Convection and grain size evolution in the mantle

Antoine Rozel

G. Golabek, M. Thielmann, T. Gerya and P. Tackley

ERC project: iGEO
Institute of Geophysics
Geophysical Fluid Dynamics Group
ETH, Zurich, Switzerland

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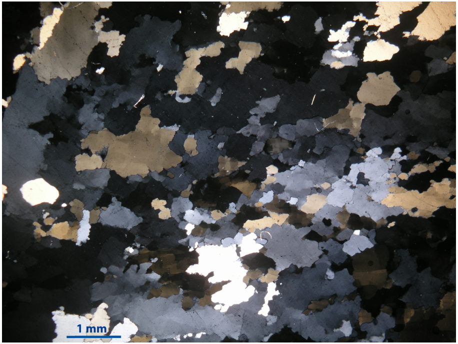
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

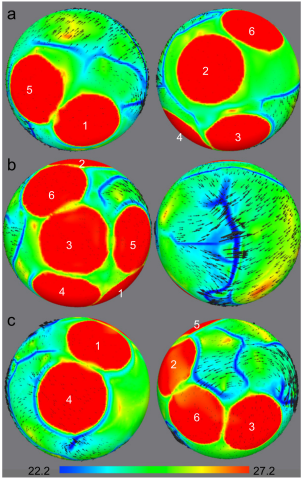
Why do we care about grain size evolution?



Quartz. Picture : E. Boutonnet

- Deformation experiments $\Rightarrow \exists$
- Often neglected because too non-linear and numerically challenging.
- Our convection models fail to generate
  - present day plate tectonics.
  - the history of plate tectonics.

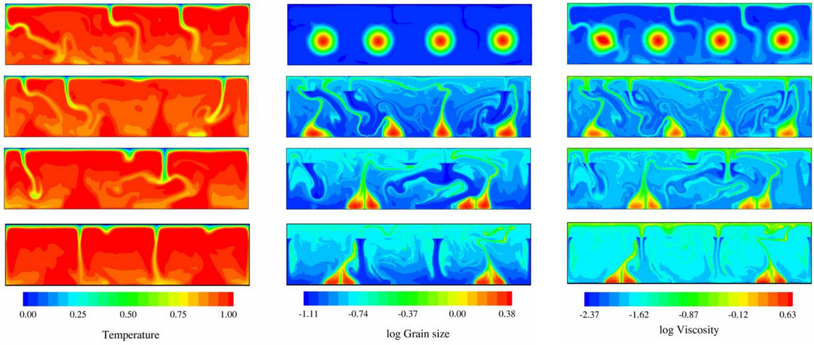
What is wrong with our plate tectonics model?



Rolf et al 2012, EPSL

- Plate boundaries disappear
- Grain size homogeneous and constant

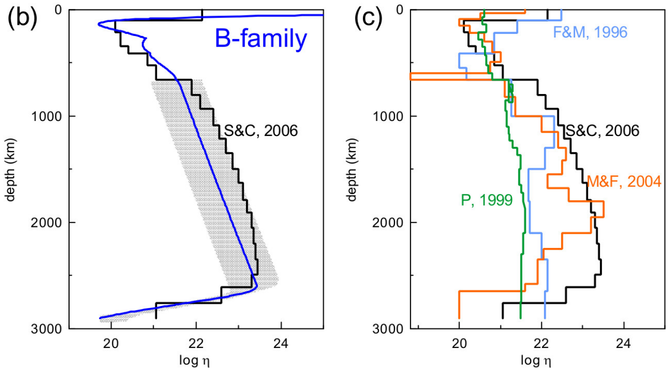
How about this?



Solomatov and Reese, 2008, JGR

- Viscosity profile unrealistic
- No dislocation creep

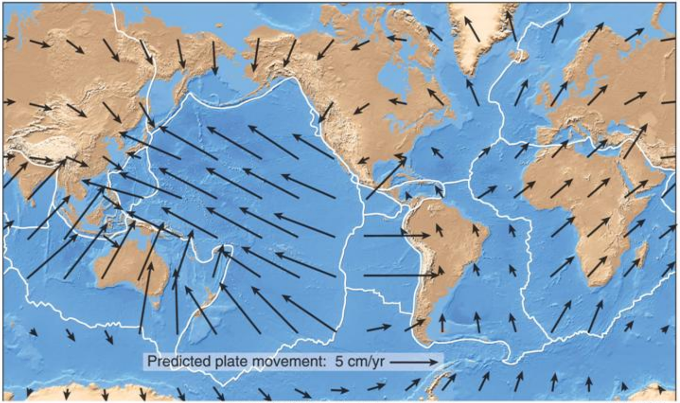
What do we want?



Čížková et al 2012, EPSL

- Present day viscosity profile

What do we want?



Copyright © 2006 Pearson Prentice Hall, Inc. Fig 12.37

Pearson Prentice Hall

- Surface plate velocities ~ 3 cm/yr.

What do we have?

POSSIBLE TOOLS

- New model of grain size evolution
- Complex composite rheology
- Models of compressible convection

PROBLEMS

- Very uncertain parameters
- No model for present day effective grain size
- No unique solution

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Static growth

Surface tension

$P(\mathcal{R})$

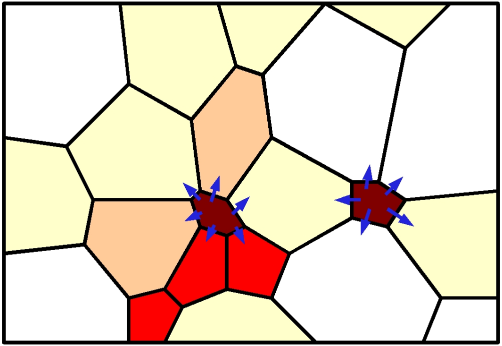
Mater flux between grains

$$\Delta P = \frac{2\gamma}{\mathcal{R}}$$

Laplace law

$\Downarrow$

$< \mathcal{R} >$ grows!



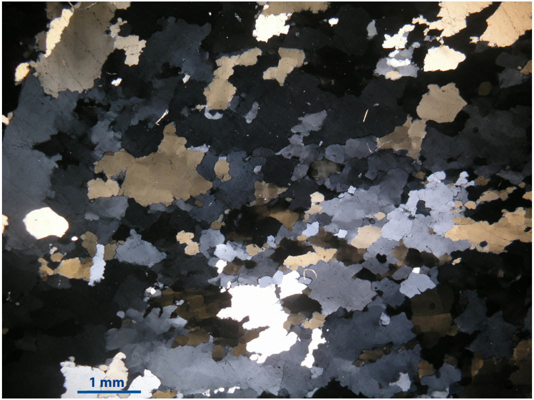
Dynamic recrystallization

Subgrain nucleation

Dislocations gathering

$\Downarrow$

$< \mathcal{R} >$ diminishes!



Quartz. Picture : E. Boutonnet

General Evolution

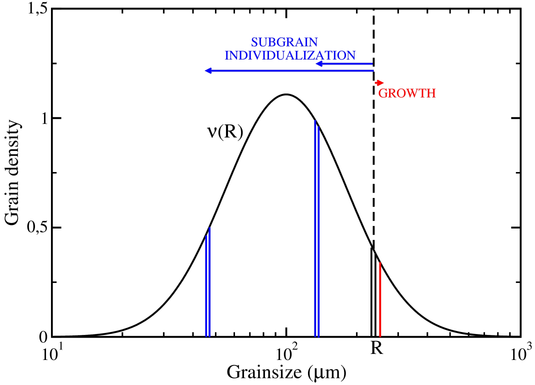
Processes

Continuous vs

discontinuous

$$\frac{\partial \nu(\mathcal{R})}{\partial t} + \frac{\partial(\dot{\mathcal{R}}\nu(\mathcal{R}))}{\partial \mathcal{R}} = \Gamma$$

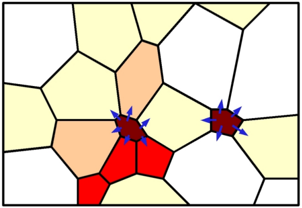
Self-similar distribution

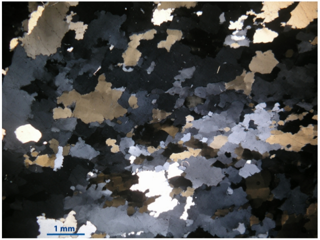


General evolution

Introduction of the partitionning parameter $f \Rightarrow 0 < f < 1$

$$\Rightarrow \frac{\partial \mathcal{R}_0}{\partial t} = \frac{G}{p\mathcal{R}_0^{p-1}} - f\frac{\mathcal{R}_0^2}{\gamma} c\underline{\tau} : \underline{\dot{\epsilon}}_{disl}$$





Austin & Evans 2007 Geology // Rozel, Ricard & Bercovici – GJI 2010

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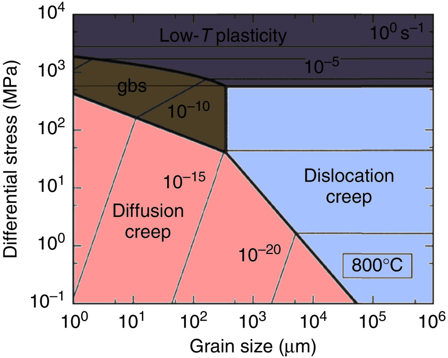
Rheological domains of olivine

Shear Stress / Grain Size

4 behaviors

Extrapolation

$$\dot{\underline{\epsilon}} = A_0 \exp\left(-\frac{E+PV}{RT}\right) \mathcal{R}^{-m} \tau^{n-1} \underline{\tau}$$



Kohlstedt 2007

Rheological domains of olivine

Diffusion creep:

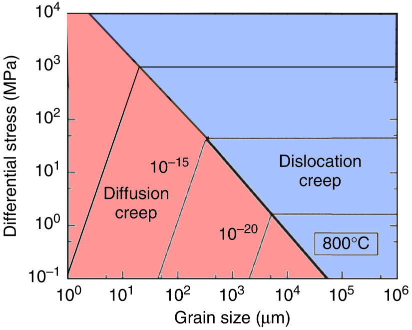
$$\eta_{df} = \exp\left(\frac{E_{df} + PV_{df}}{RT}\right)\frac{\mathcal{R}^m}{2A_{df}}$$

Dislocation creep:

$$\eta_{ds} = \exp\left(\frac{E_{ds} + PV_{ds}}{RT}\right)\frac{\tau^{1-n}}{2A_{ds}}$$

Composite viscosity

$$\frac{1}{\eta} = \frac{1}{\eta_{df}(\mathcal{R}, T)} + \frac{1}{\eta_{ds}(\tau, T)}$$



Kohlstedt 2007

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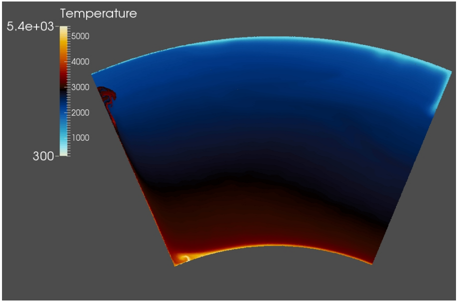
Conceptual model

Conceptual model

- Plate teconics
- Present day temperature profile
- Compressible convection
- Spherical geometry



1D Conceptual Model

Let's do a

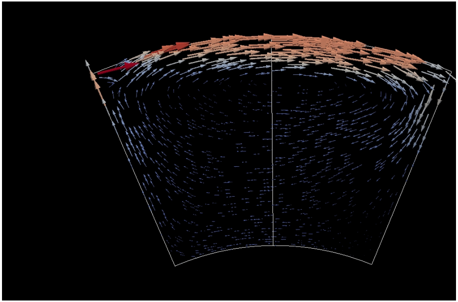
1D analytical model

that predicts grain size!

1D Conceptual Model

Conceptual model

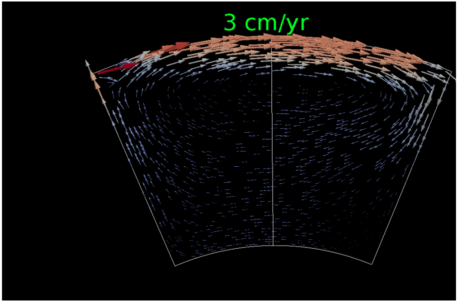
-
-
-
-



1D Conceptual model

What we want:

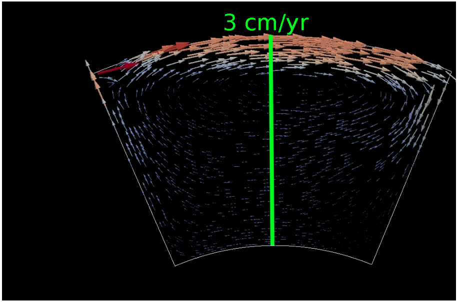
- Surface velocity = 3 cm/yr
-
-
-



1D Conceptual model

What we want:

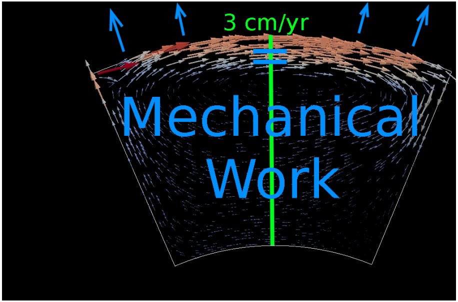
- Surface velocity = 3 cm/yr
- Mass conservation
-
-



1D Conceptual model

What we want:

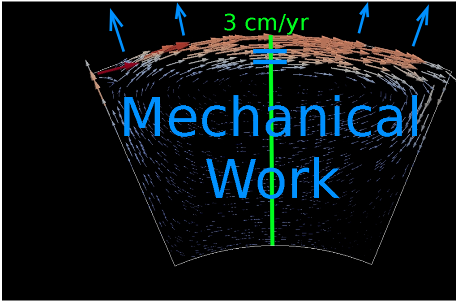
- Surface velocity = 3 cm/yr
- Mass conservation
- Advective heat flux = work
-



1D Conceptual model

What we want:

- Surface velocity = 3 cm/yr
- Mass conservation
- Advective heat flux = work
- Lower mantle viscosity $= 10^{23} Pa \cdot s$



1D Conceptual model

What we want		What it means in the centerline
Surface velocity = 3 cm/yr	$\rightarrow$	
Advective heat flux = work	$\rightarrow$	
Mass conservation	$\rightarrow$	
Lower Mantle viscosity $= 10^{23} Pa.s$	$\rightarrow$	

1D Conceptual model

What we want		What it means in the centerline
Surface velocity = 3 cm/yr	$\rightarrow$	top v_x forced
Advective heat flux = work	$\rightarrow$	
Mass conservation	$\rightarrow$	
Lower Mantle viscosity $= 10^{23} Pa.s$	$\rightarrow$	

1D Conceptual model

What we want		What it means in the centerline
Surface velocity = 3 cm/yr	→	top v_x forced
Advective heat flux = work	→	$\tau(z)\dot{\epsilon}(z) = \frac{\alpha g}{C_p} F \left(1 - \frac{1}{Nu}\right)$
Mass conservation	→	
Lower Mantle viscosity $= 10^{23} Pa.s$	→	

1D Conceptual model

What we want		What it means in the centerline
Surface velocity = 3 cm/yr	$\rightarrow$	top v_x forced
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	$\Leftrightarrow$	$2\eta(z)\dot{\epsilon}(z)^2 = \frac{\alpha g}{C_p} F \left(1 - \frac{1}{Nu}\right)$
Mass conservation	$\rightarrow$	
Lower Mantle viscosity $= 10^{23} Pa.s$	$\rightarrow$	

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Mass conservation	$\rightarrow$	$\int_{z=0}^{h} \rho(z) v(z)\, 4\pi R(z)^2\, dz = 0$
Lower Mantle viscosity		$\downarrow$
$= 10^{23} Pa.s$	$\rightarrow$	

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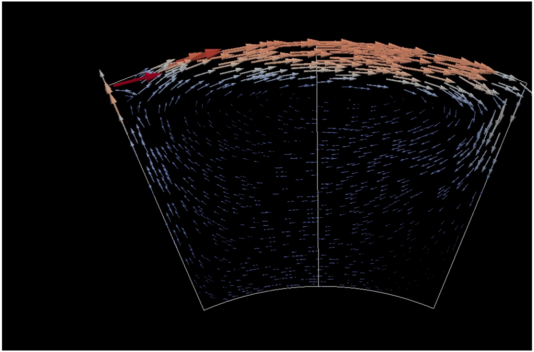
Lower Mantle viscosity		$\downarrow$
$= 10^{23} Pa.s$	$\rightarrow$	adjust free parameters

1D Conceptual model

List of free parameters

- Activation Energy E
- Activation Volume V
- Viscosity Jump $\Delta\eta_{660}$
- Reference viscosity η_0
- Grain growth kinetics
- Intensity of dynamic recrystallisation
- How long should the grains grow??



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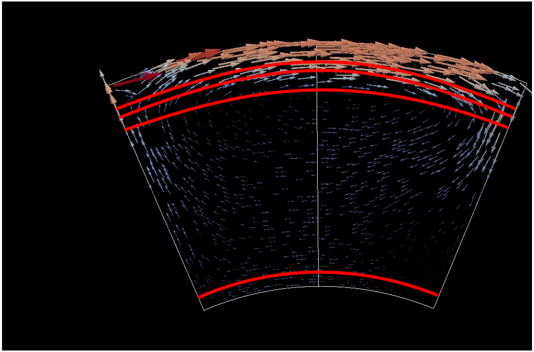

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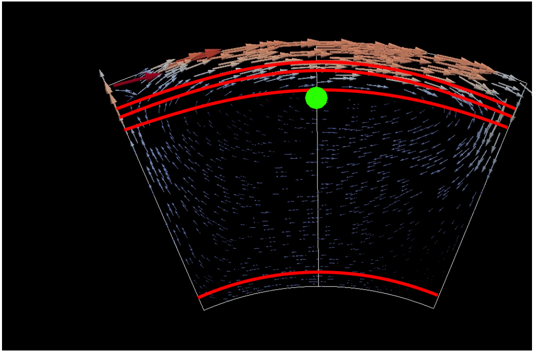

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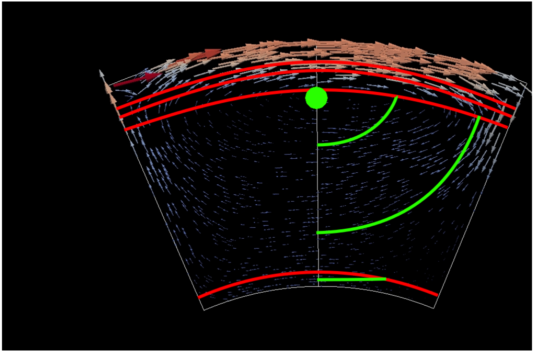

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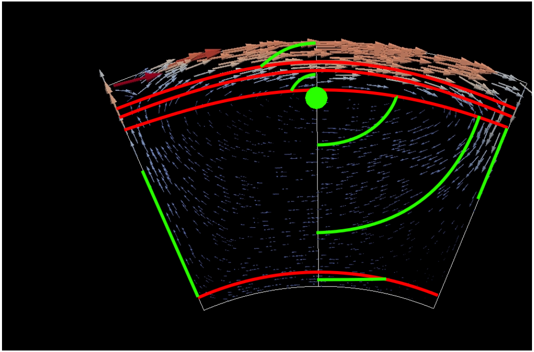
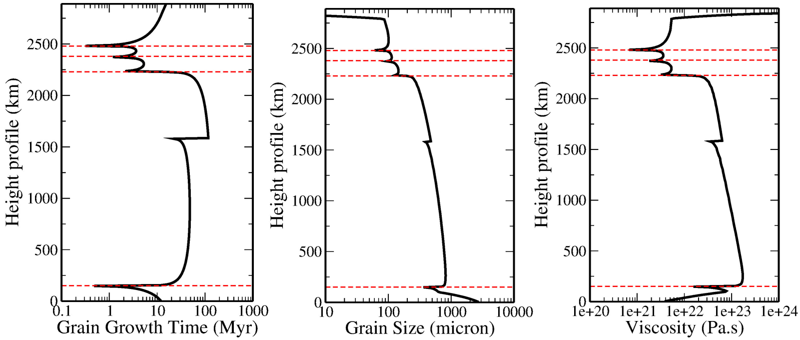
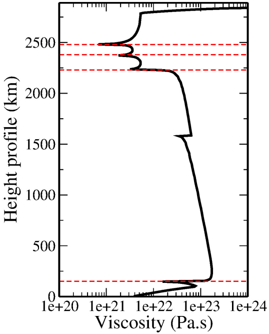


1D Conceptual model



How about dislocation creep?

How about dislocation creep?



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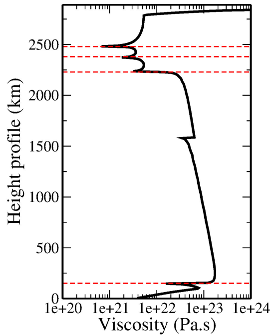

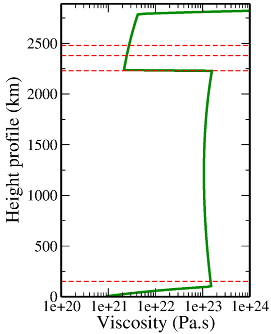

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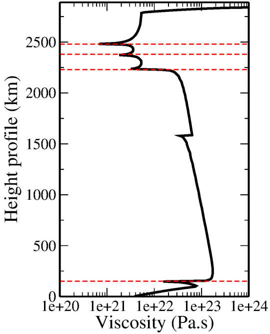
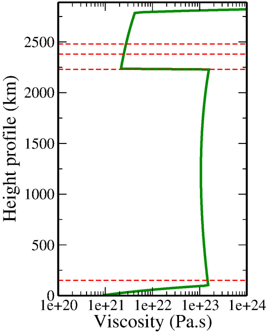
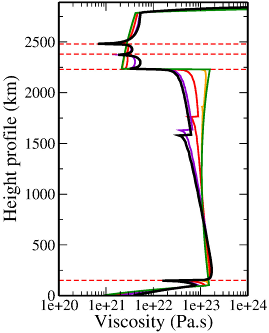
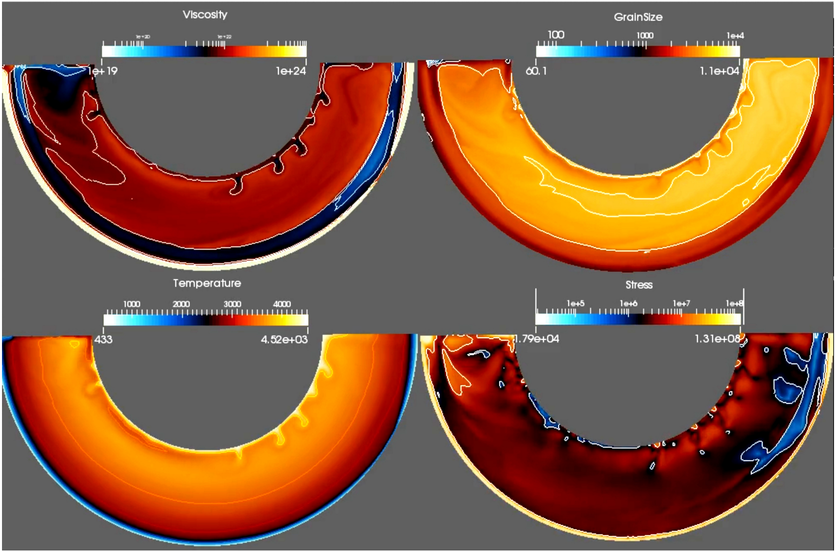


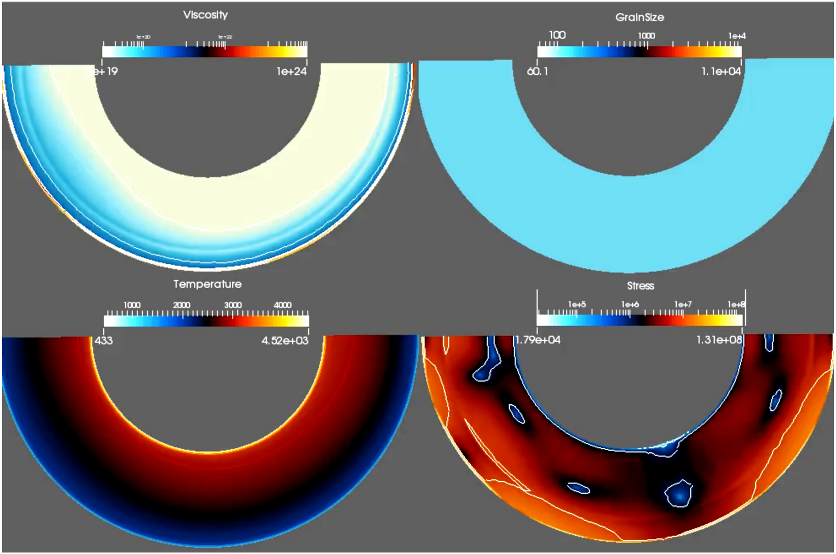




Preliminary results – non-equilibrium grain size



Preliminary results – initial situation



Conclusion

- Rheological parameters for convection models difficult to know
- Grain size in the mantle a priori unknown
- 1D convection model created
- Self-consistent grain size/rheology converged
- Grain size-dependent viscosity jump predicted at the 660
- Numerically confirmed!

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THANK YOU FOR YOUR ATTENTION