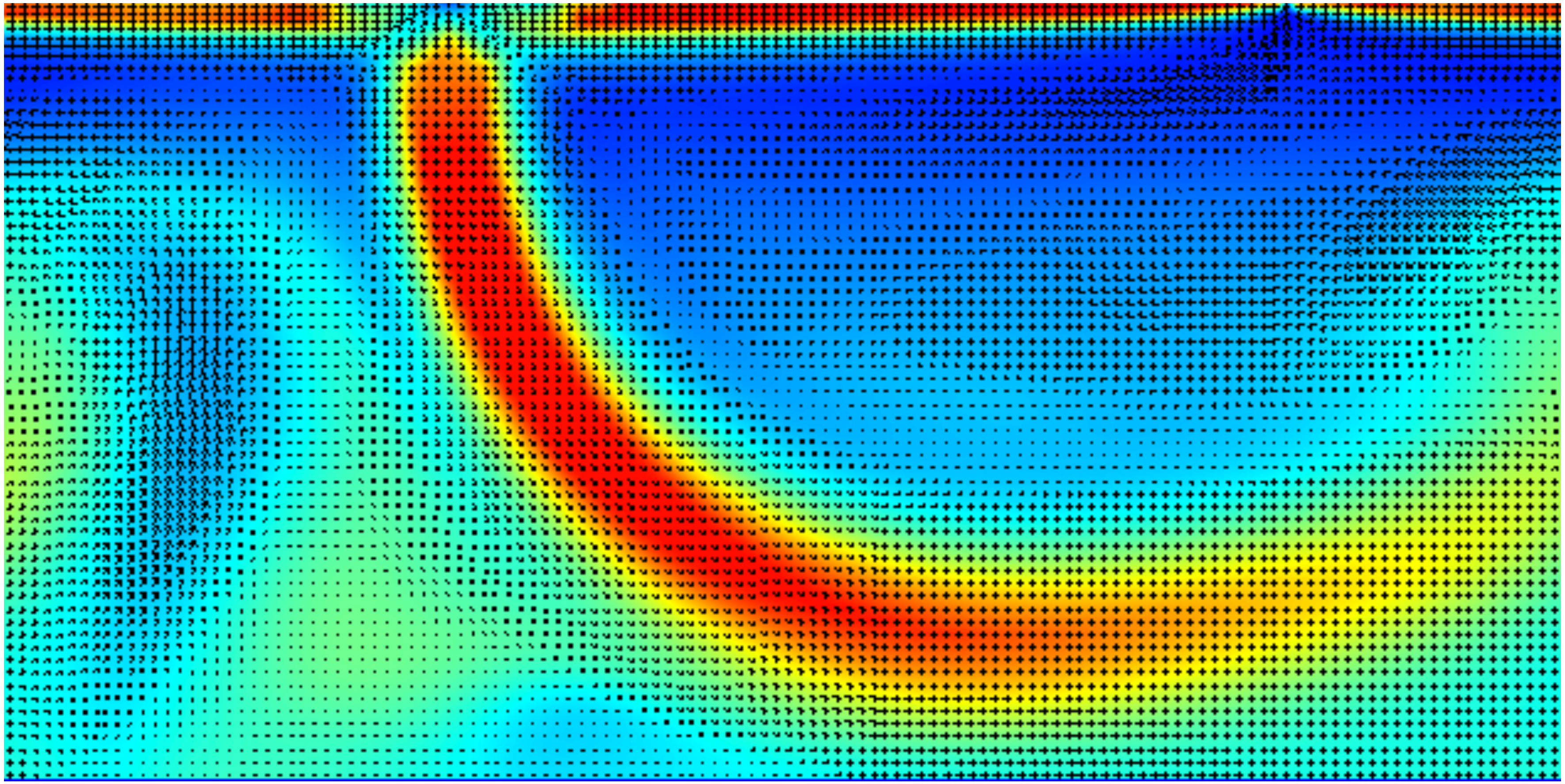
SEVENTH FRAMEWORK PROGRAMME

MARIE CURIE ACTIONS


X
Z
Y


Viscosity - Front
Viscosity - Back
Z
Y
X
Z
Y
X

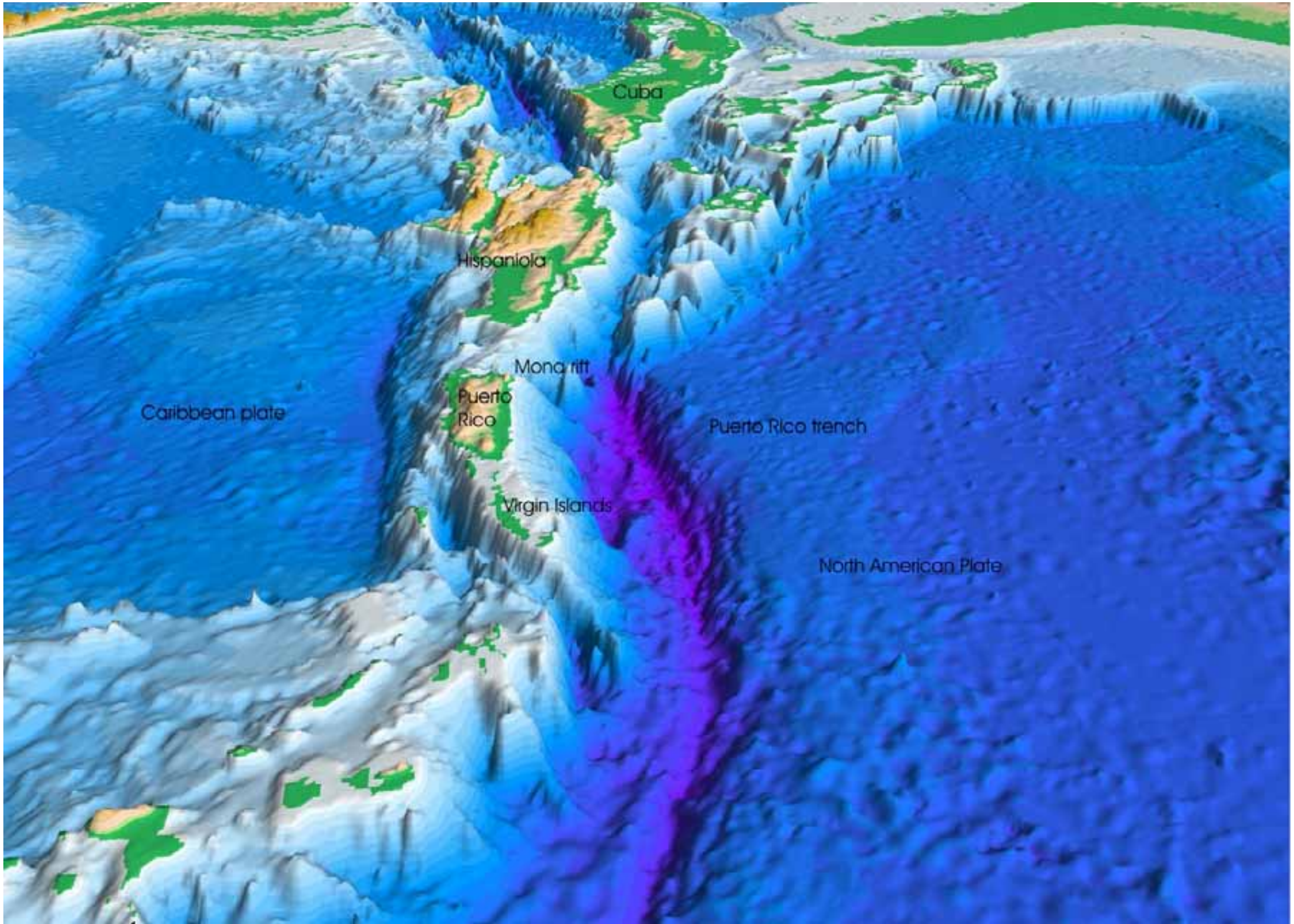
The problem with all these models: 2-sided subduction!



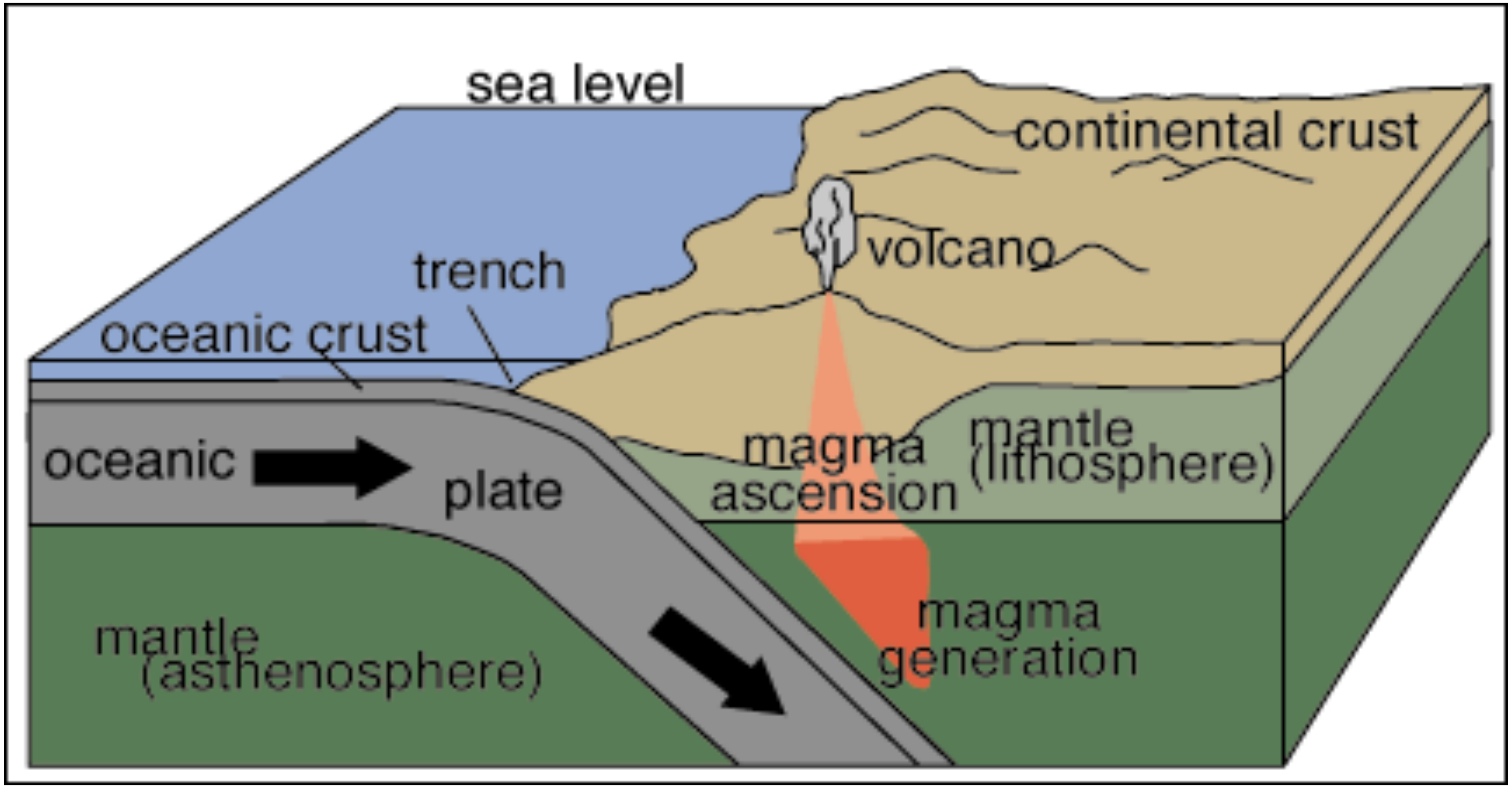
Mantle convection codes assume a free-slip upper boundary: surface is FLAT

- Zero shear stress but finite normal stress, proportional to what the topography would be if allowed.
- But this may create unnatural geometries at subduction zones….

Real subduction zone: NOT FLAT



Trench due to bending



Numerical models with a free surface: also get a trench

Physics of the Earth and Planetary Interiors 171 (2008) 198–223

A benchmark comparison of spontaneous subduction models—Towards a free surface

H. Schmeling[a,*], A.Y. Babeyko[a,b], A. Enns[a], C. Faccenna[c], F. Funiciello[c], T. Gerya[d], G.J. Golabek[a,d], S. Grigull[a,e], B.J.P. Kaus[d,g], G. Morra[c,d], S.M. Schmalholz[f], J. van Hunen[h]

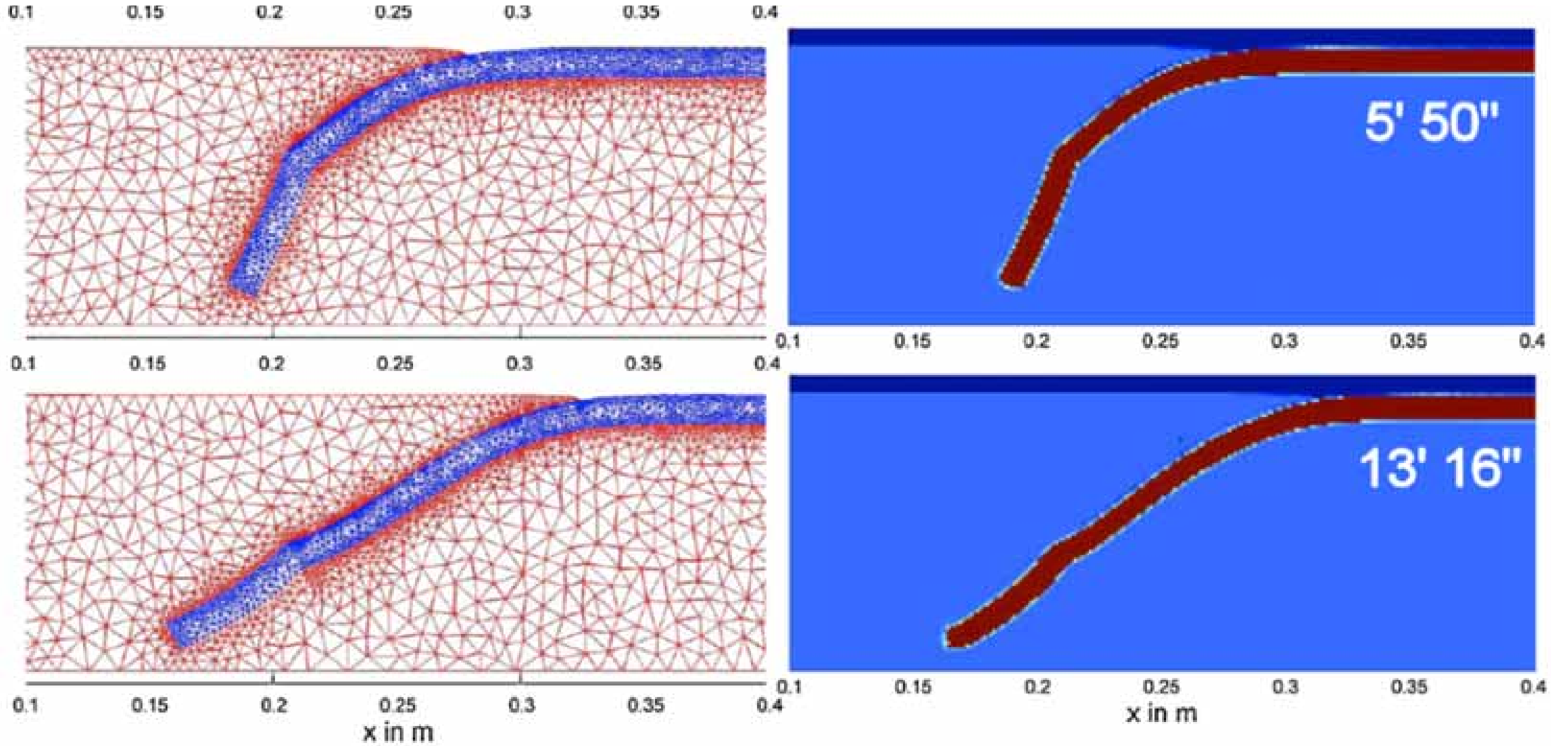
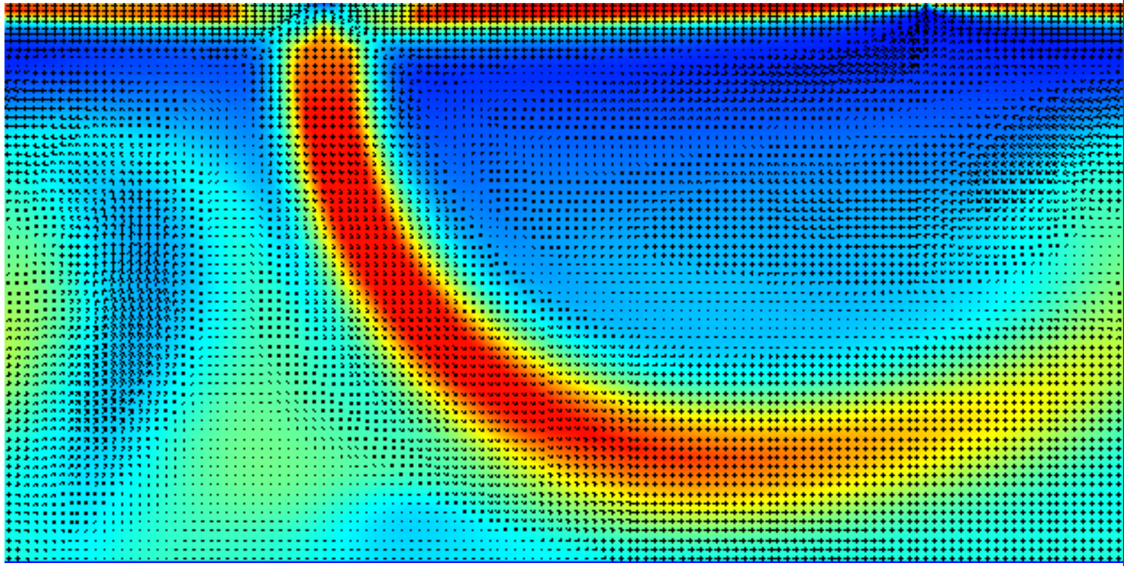


Fig. 16. Zoom in for viscosity snapshots of the FEMS-2D (left), FDCON (right) numerical models for times 57s, 5′ 50″, and 13′ 16″ which are comparable to the time steps presented for the laboratory experiment. For FDCON the harmonic mean for viscosity is used.

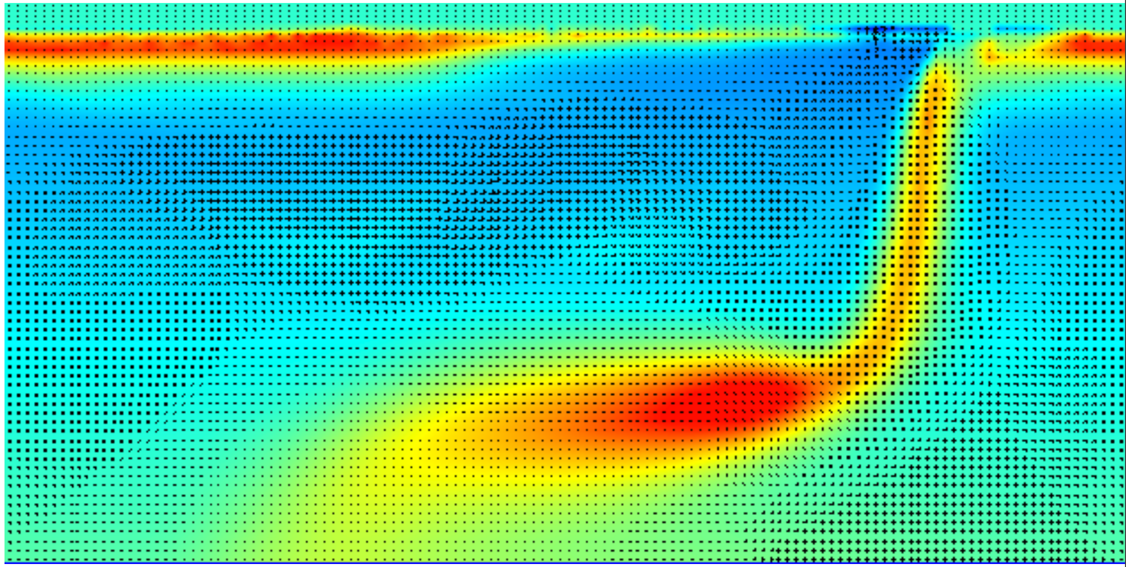
"Sticky-air" method gives same result as true free surface

Free-slip to free comparison

Free-slip



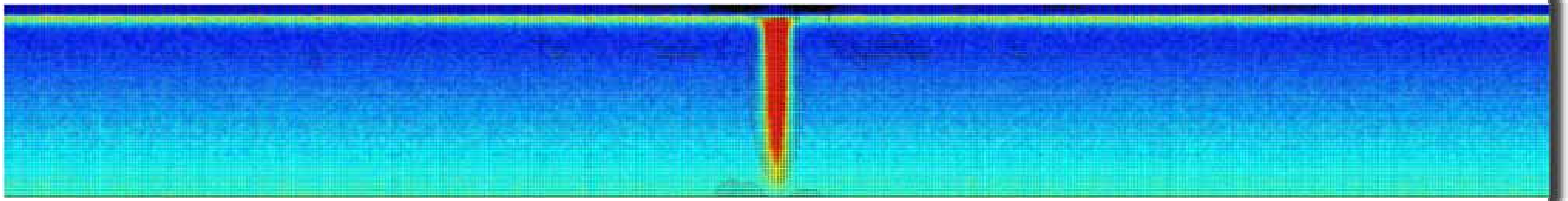
Free surface



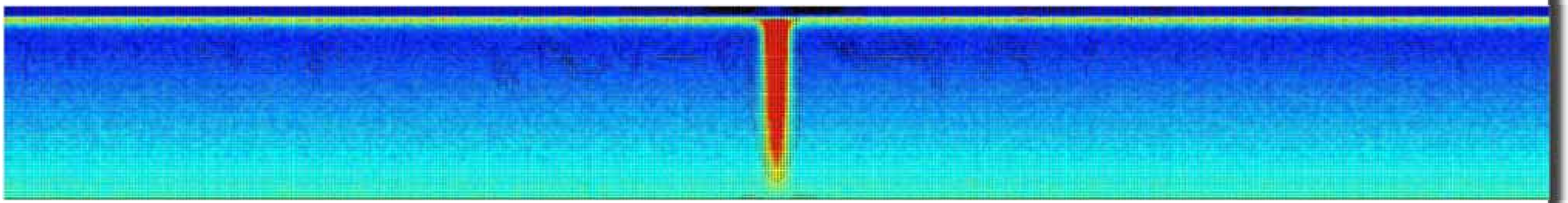
Single sided subduction!

Movies

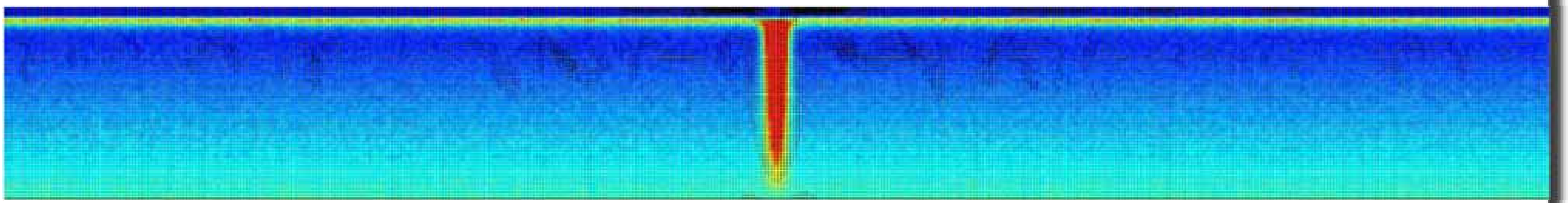
Friction coeff = 0.05

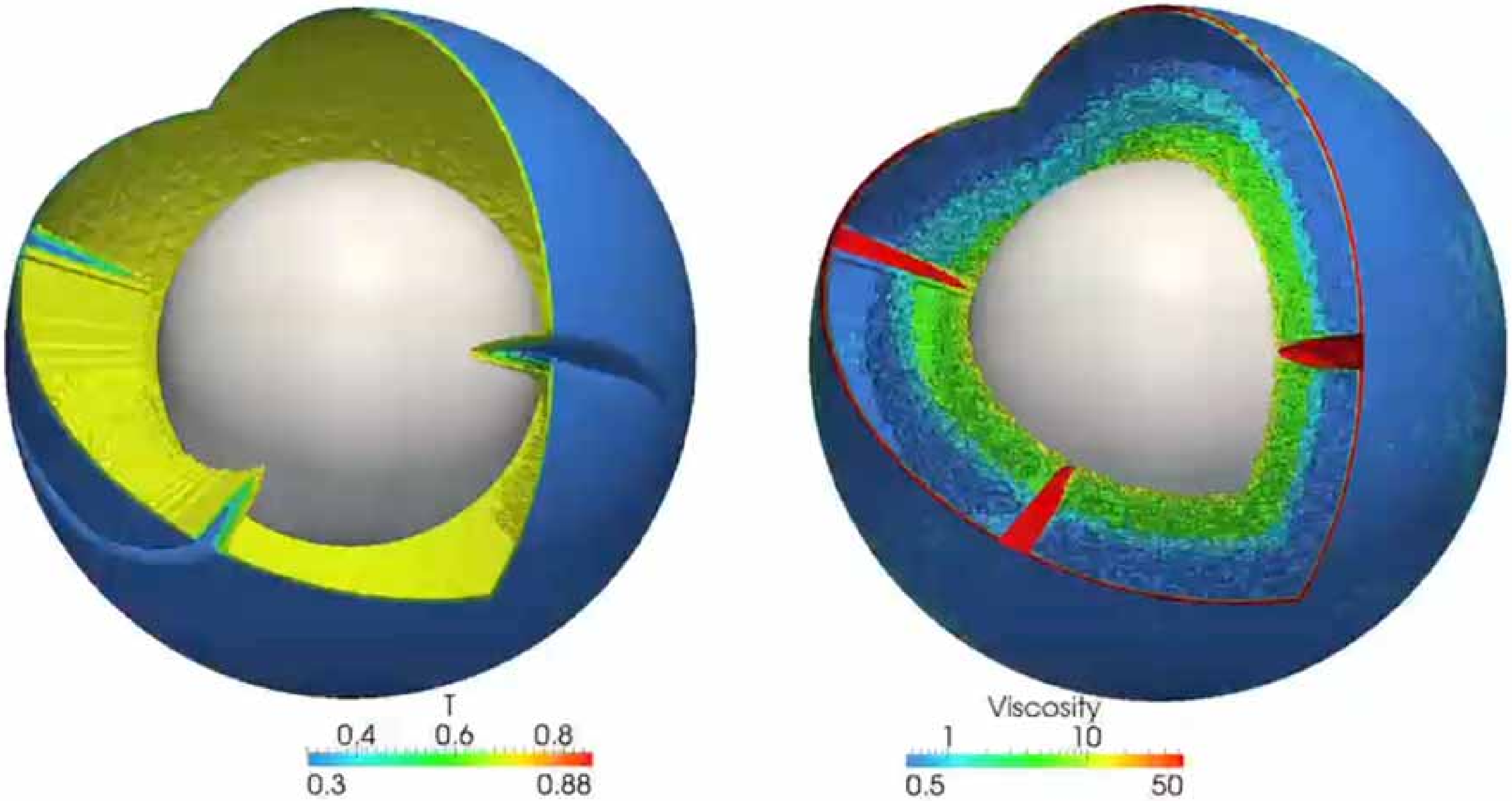


Friction coeff = 0.1



Friction coeff = 0.11





T
0.4 0.6 0.8
0.3 0.88
Viscosity
1 10
0.5 50

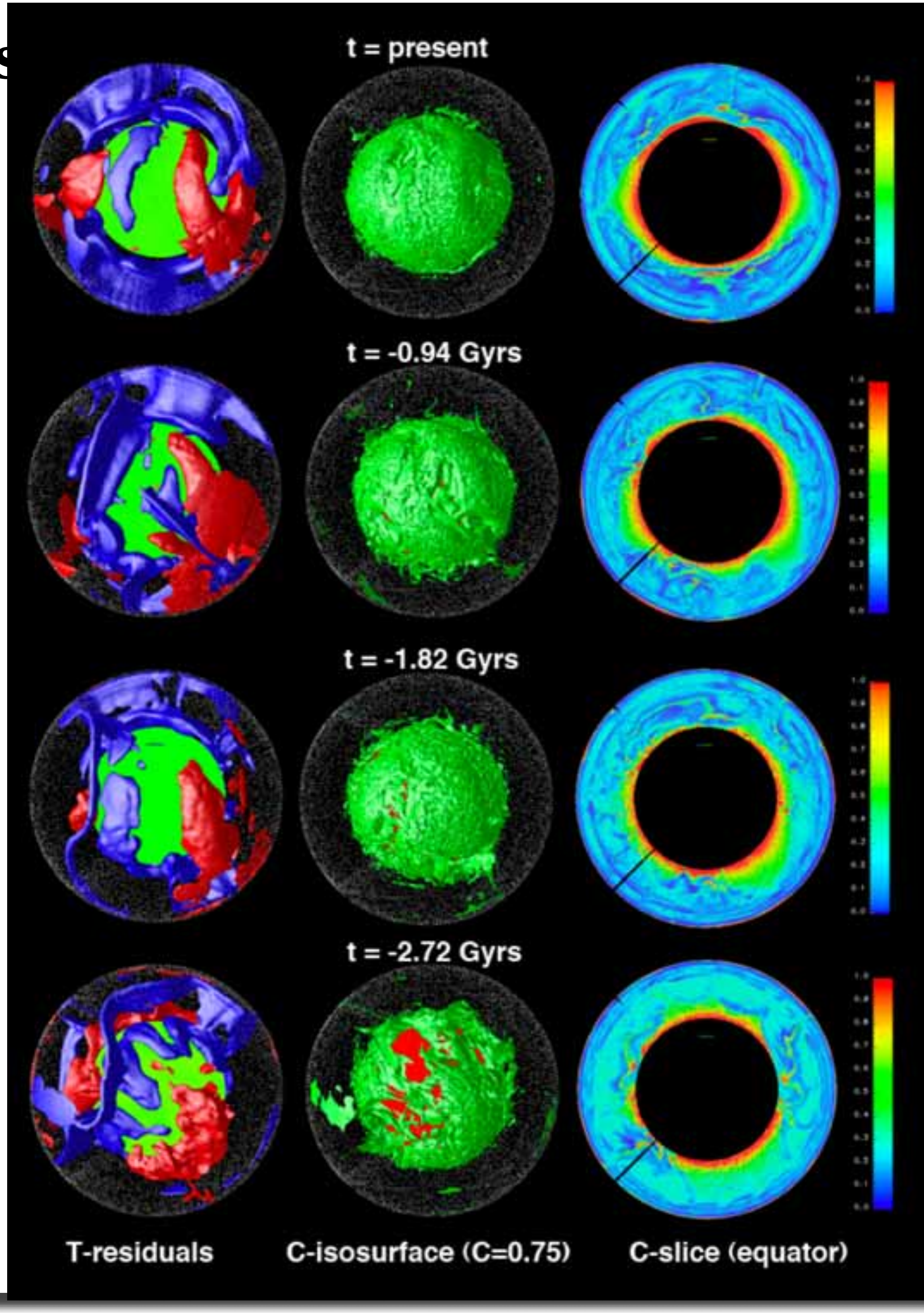
Findings

- Free surface leads to (thermally) single-sided subduction over a wide parameter range
- But so far, eventually a rigid lid is obtained, even for parameters that lead to stable “plate tectonics” with a free-slip surface
- Research is ongoing…

More realistic Earth models

Thermo-chemical Earth evolution including
- •Melting produced crust
- •Phase transitions
- •Compressibility
- •Visco-plastic rheology
- •Core cooling

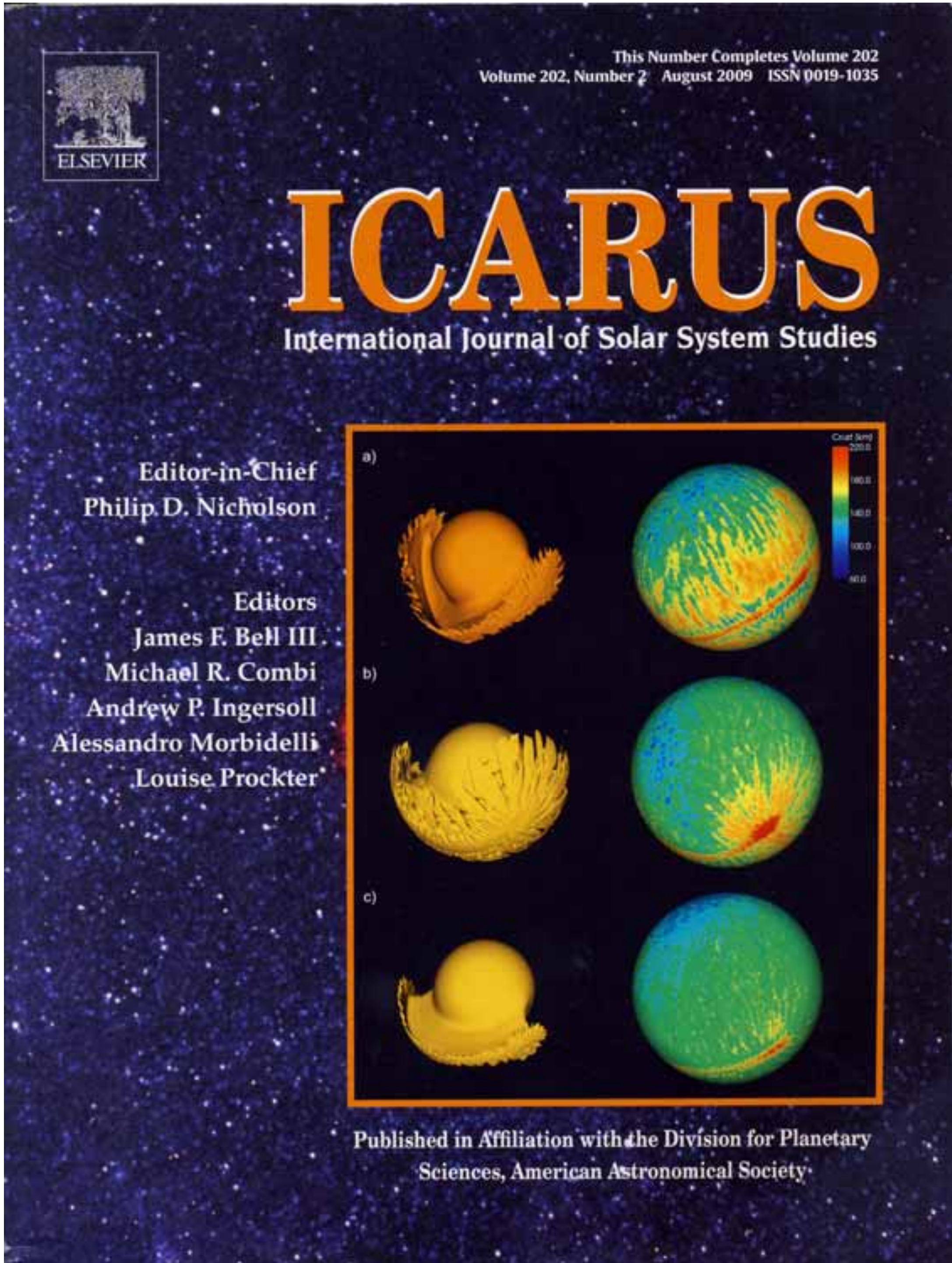
Takashi Nakagawa & me



MARS: Modelling mantle dynamics and crustal formation

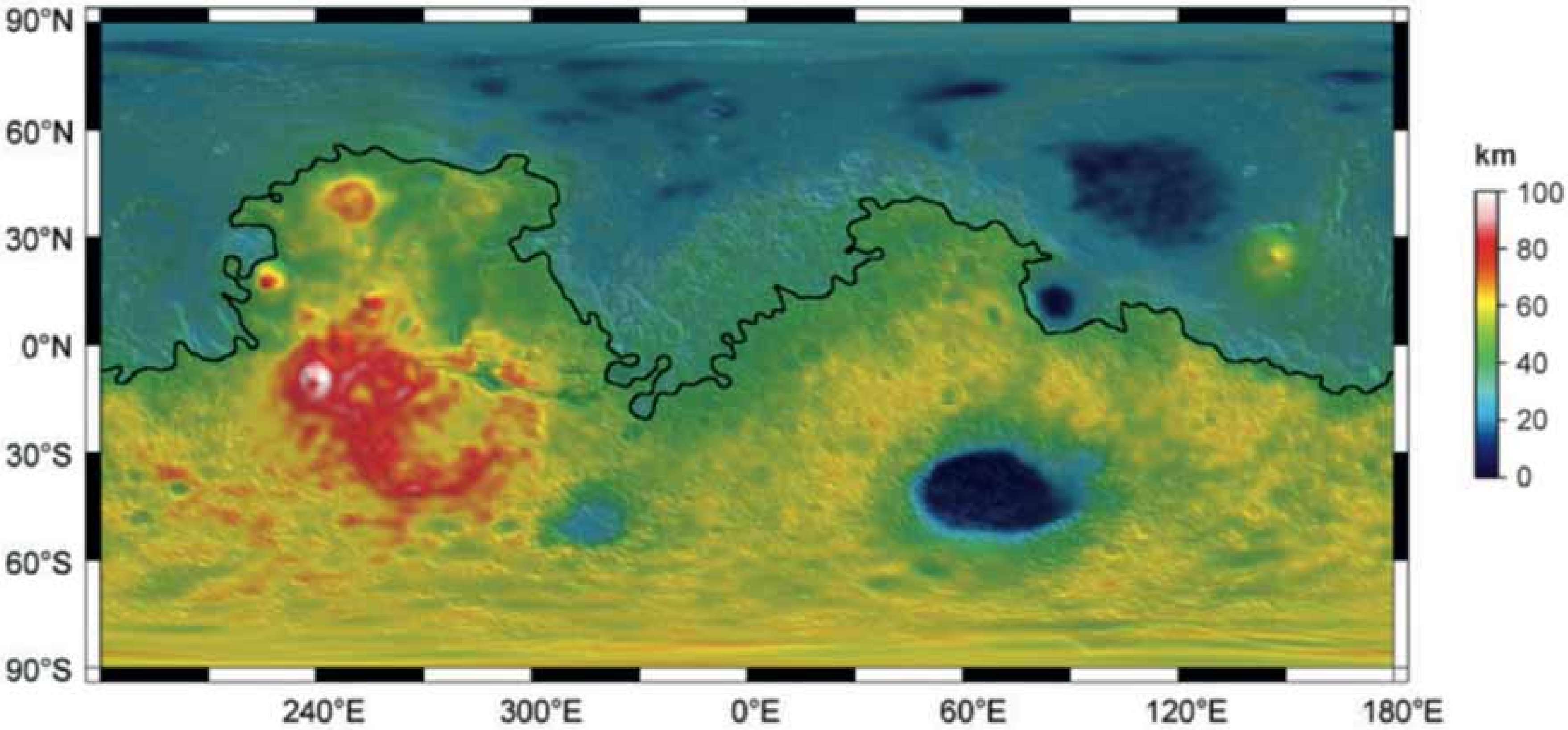
Tobias Keller & Paul J. Tackley

ETH Zürich, Geophysical Fluid Dynamics



ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

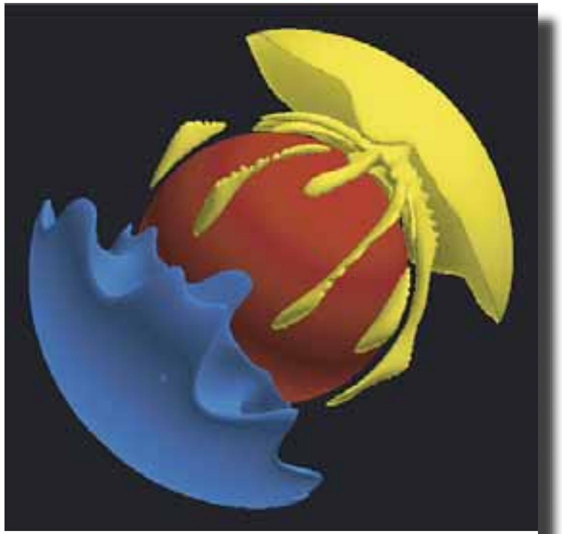
The crustal dichotomy



Causes: **Extrinsic** (impacts) or **intrinsic** (degree 1 mantle convection)?

MOLA data: Zuber (2001), Watters et. al (2007)

Degree-1 convection



Yoshida and Kageyama (2006)

Previous studies on degree-1 convection on Mars

- Perovskite phase transition

  Harder (1998), Breuer et al. (1998), Yoshida & Kageyama(2006)
- Depth- and T-dependent viscosity

  Yoshida & Kageyama (2006), Roberts and Zhong (2006)

  ⇒ This seems to be the most promising and reliable approach!

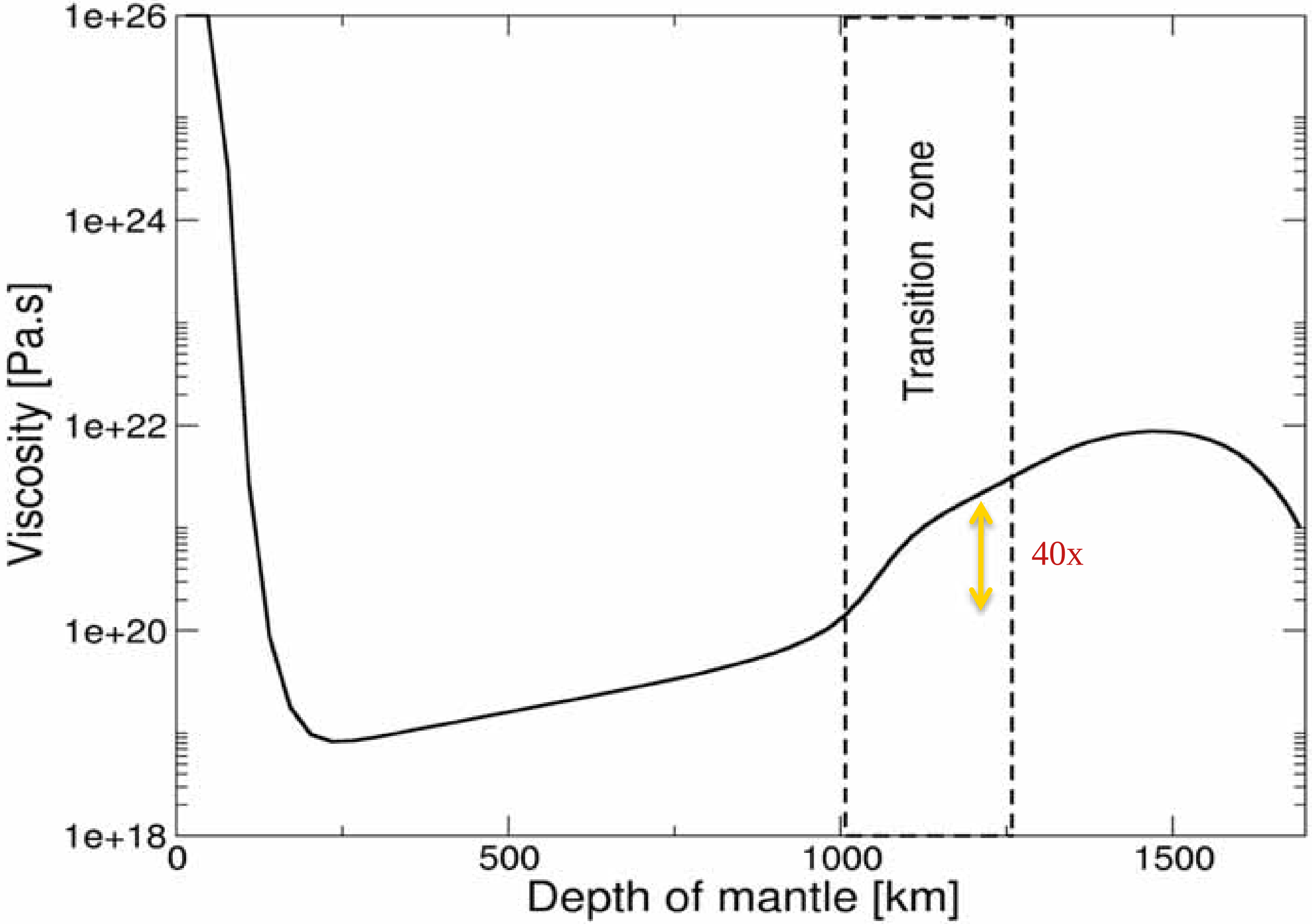
This is the main challenge

- How to get very low-degree convection under a rigid-lid lithosphere!?
- Small-scale downwellings beneath stable lithosphere dominate convective behaviour for purely T-dependent viscosity

⇒ The solution is depth-dependent viscosity and viscosity layering!

The Martian mantle

- weak upper mantle
- strong lower mantle (mineralogical phase transitions)



Activation Energy

200 kJ/mol

Activation Volume

4.5 cm^3/mol

Numerical modelling

Internal heating

- chondritic heating rate, decays with time

$\Rightarrow$ *initially high* internal heating

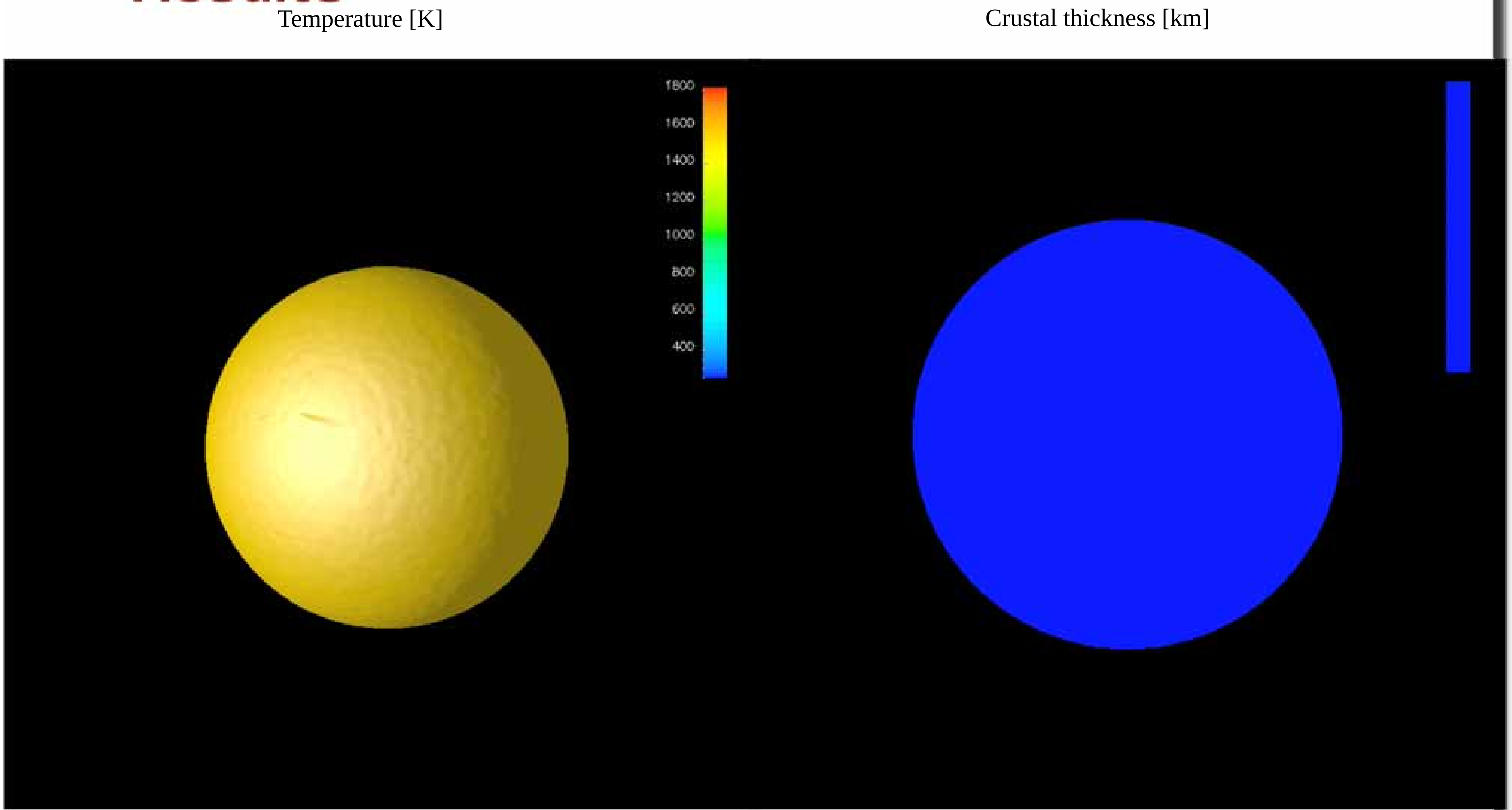
Composition

- modelled as a two-component system: *basalt* and *harzburgite*
- both components consist of fractions of *olivine* and *garnet / pyroxene*

Melting and differentiation

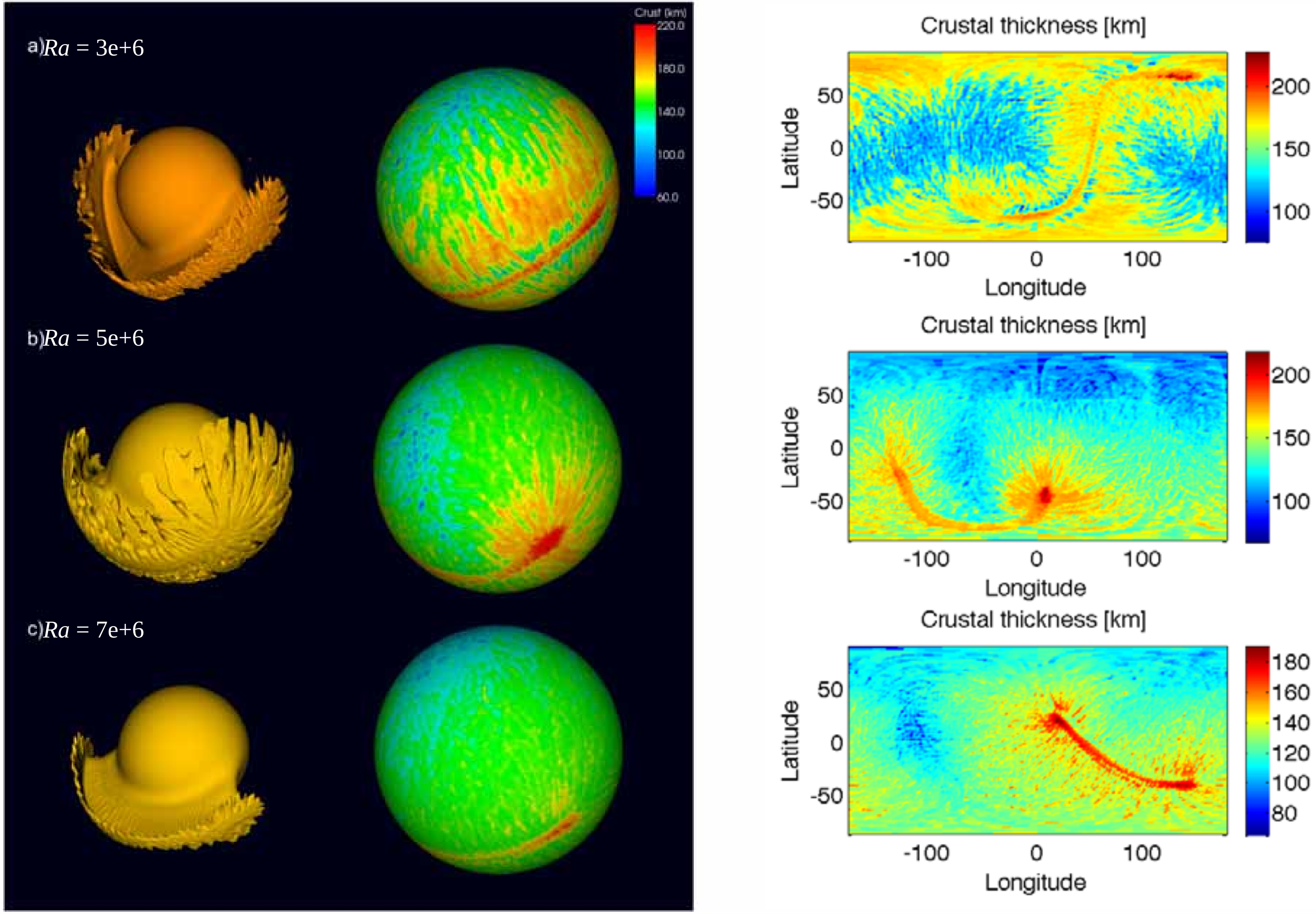
- *Melt* is generated to keep T from exceeding *solidus-T* (latent heat!)
- All melt is *vertically removed* to the surface and *erupted* as crust

Results

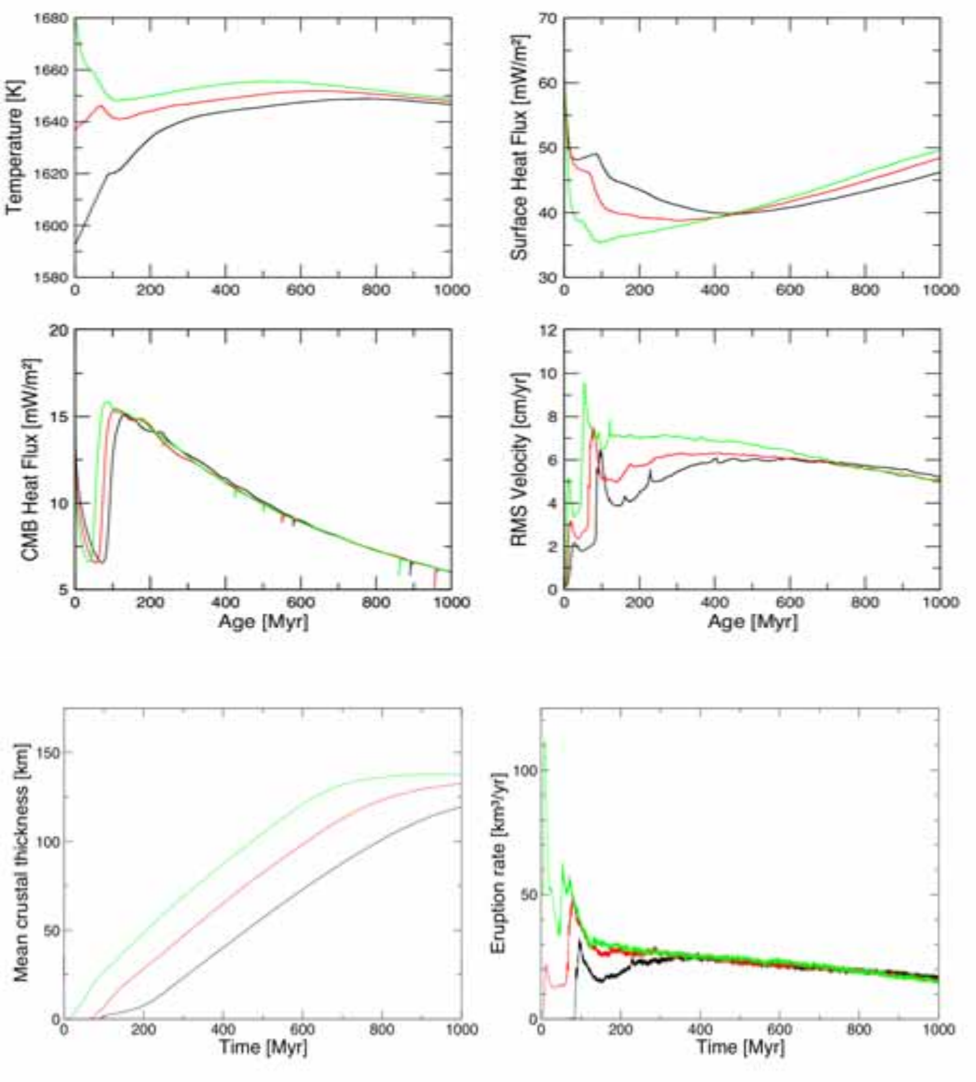


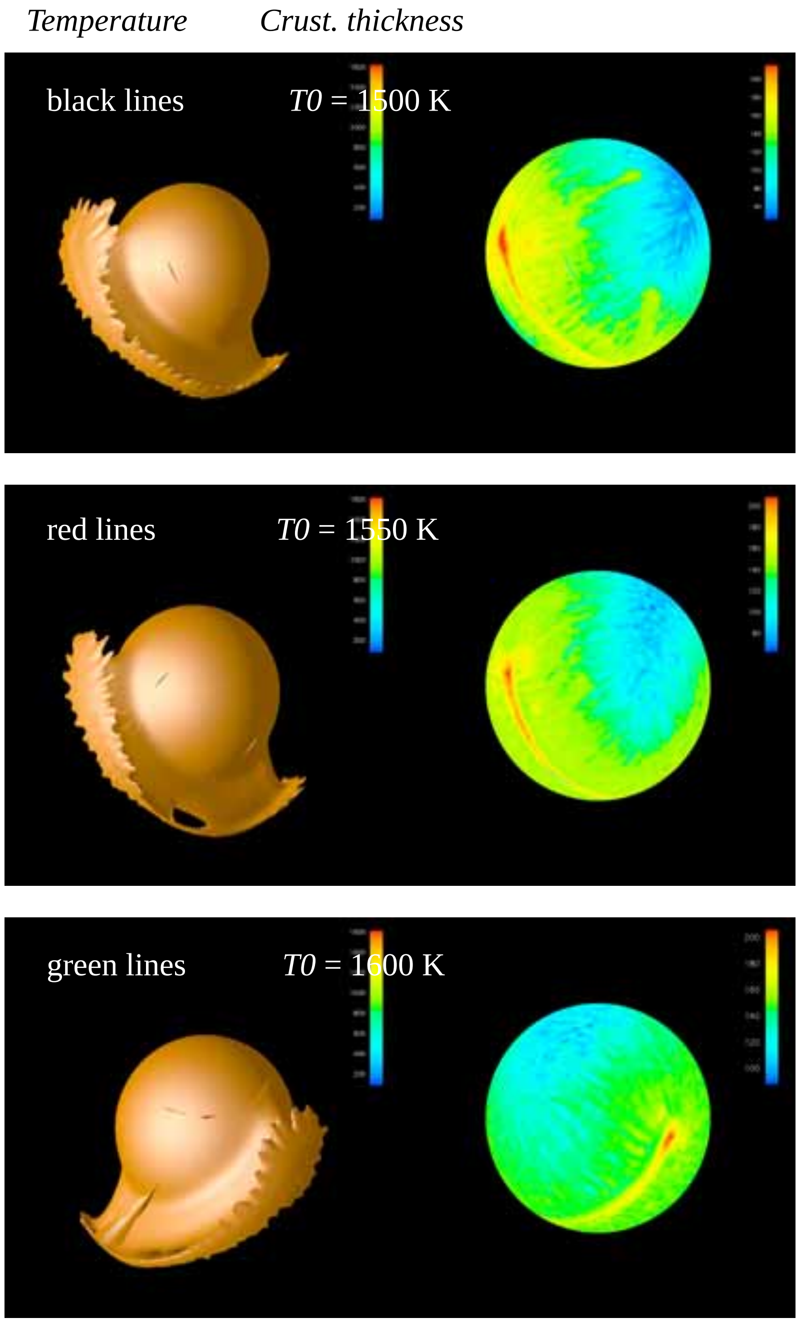
Ra = 7.0 e+6

Results at time = 1.0 Gyr



Results after 1 billion years: vary T0



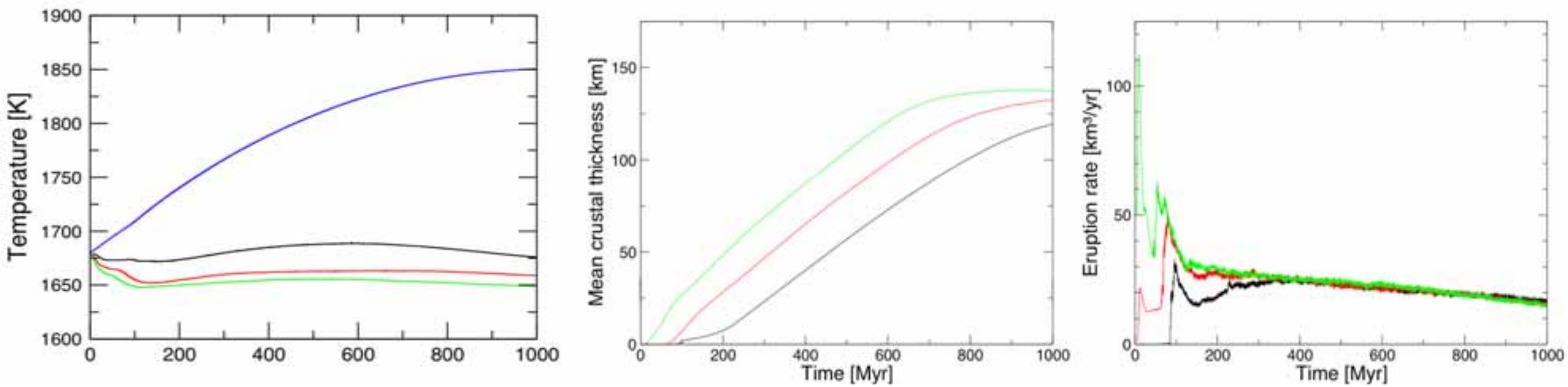


Discussion

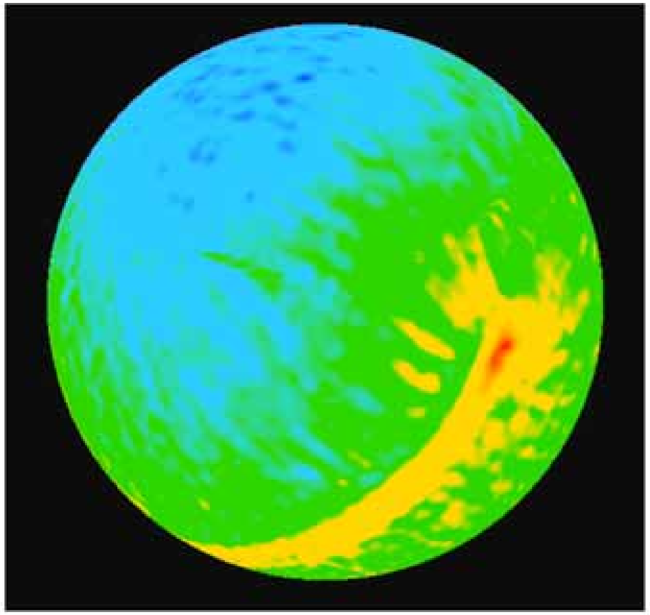
Thermal impact of melting and eruption

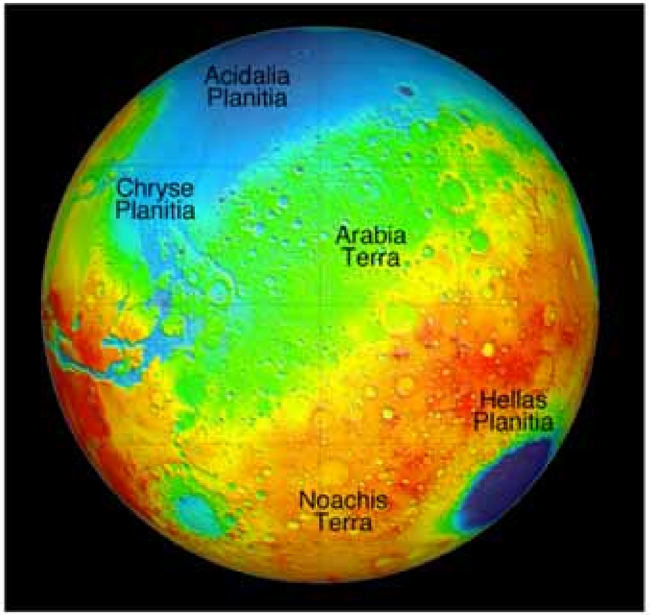
Melting and eruption

- serve as a major cooling system for the planet's mantle
- due to various coupling mechanisms, they also tend to regulate temperature
- lead to very similar thermal evolutions after various initial temperatures
- High initial T and internal heating promote early crust formation



Interpretation





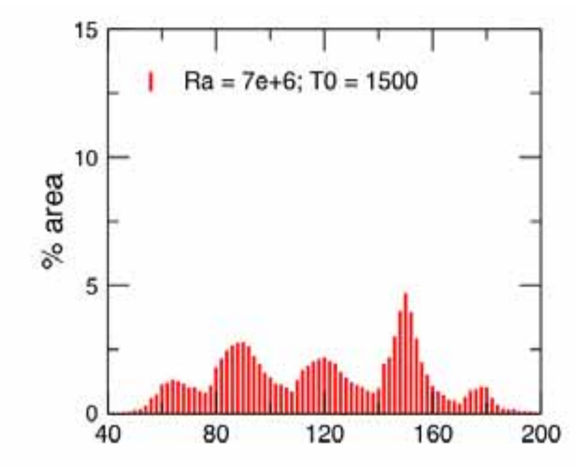
Striking first-order similarity!

Discussion

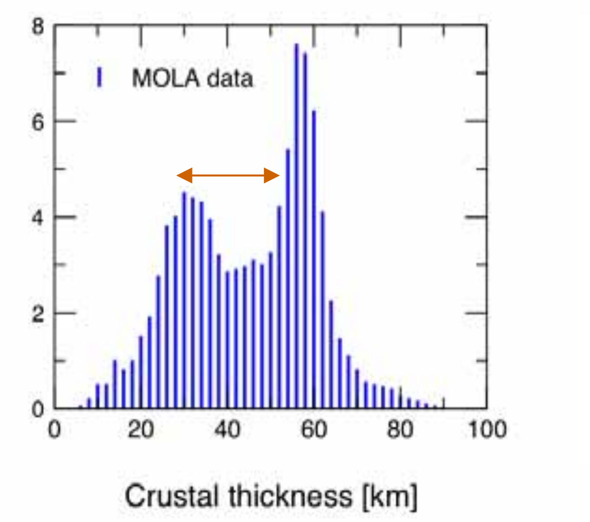
Crustal thickness distribution histograms

- two peaks for northern plains and southern highlands

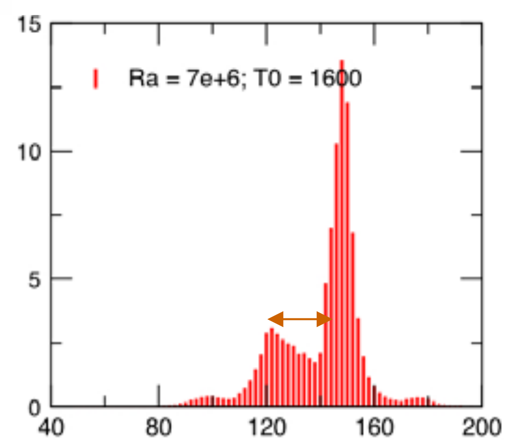
bad fit



Mars data

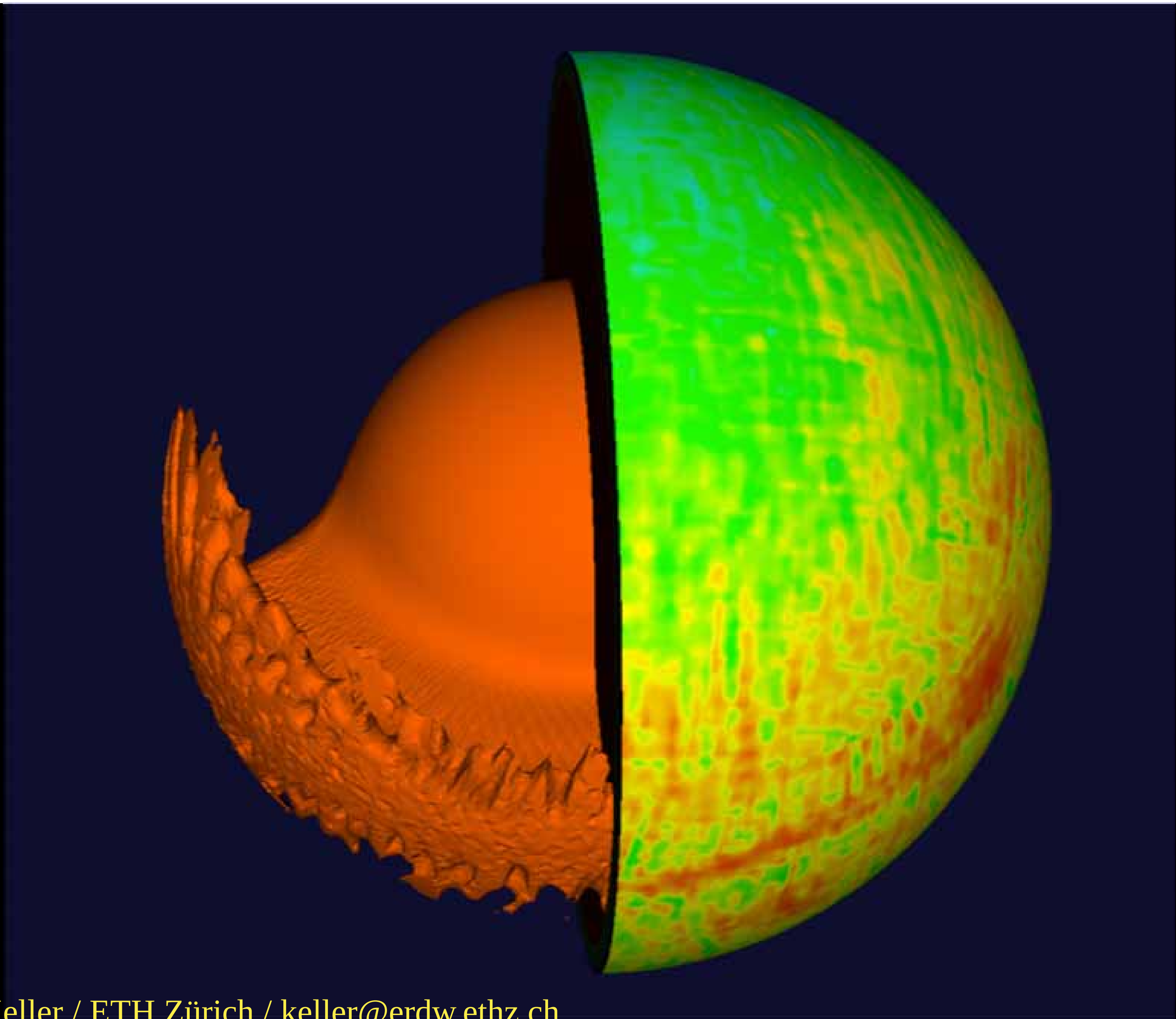


best fit



N-S difference = 26 km

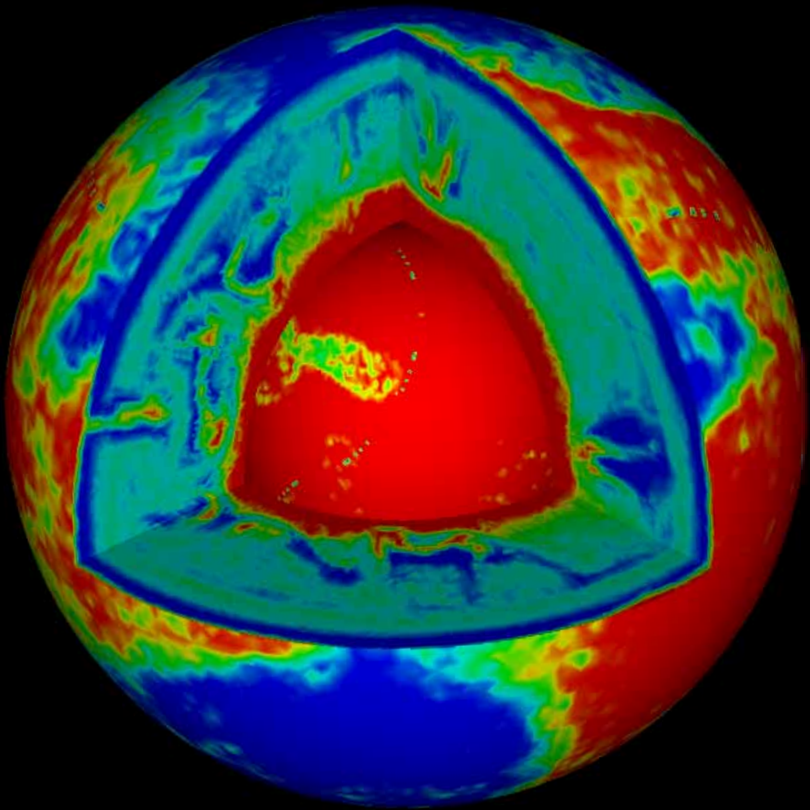
MOLA data from Watters et al. (2007)



Tobias Keller / ETH Zürich / keller@erdw.ethz.ch

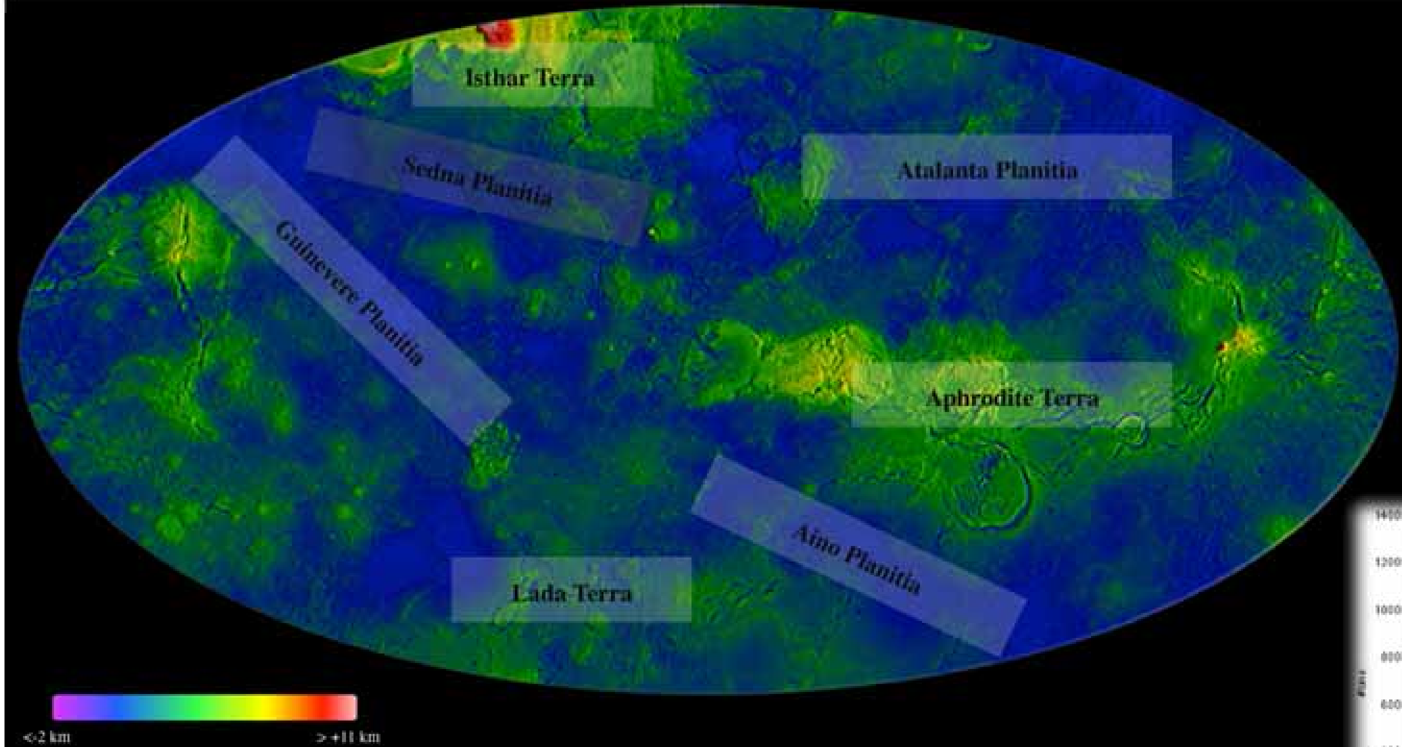
Keller, T., Tackley P.J., 2009. Towards self-consistent modeling of the martian dichotomy: The influence of one-ridge convection on crustal thickness distribution. Icarus 202, 429-443

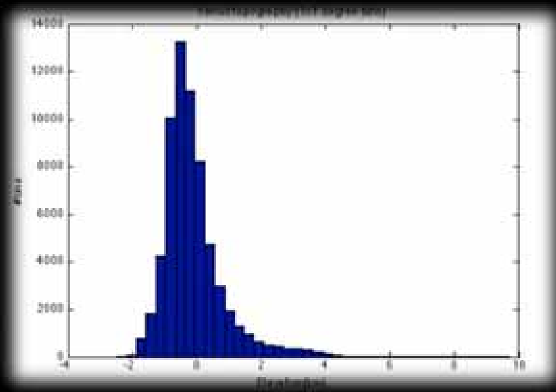
THERMO-CHEMICAL EVOLUTION OF VENUS' MANTLE AND CRUST



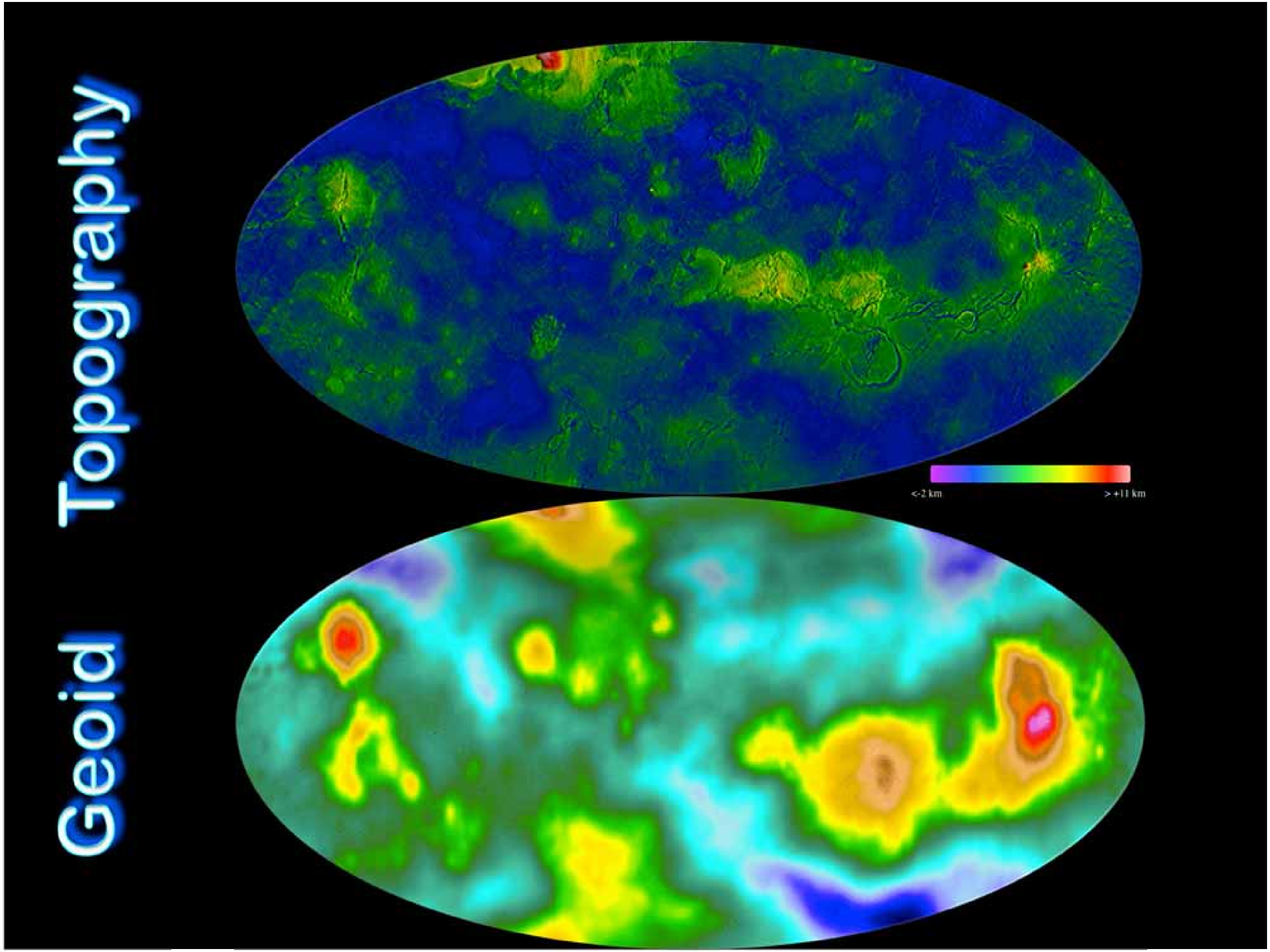
by M. Armann & P.J. Tackley
ETH Zurich

Topography





- ★ 80% surface smooth volcanic plains
- ★ highland "continents"
- ★ Unique surface features of volcanic origin: farra, novae, arachnoids and coronae
- ★ Nearly 900 Impact craters (from Magellan), crater counts used for age determination
- ★ Random distribution, implying that surface roughly same age
- ★ Hypothesis: Venus underwent global resurfacing event 300-700 Ma ago



Topography
Geoid
<-2 km
> +11 km

Motivation, unanswered questions ..

★ **How does Venus lose its heat?**
  - Magmatism?
  - Episodic overturn?
  - Conduction?

Lithospheric thickness?
  - 100s km or 10s km?
  - Admittance ratios: require thick lithosphere?

★ **Uniform surface age (from craters) of 300-700 Ma**
  - Global resurfacing @ this time?
  - Continuous random local volcanism?

★ **Relationship between topography and underlying convection**
  - Are highlands above upwellings or downwellings?

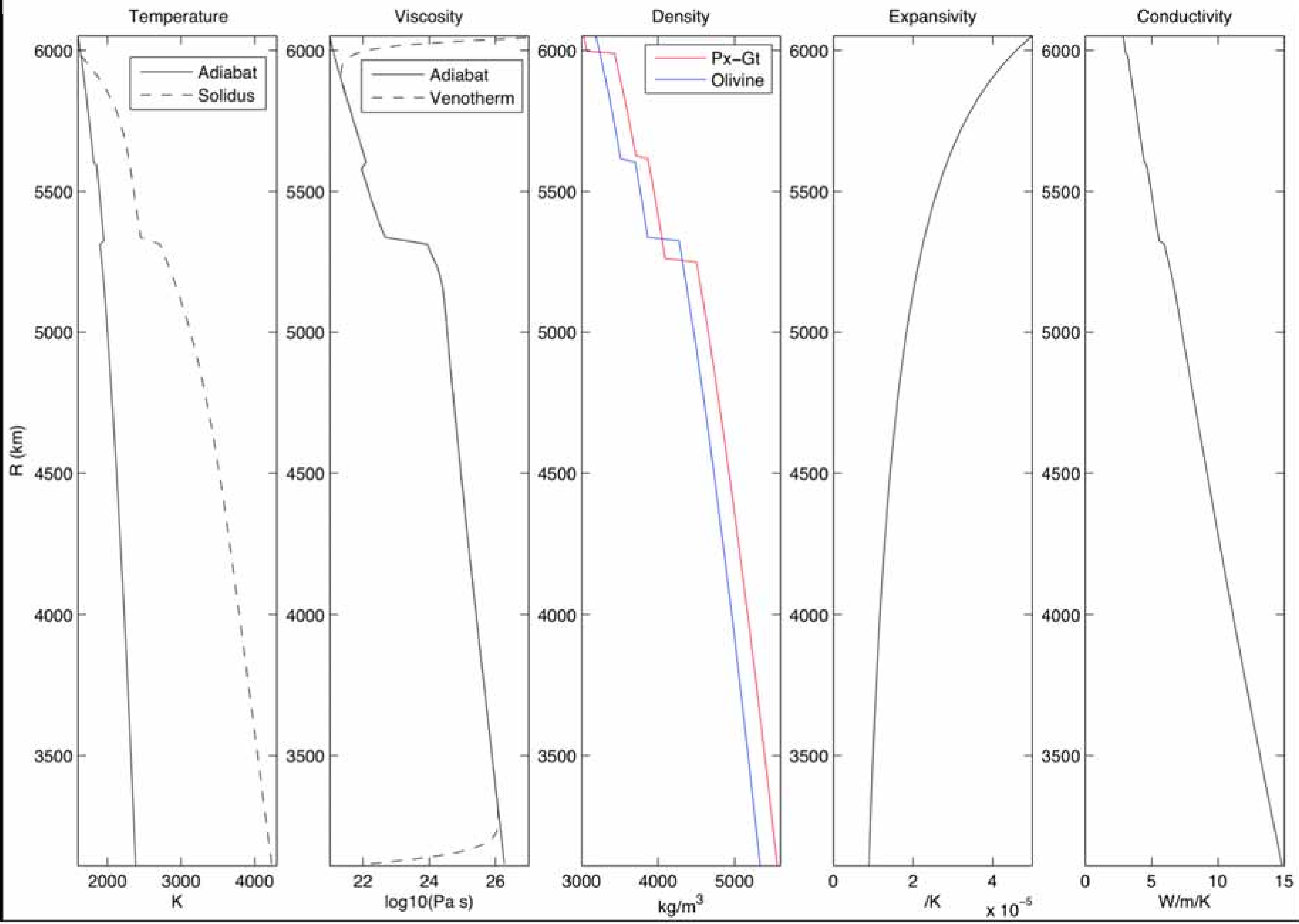
★ **Importance of composition variations in interior dynamics**
  - Episodic overturn of sub-lithospheric residue layer?

Improved modeling technology now exists, time to revisit this issues

Physical Model - Summary

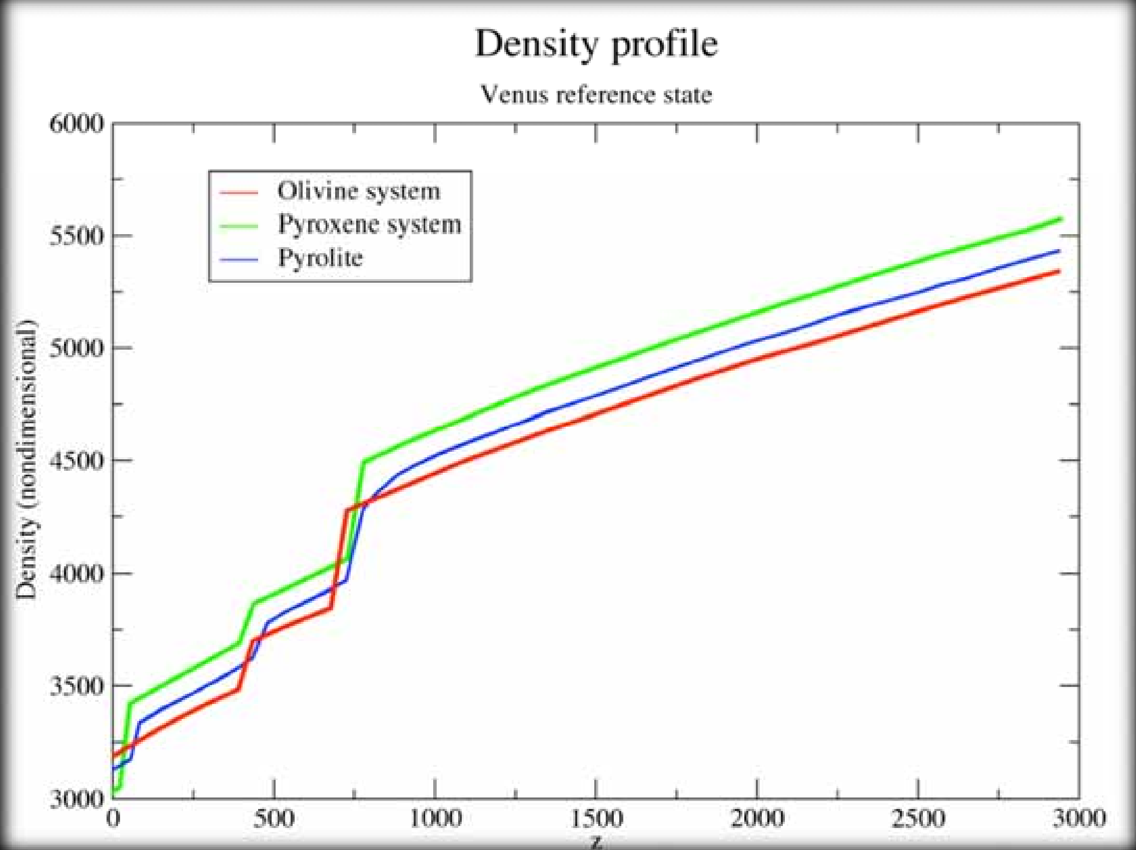
- ★ Compressible with depth-dependent physical properties
- ★ "Laboratory" rheology. +plastic yielding in some cases
- ★ Compositional variations + melting produces crust
- ★ Core cooling using parameterized core heat balance

A: Depth-Dependent Properties



B: Composition-Dependent Phase Changes

2 in olivine system (“453” “730”), 3 in pyroxene-garnet system (+“basalt-eclogite”)



66 km Basalt -> Eclogite

453 km Olivin -> Spinel

520 km Pyroxene -> Majorite

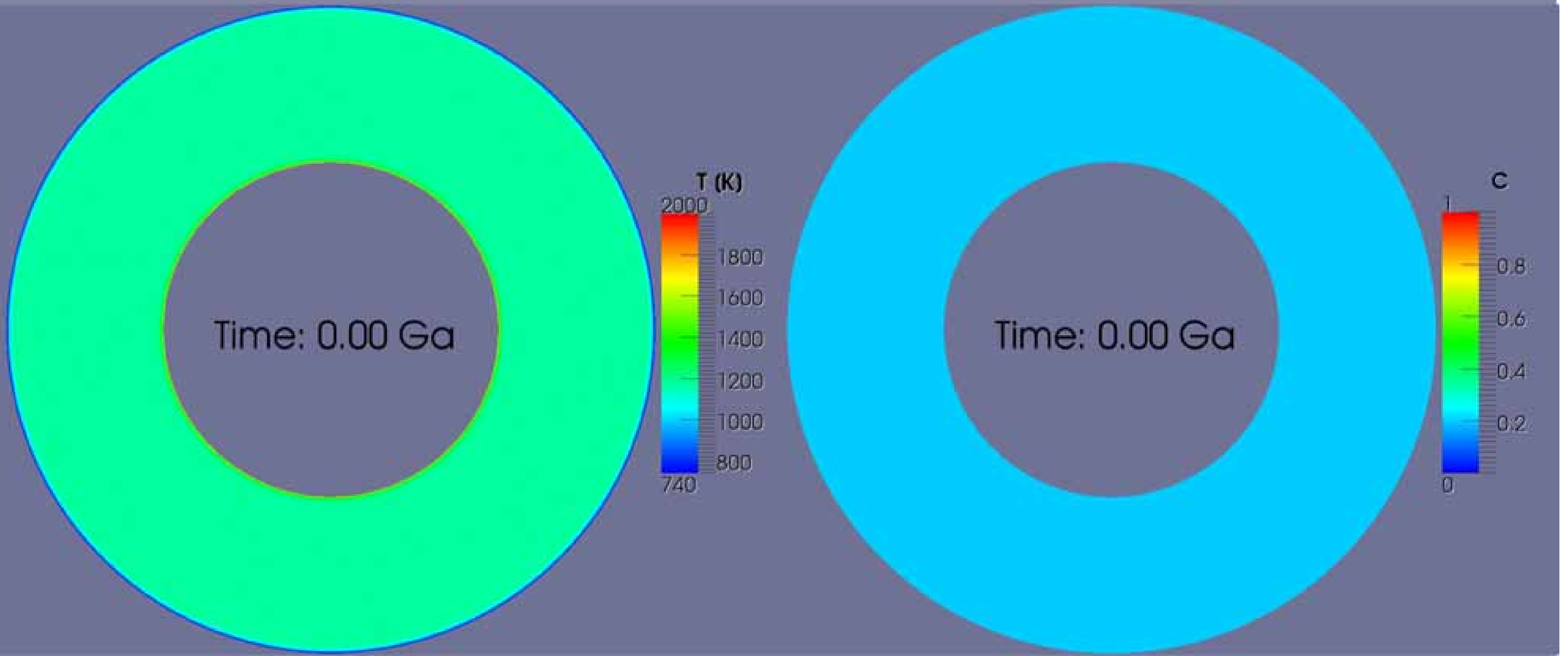
730 km Spinel -> Perovskite + Magnesiowüstite

796 km Majorite -> Perovskite

Stagnant Lid Cases

Reference Case

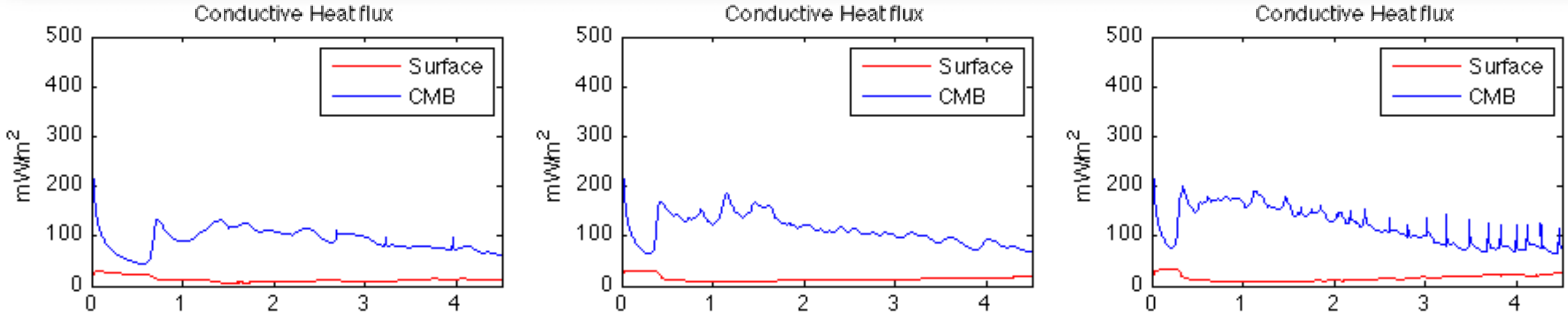
Ra = 6.15E8 -> $\eta = 2 \times 10^{20}$ Pa s



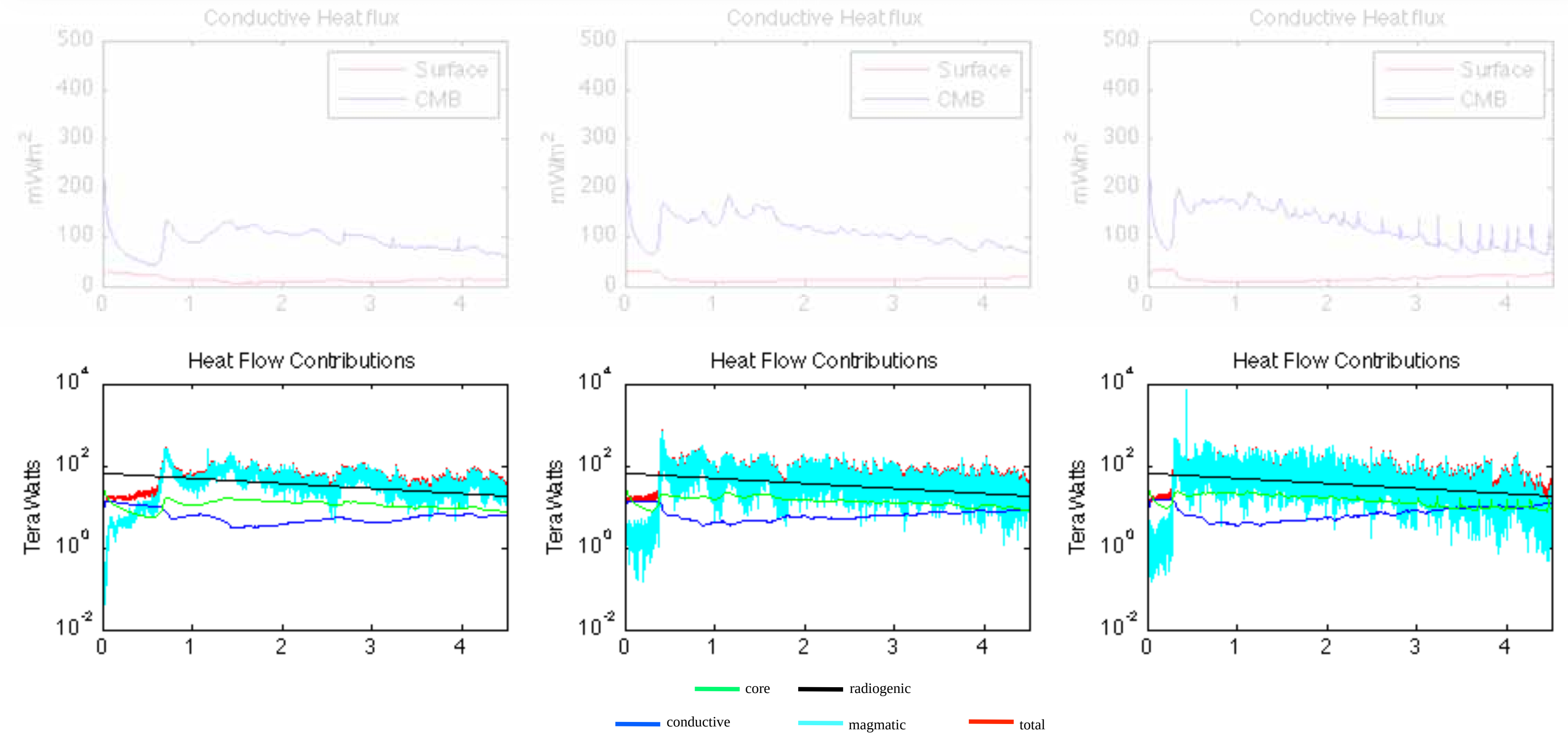
Temperature

Composition

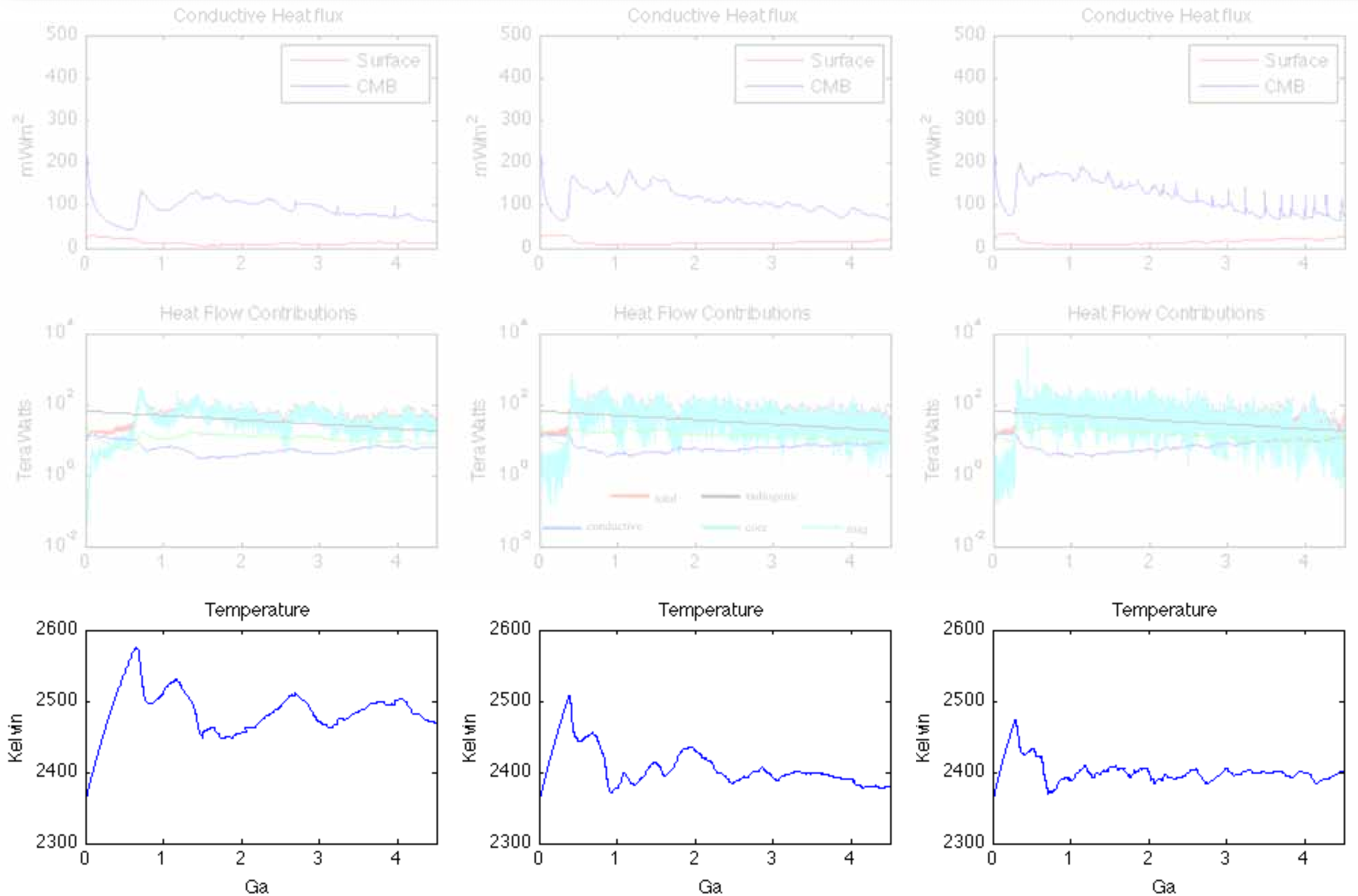
10^{21} Pa s | 2.10^{20} Pa s | 10^{20} Pa s



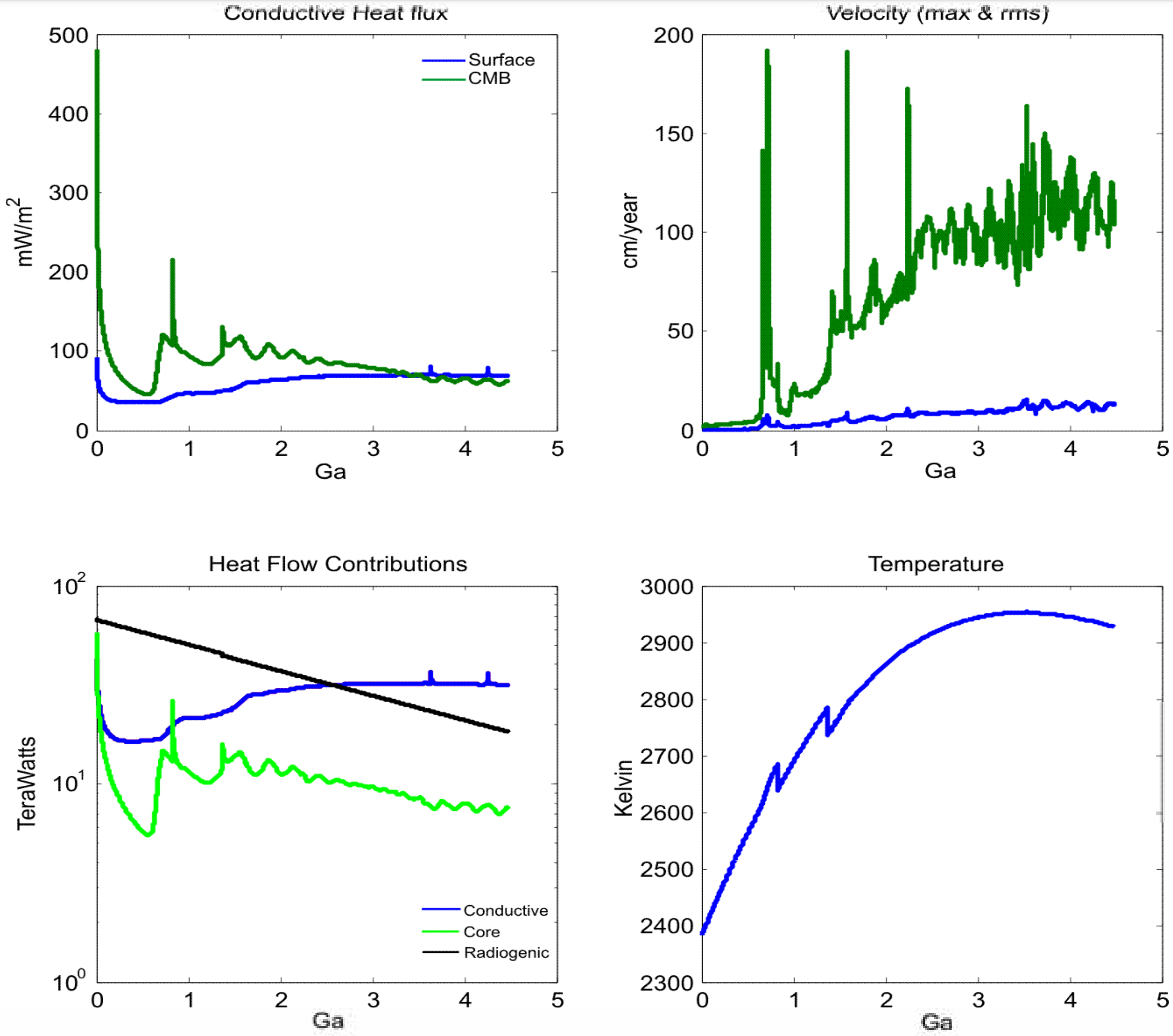
10^{21} Pa s | 2.10^{20} Pa s | 10^{20} Pa s



10^{21} Pa s | 2.10^{20} Pa s | 10^{20} Pa s

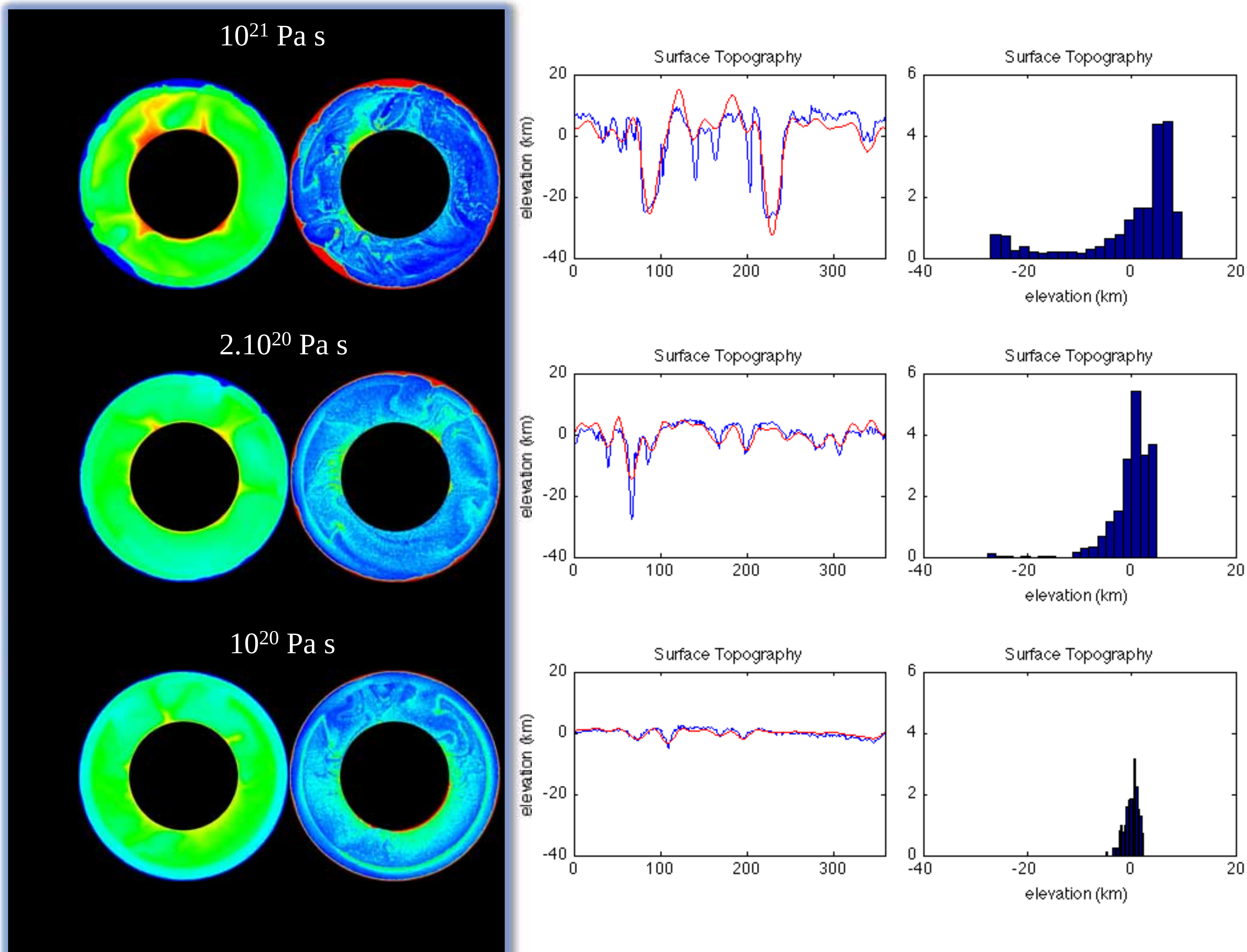


Stagnant Lid Case with no melting

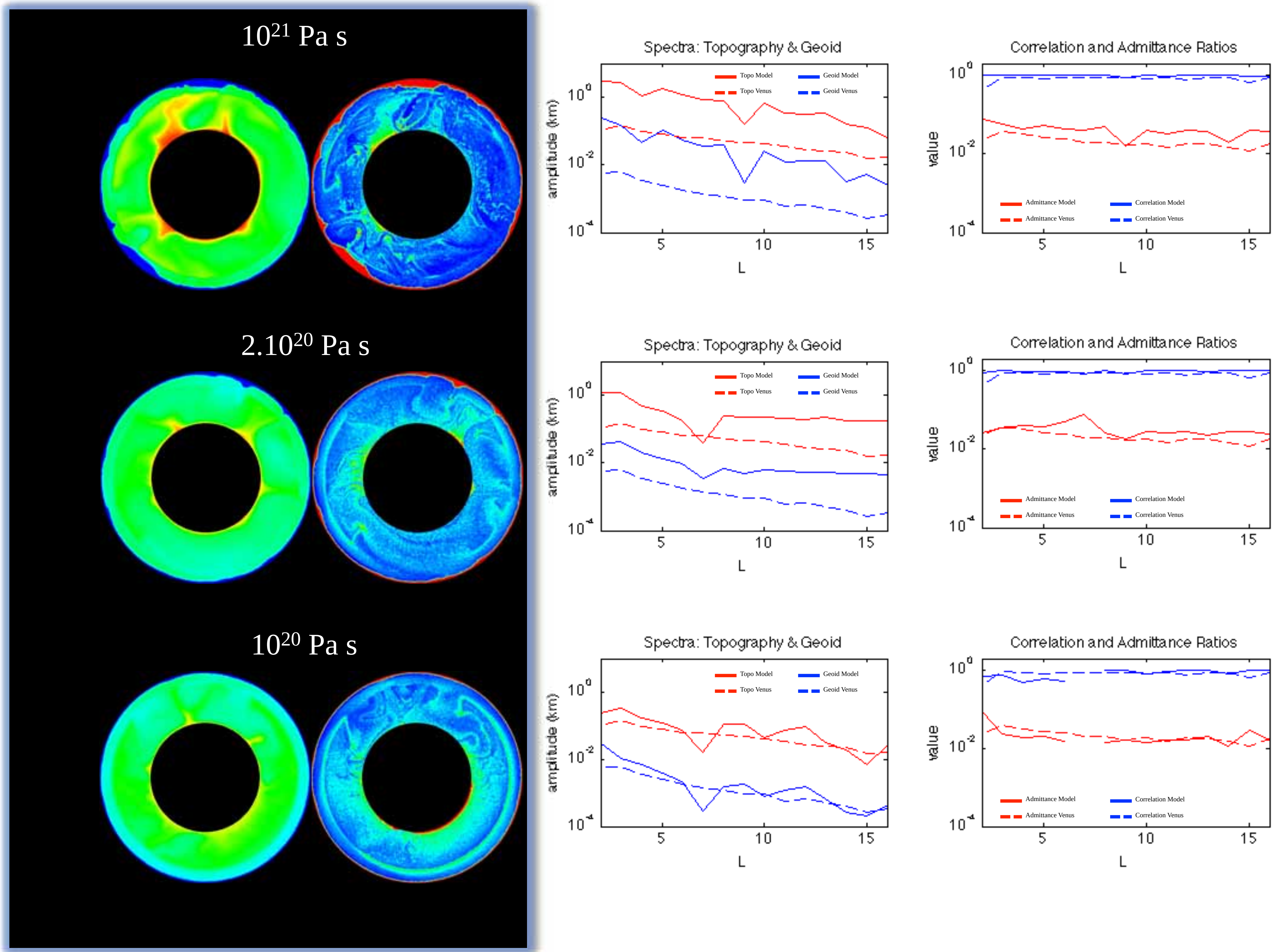


Very high T!

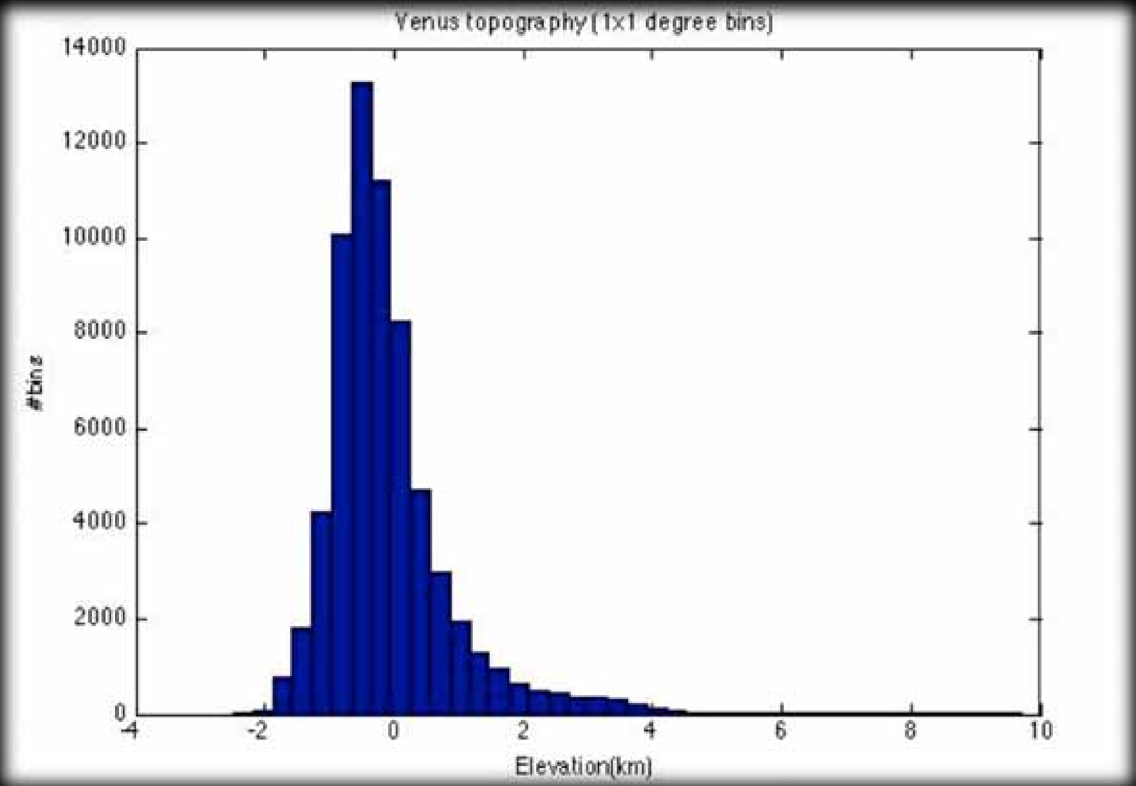
Melting has a huge effect on thermal evolution!



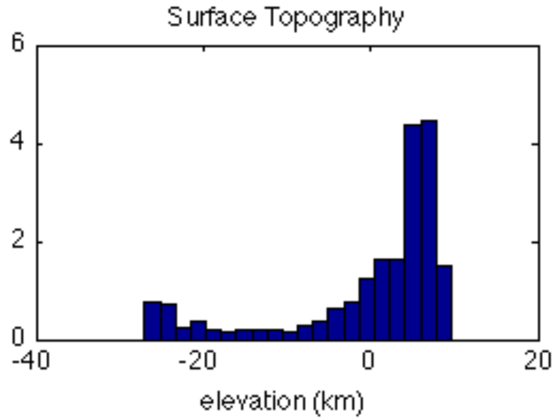
10^21 Pa s
2.10^20 Pa s
10^20 Pa s
Surface Topography
elevation (km)



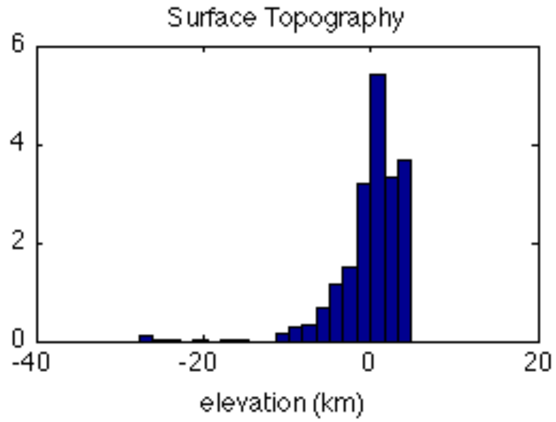
10^{21} Pa s
2.10^{20} Pa s
10^{20} Pa s
Spectra: Topography & Geoid
Topo Model
Topo Venus
Geoid Model
Geoid Venus
amplitude (km)
L
Correlation and Admittance Ratios
Admittance Model
Admittance Venus
Correlation Model
Correlation Venus
value
L



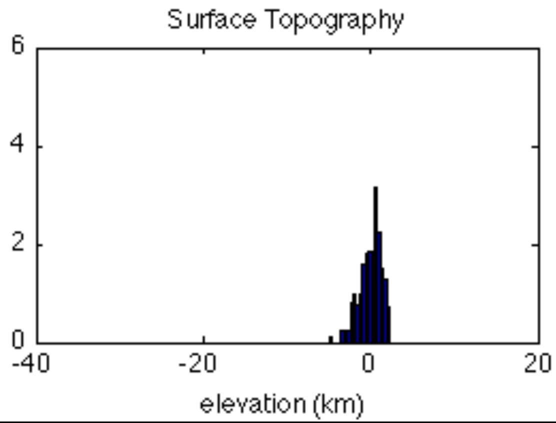
Ra1.23E8

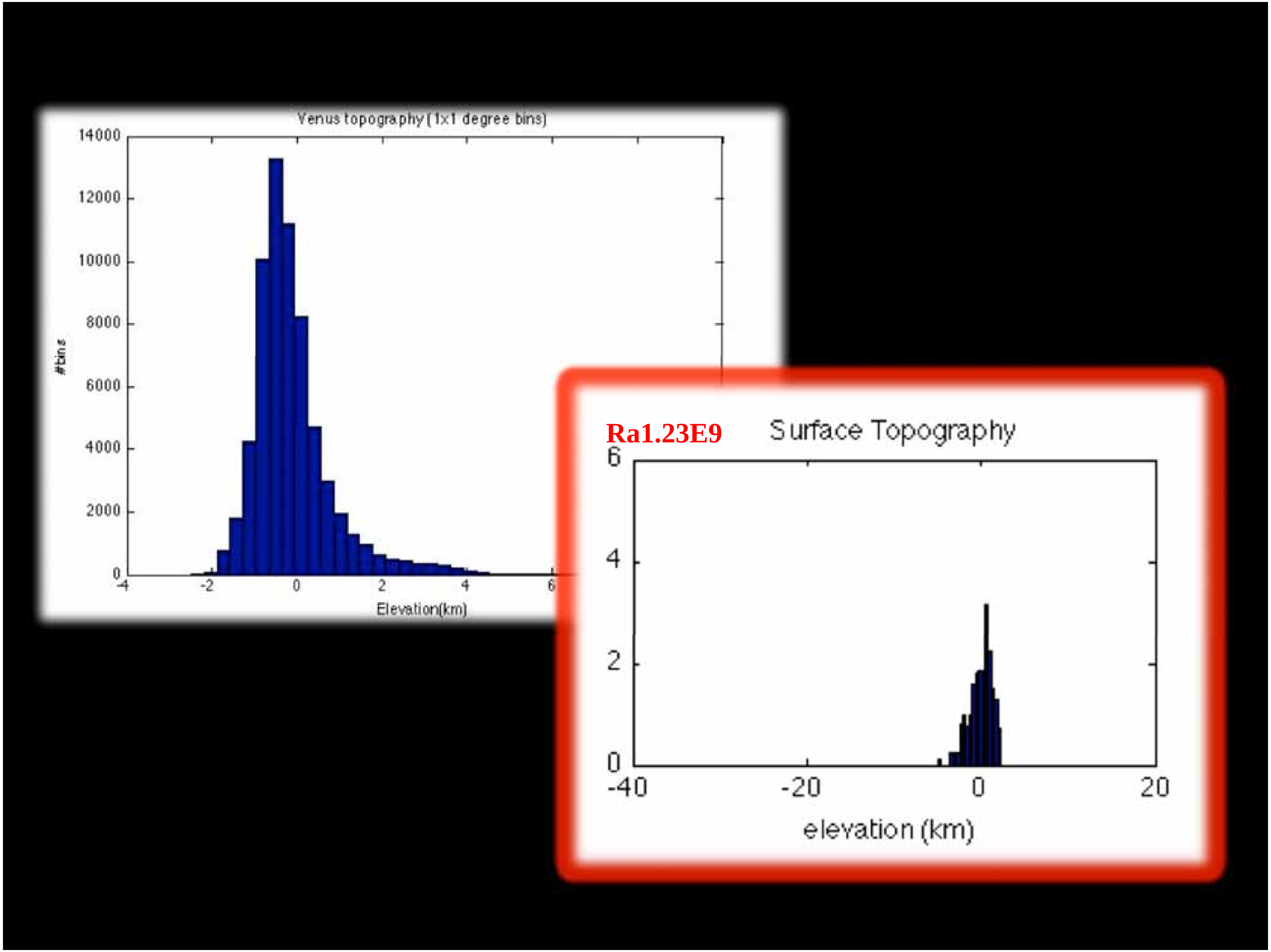


Ra6.15E8



Ra1.23E9

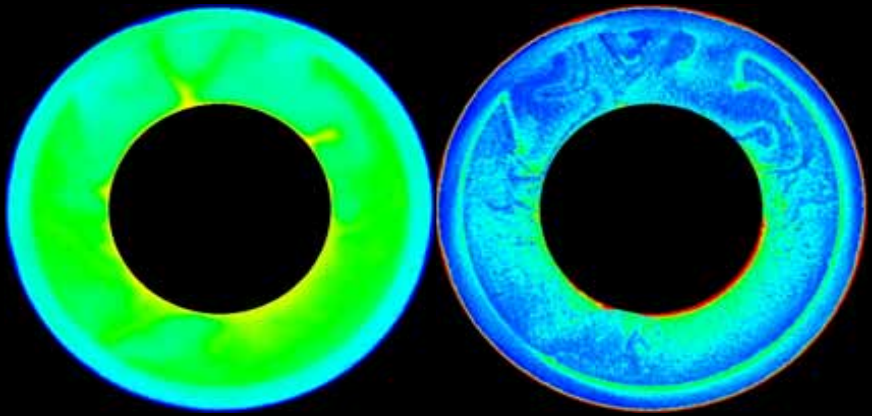




Venus topography (1x1 degree bins)
14000
12000
10000
8000
6000
4000
2000
0
#bins
-4
-2
0
2
4
6
Elevation(km)
Ra1.23E9
Surface Topography
6
4
2
0
-40
-20
0
20
elevation (km)

Best fit case

Ra1.23E9



Topography ✔

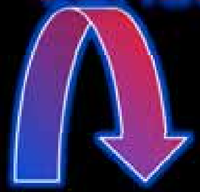
Crustal Thickness ✔

Geoid ✔

Admittance ✔

But

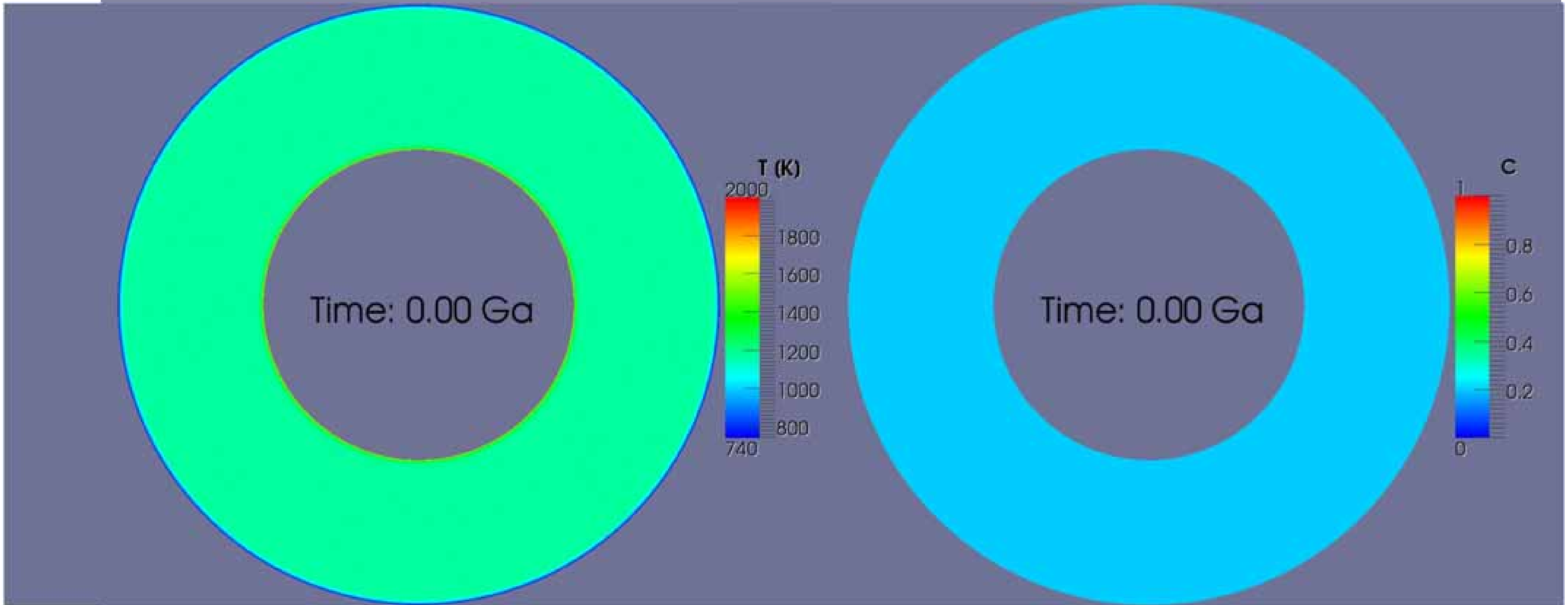
Surface too young (ongoing magmatism)



Cases with Plasticity

Episodic Lid Cases

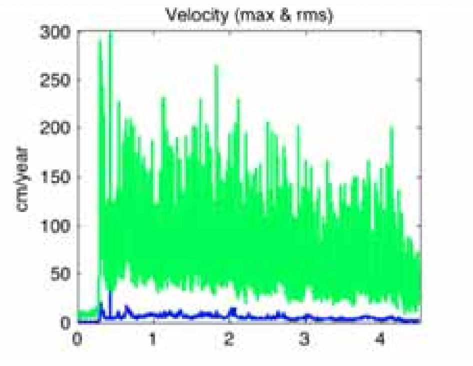
$Ra = 1.23E9 \rightarrow \eta = 1\times10^{20}$ Pa s
$\sigma y = 100$ MPa

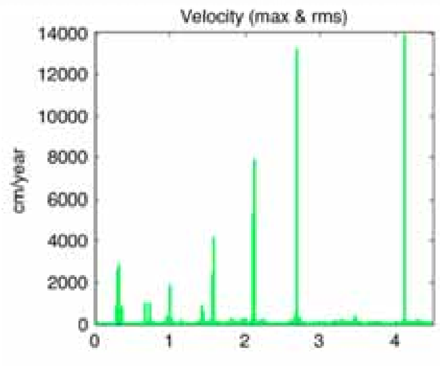


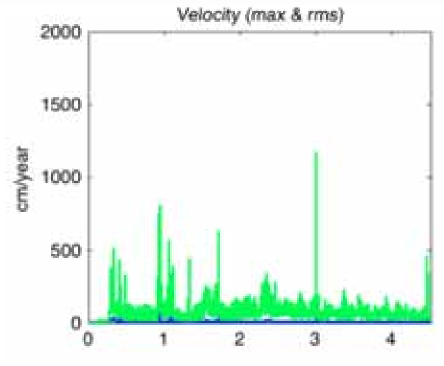
Temperature

Composition

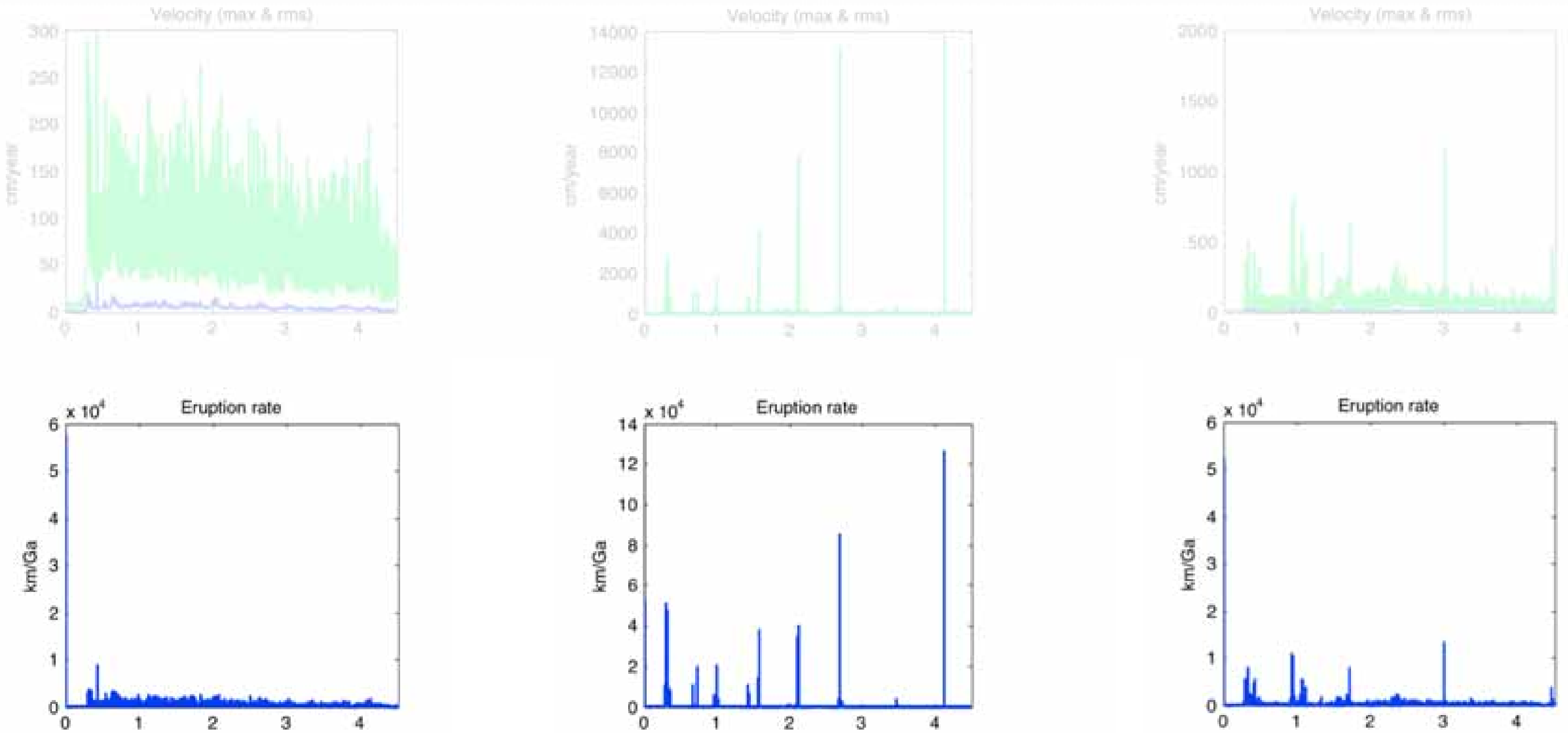
Stagnant	Ys=100	Ys=200



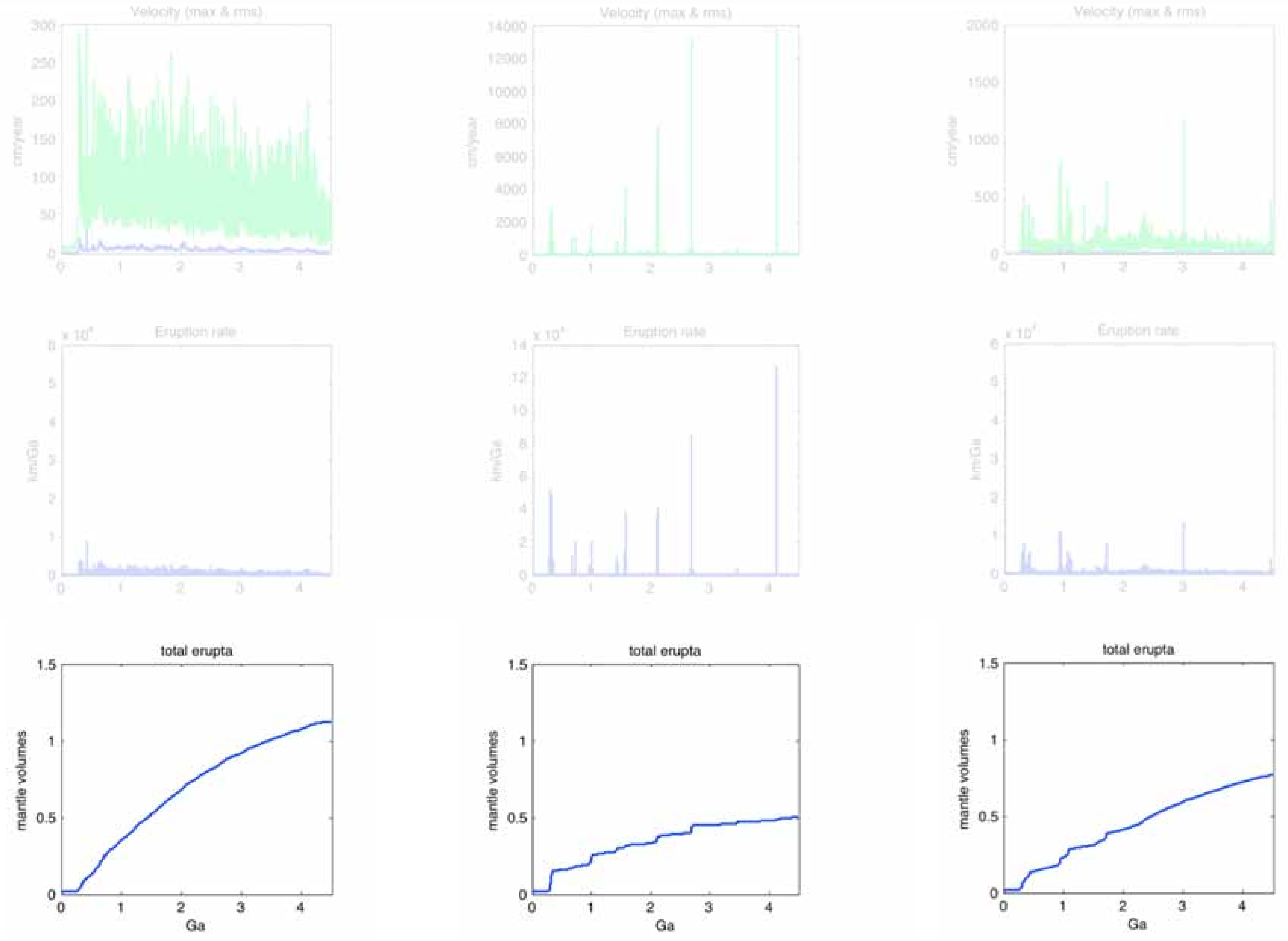




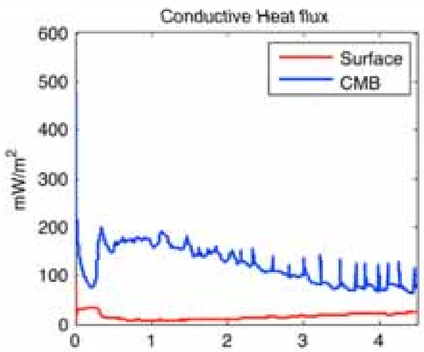
Stagnant	Ys=100	Ys=200

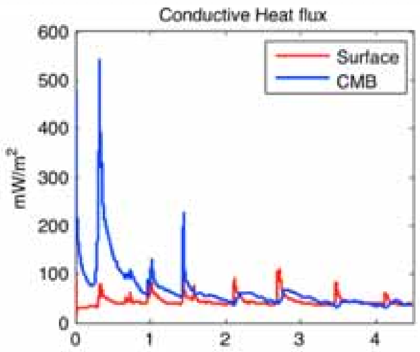


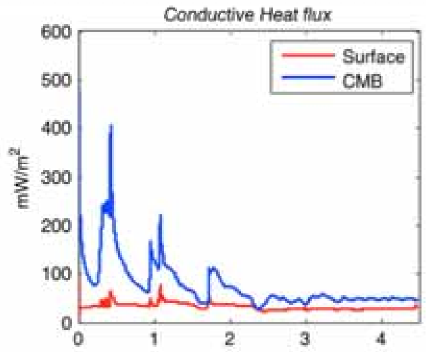
Stagnant	Ys=100	Ys=200



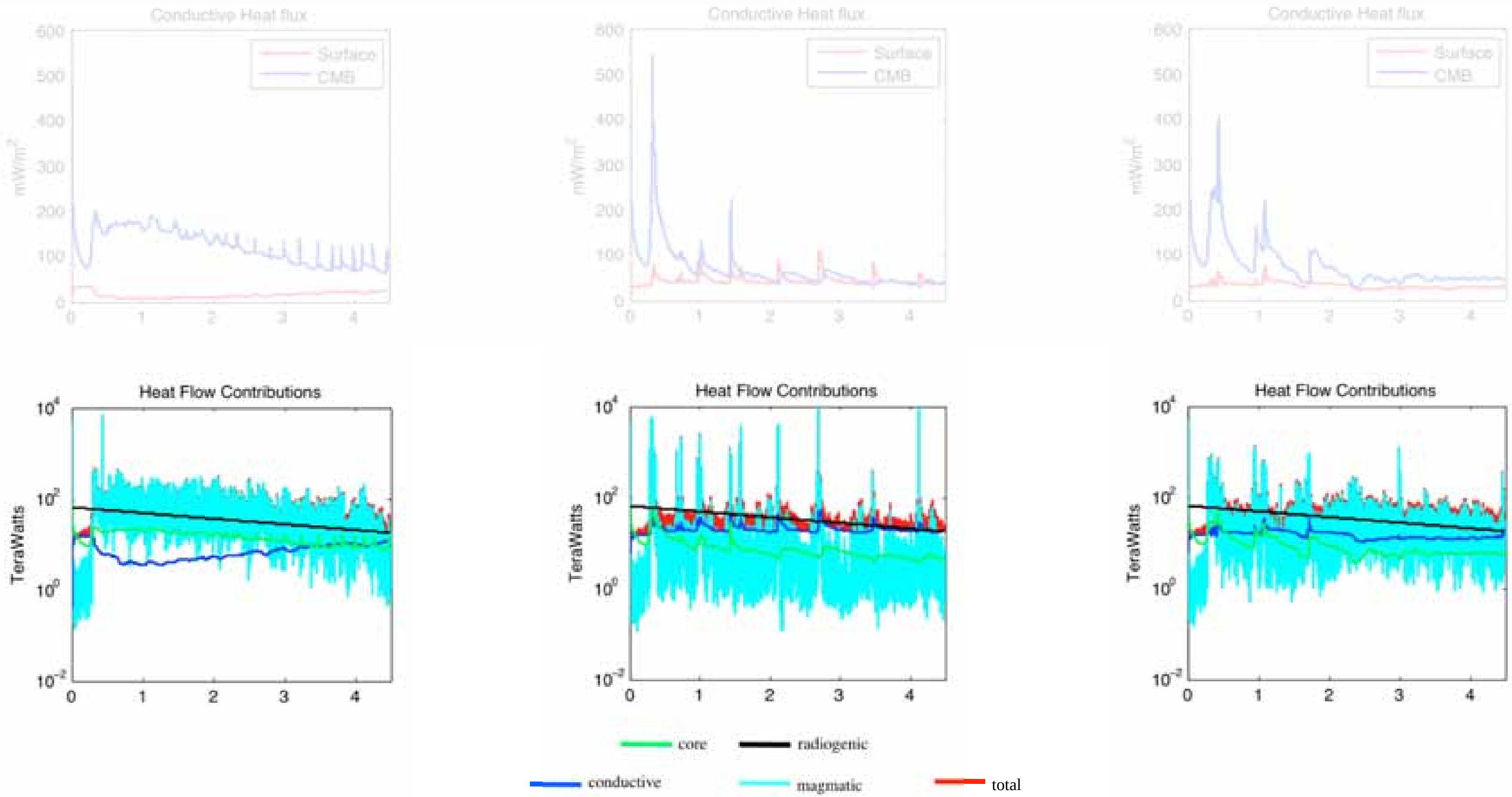
Stagnant   Ys=100   Ys=200



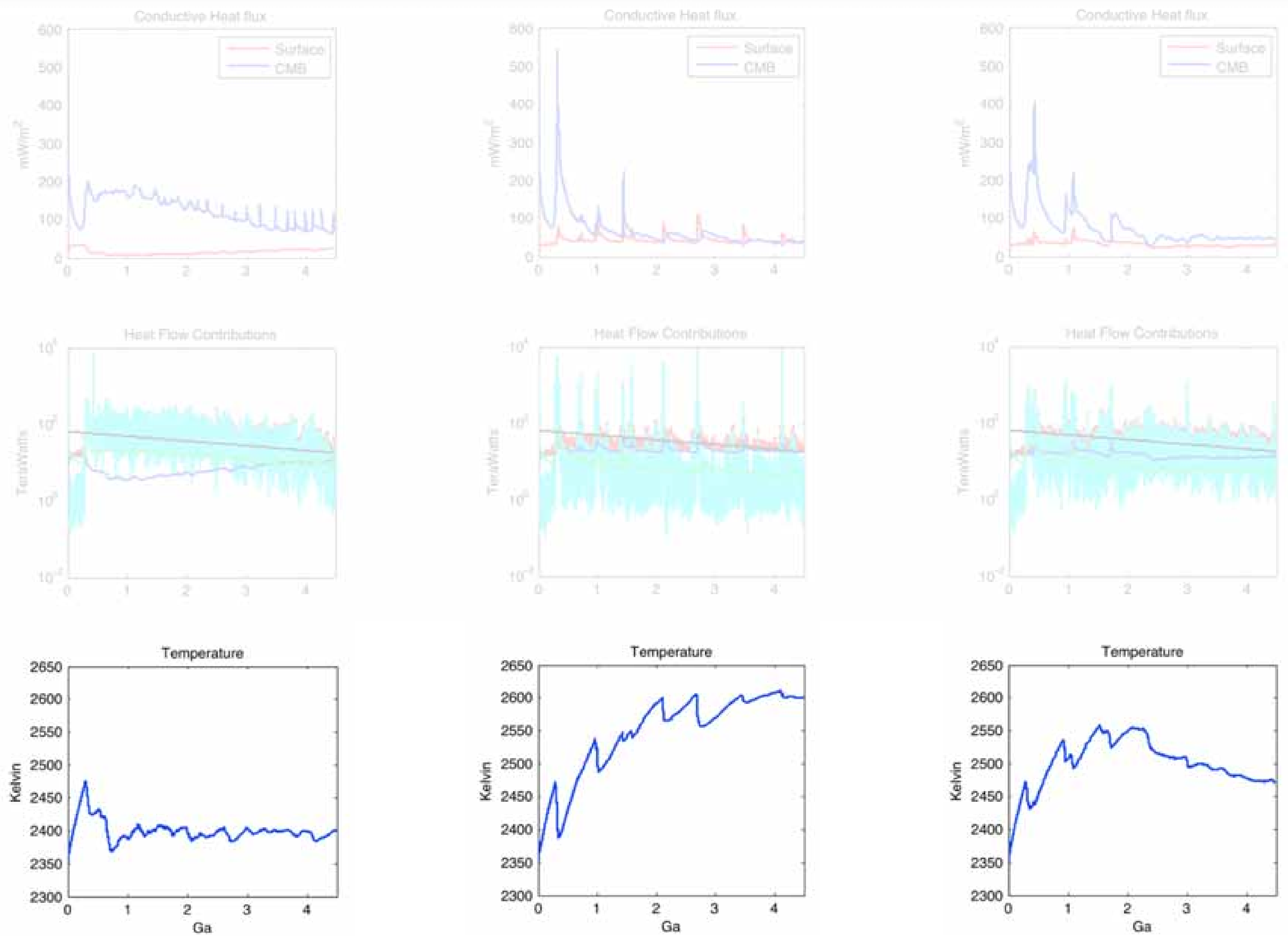




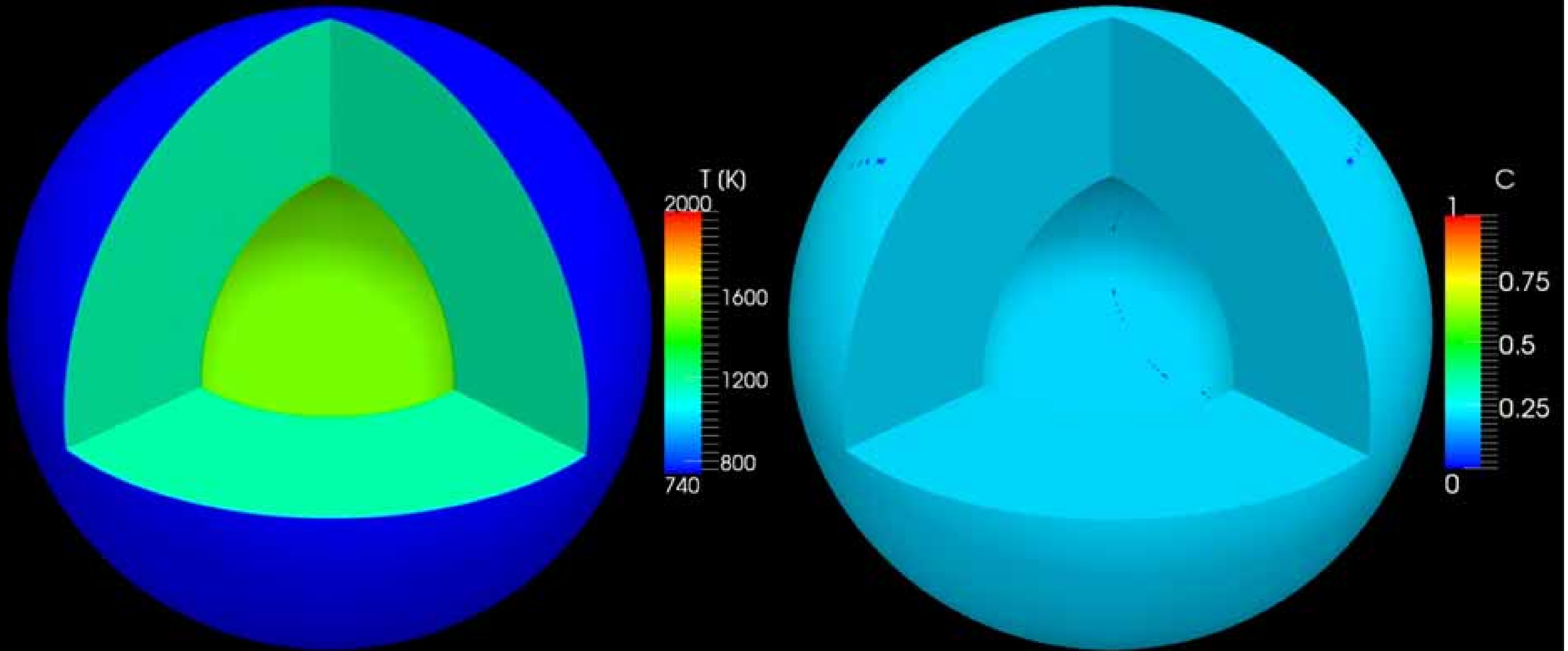
Stagnant | Ys=100 | Ys=200



Stagnant	Ys=100	Ys=200

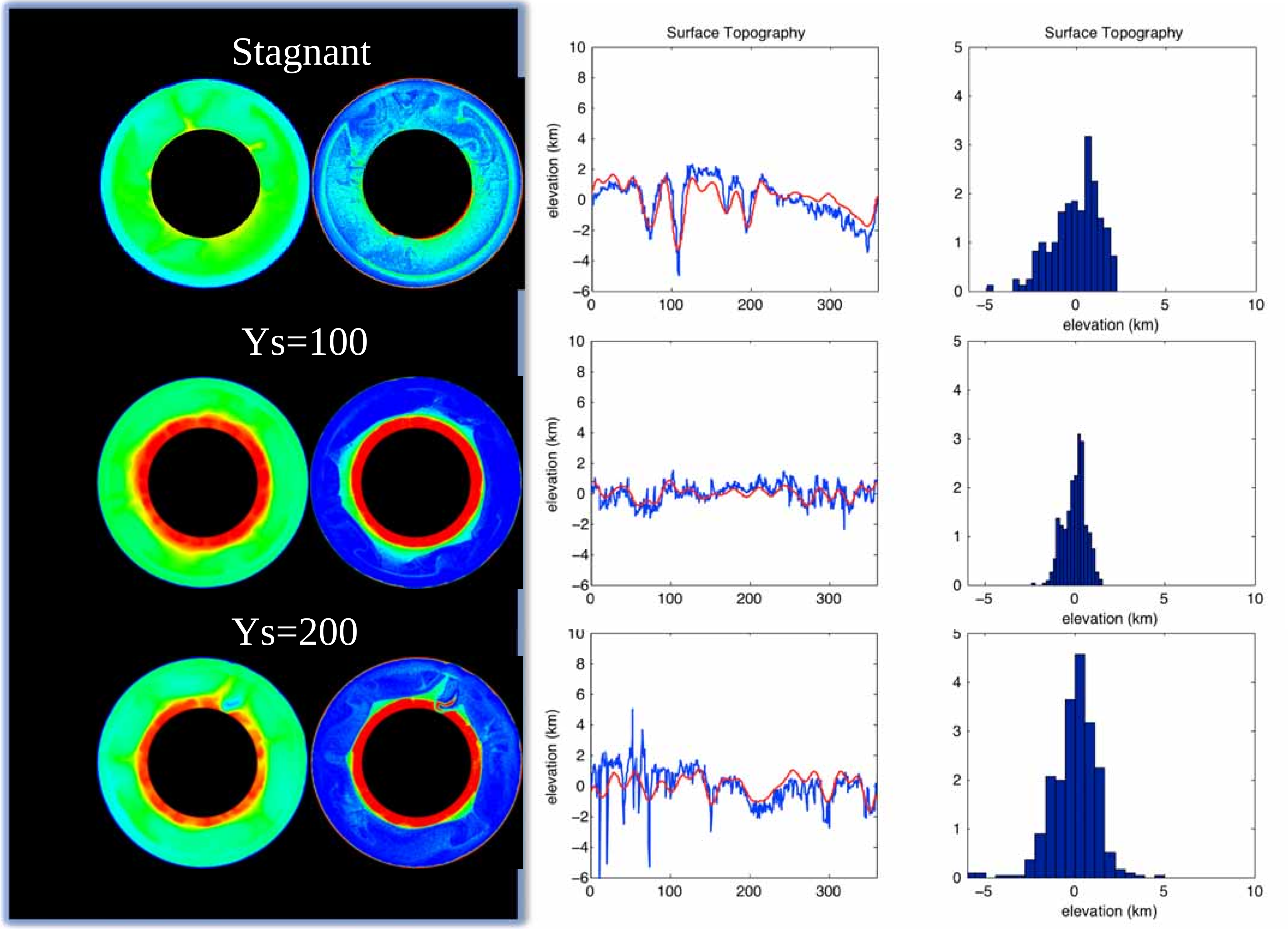


Episodic 3-D model

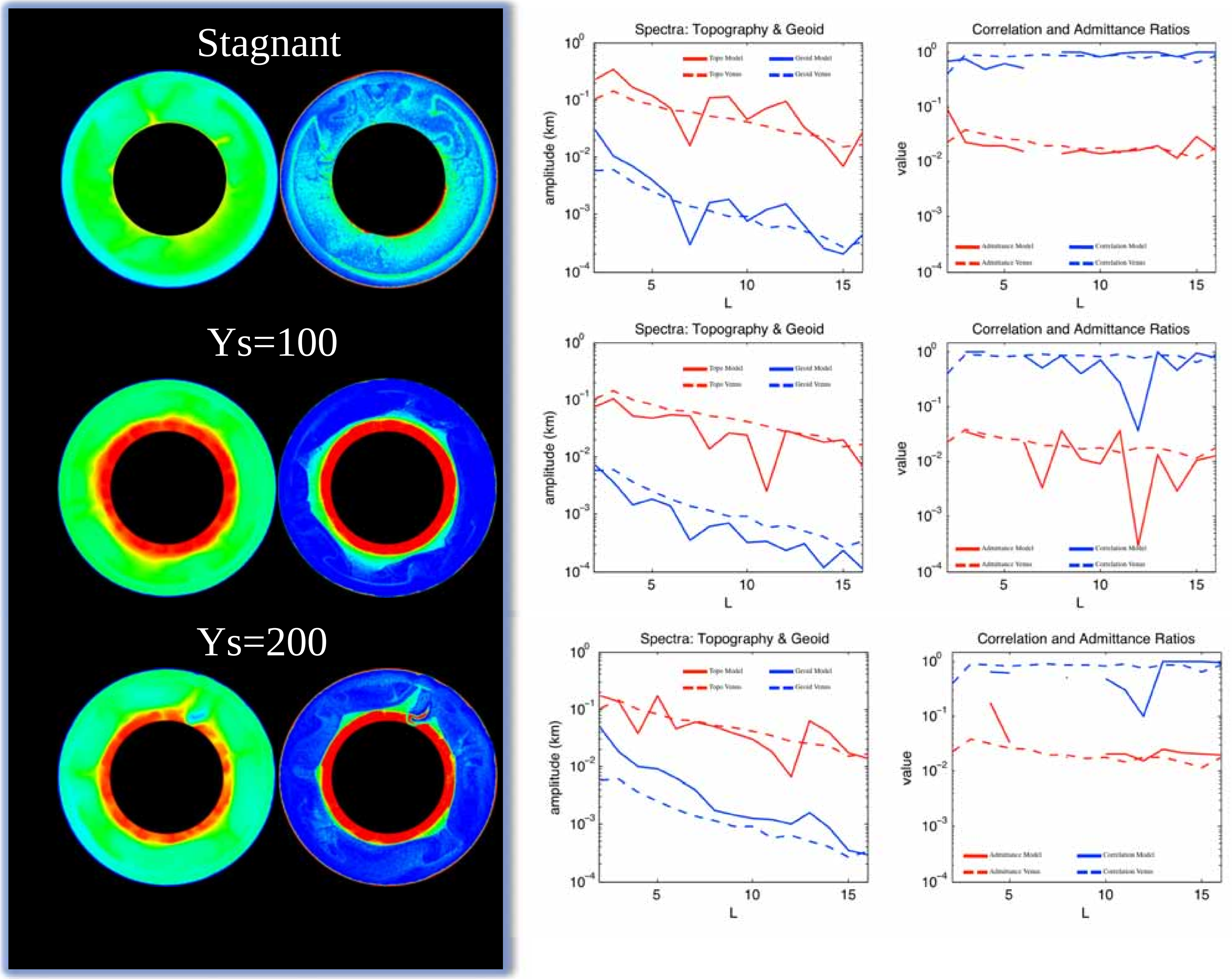


Temperature

Composition



Stagnant
Ys=100
Ys=200
Surface Topography
Surface Topography
elevation (km)
elevation (km)



Stagnant
Ys=100
Ys=200
Spectra: Topography & Geoid
Correlation and Admittance Ratios
amplitude (km)
value
L

Conclusions

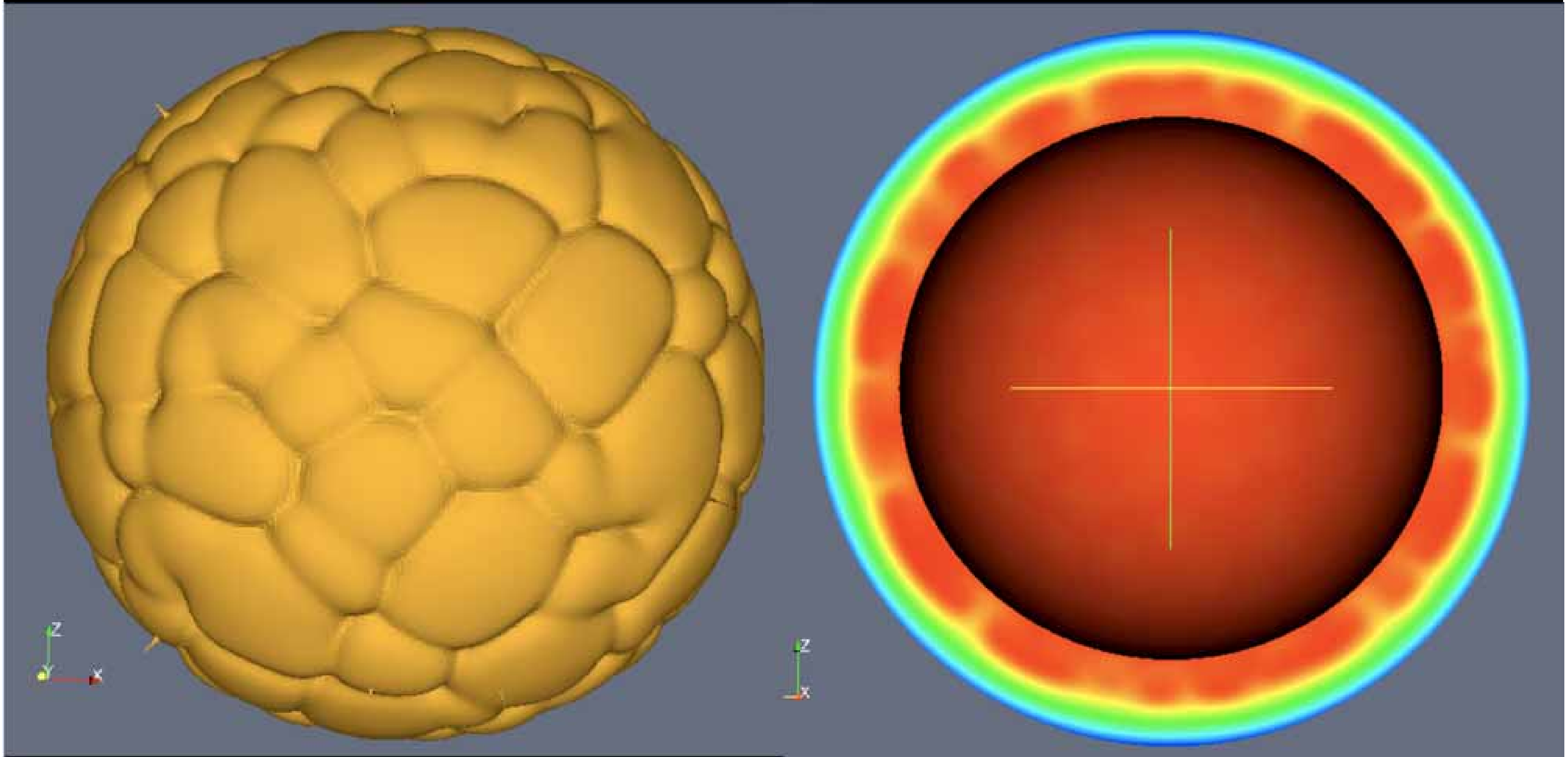
- Rigid lid: Magmatism dominant heat transport mode, crustal delamination. Match geoid & topography for reference viscosity ~10^{20} Pa s

- Episodic overturn: deep crustal recycling, conduction more important, geoid & topo OK

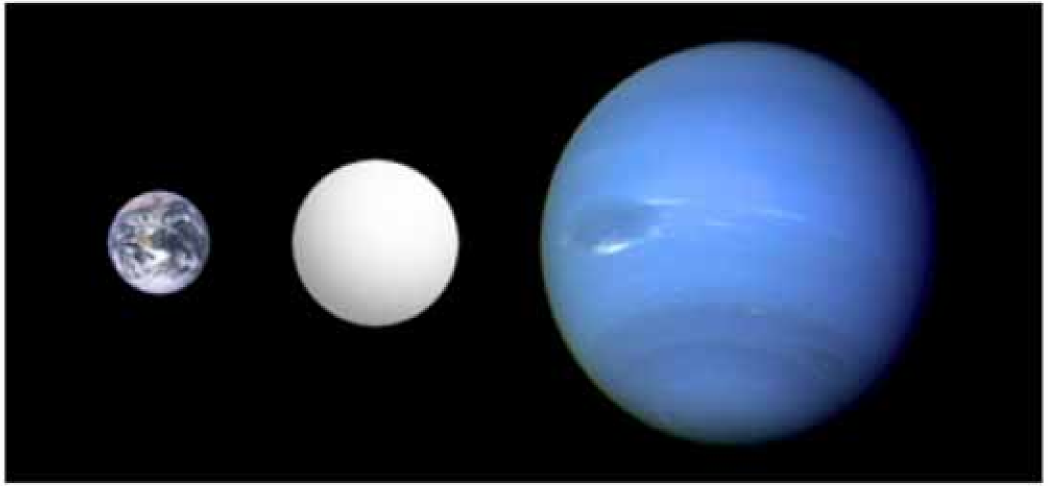
- Geoid, topography, admittance ratios favour viscosity~10^{20}-10^{21} Pa s

- Preferred case: episodic yielding with ys 100 MPa

Mercury: 3D spherical model



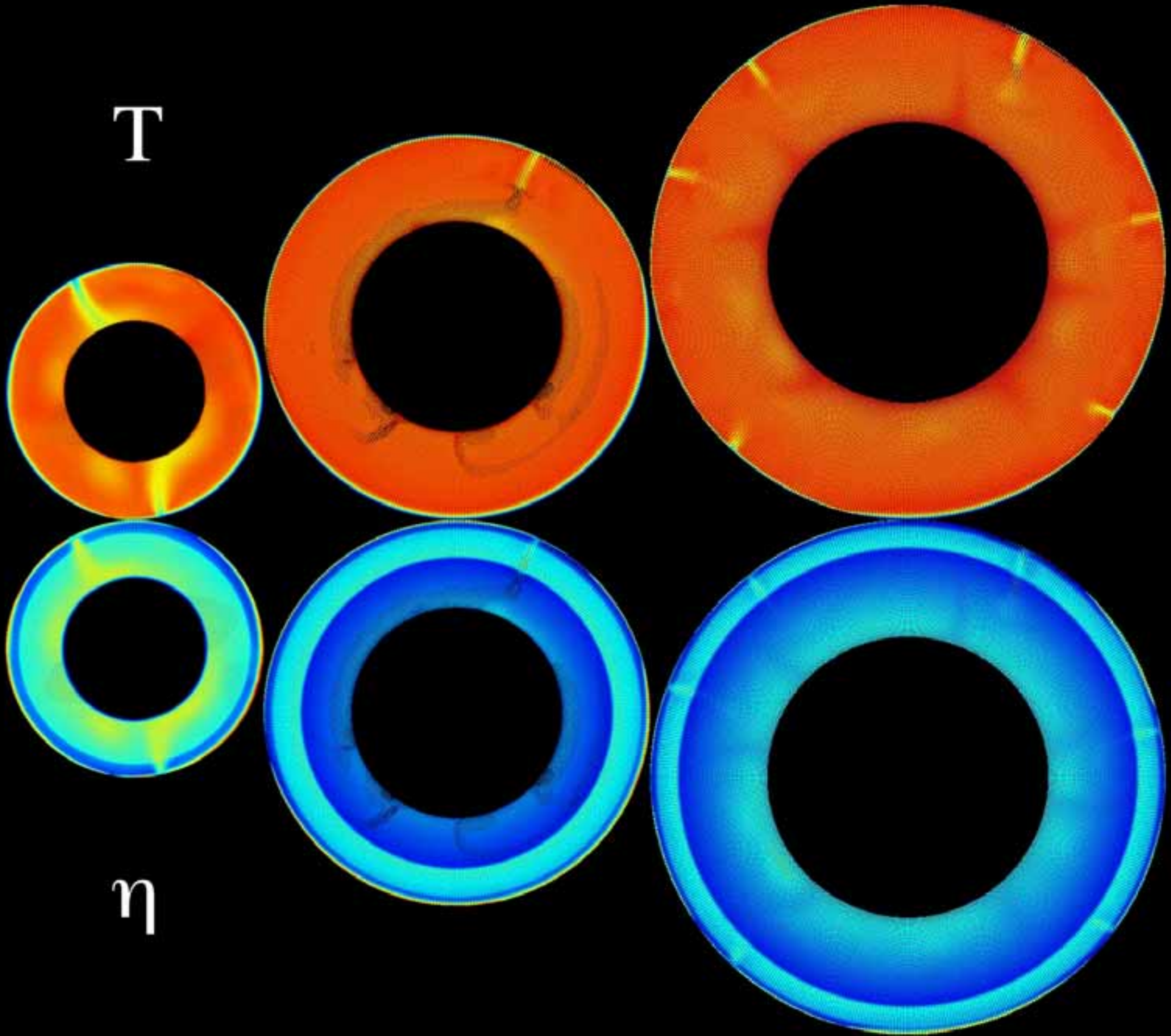
Dynamics of extrasolar Super-Earths?

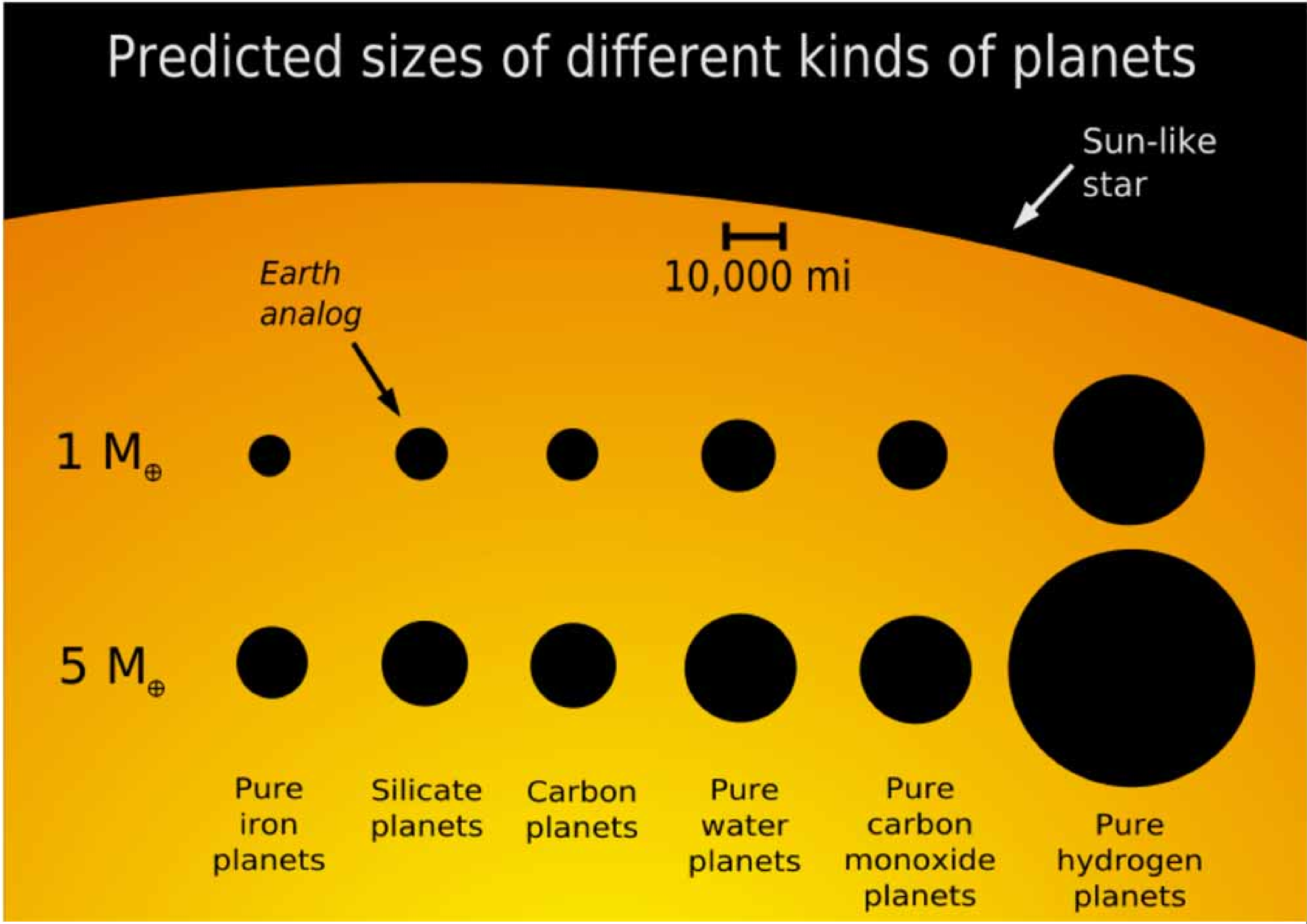


COROT-7b

- A few Super-Earths (1-10 * mass of Earth) have been found; many more expected.
  Do we expect them to have plate tectonics?
- Extending our previous study of self-consistent plate tectonics to study this question, using a joint analytic – numerical approach: (van Heck & Tackley 2011)
- **Super-Earths are equally-likely or more likely to have plate tectonics than Earth, other things being equal**

ongoing work: more realism




Predicted sizes of different kinds of planets
Sun-like star
10,000 mi
Earth analog
1 $M_\oplus$
5 $M_\oplus$
Pure iron planets
Silicate planets
Carbon planets
Pure water planets
Pure carbon monoxide planets
Pure hydrogen planets

wikipedia

Overall summary/conclusions

- Scaling of plate tectonic convection can be predicted using a joint analytic-numerical approach
- Free surface top boundary allows 1-sided subduction in "self-consistent" plate tectonics models
- Mars: Intrinsic (internal) dynamics may be able to explain crustal dichotomy.
- Venus: Episodic lid needed to fit surface age & low magmatism
- Many more terrestrial planets!

THE END!