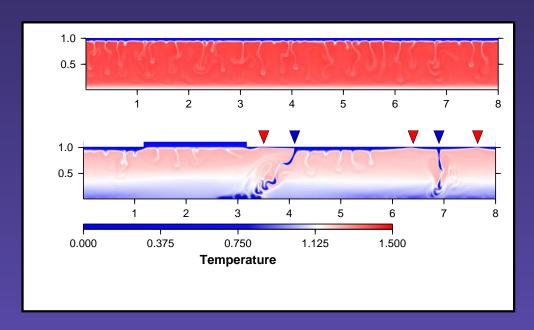
Onset of Plate Tectonics: The Effect of Continent-like Heterogeneities



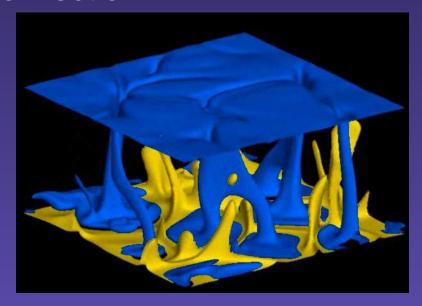
Thanks to: P. Tackley and the GFD group seminar ETH Zürich

A very thrilling problem from a modeler's point of view:

- Why is there plate tectonics on Earth and not on other terrestrial planets?
 - "(The) <u>fundamental</u> question of how plates arise from mantle convection" (Bercovici).
 - "The greatest unresolved problem" (Stevenson).
 - "The Quest for Self-Consistent Generation of Plate Tectonics in Mantle Convection Models: (...) a type of Holy Grail (for) mantle convection modelers", "a long standing puzzle" (Tackley).

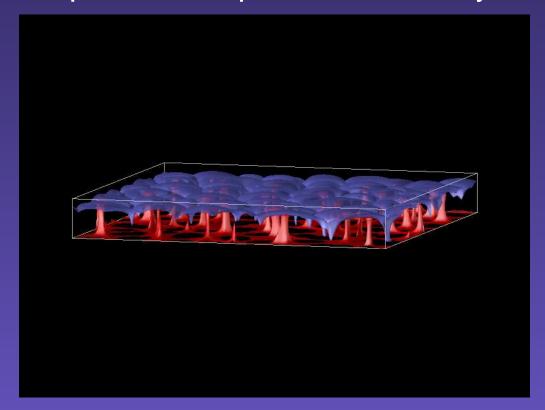
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 - Isoviscous convection:



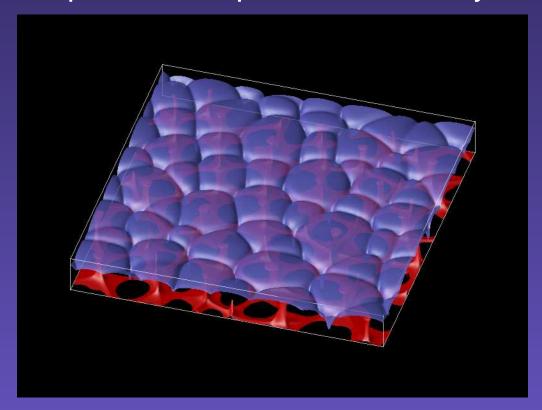
(Model by Stéphane Labrosse, $Ra = 10^7$ H = 20)

- 'Classical' models of mantle convection do not exhibit a plate-like behavior:
 - Strongly-temperature dependent viscosity:



(Ra =
$$10^6$$
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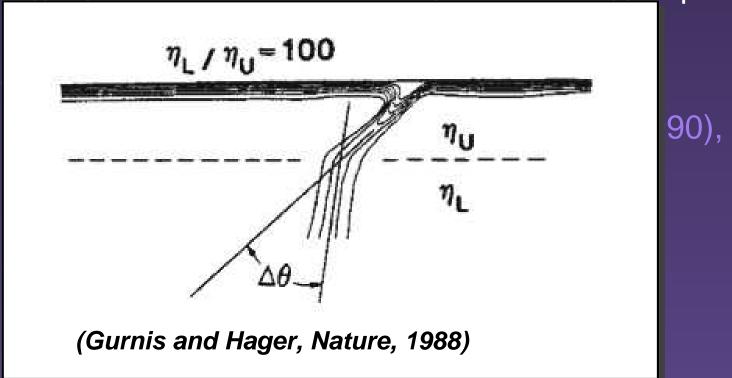
■ Kinematic plates (plate velocity imposed): (e.g. Davies, *JGR*, 1988; Bunge and Richards, *GRL*, 1996).

■ Weak zones:

 Rigid plates and weak zones (low viscosity) at plate boundaries.

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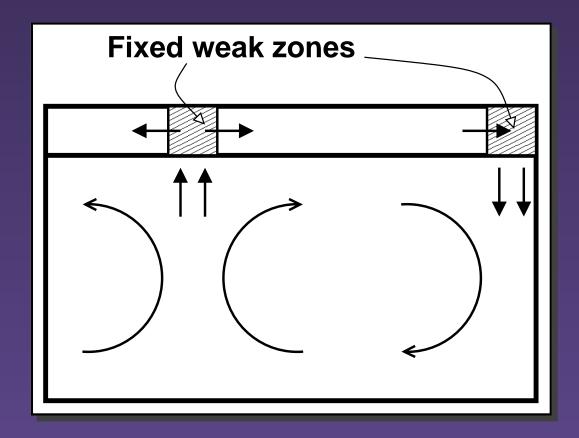
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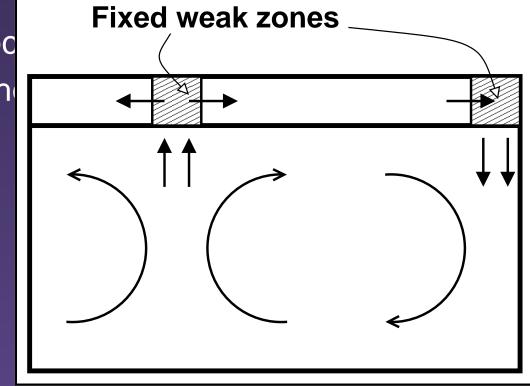
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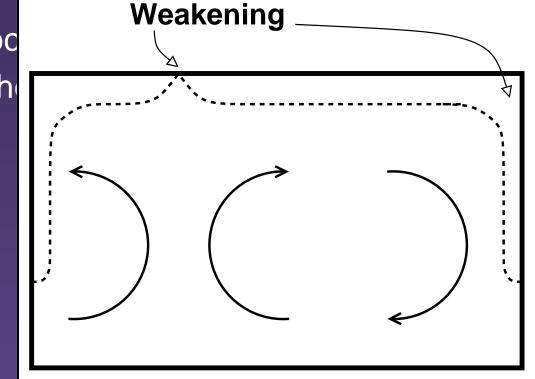
- First steps towards generating plate tectonics in models.
- ▶ Plates considered as a boundary condition on top of the convective mantle.
- But velocity and heat flux observations: the plates are the upper thermal boundary layer for mantle convection.

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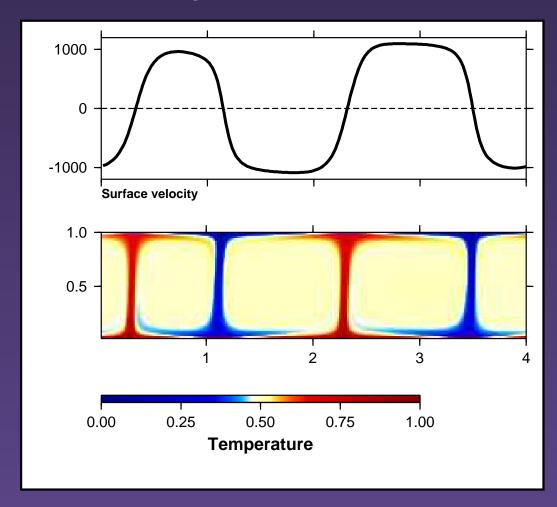
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 - "plates and convection are one coupled system" (Tackley, AGU Monog., 1999).
 - "the plates are convection" (Bercovici, EPSL, 2003).

- First steps towards generating plate tectonics in models.
- Plates considered as a boundary condition on top of the convective mantle.
 - "plates and convection are one coupled system" (Tackley, AGU Monog., 1999).
 - "the plates are convection" (Bercovici, EPSL, 2003).
- Need for a <u>self-consistent</u> approach:
 - Fully dynamical approach.
 - One description for mantle and plates.

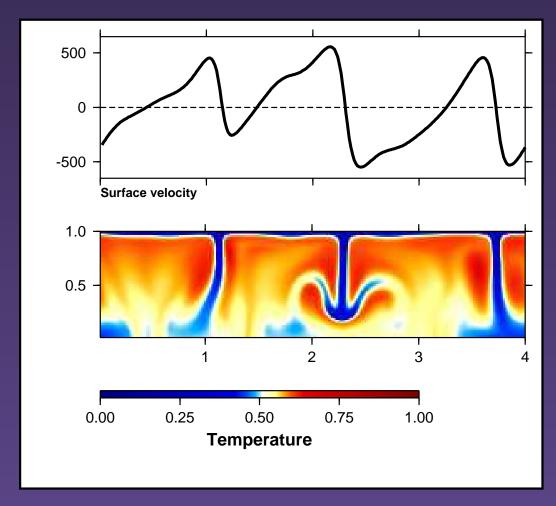
- What do we want to get?
- Two-dimensional models:
 - Strong plate interiors and narrow deforming boundaries.
 - Plate-like velocity at the surface: uniform at the scale of a plate.
 - One-sided subduction zones.
- Three-dimensional models:
 - Large Toroidal/Poloidal ratio.
 - Strike-slip (transform faults).

■ What do we get with "simple" rheologies?

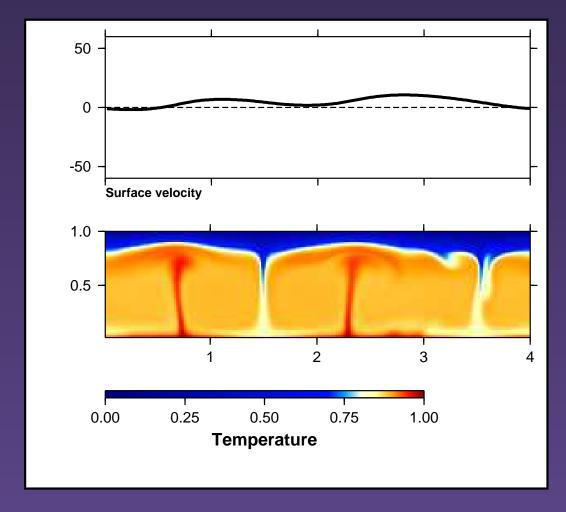
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- What do we get with "simple" rheologies?
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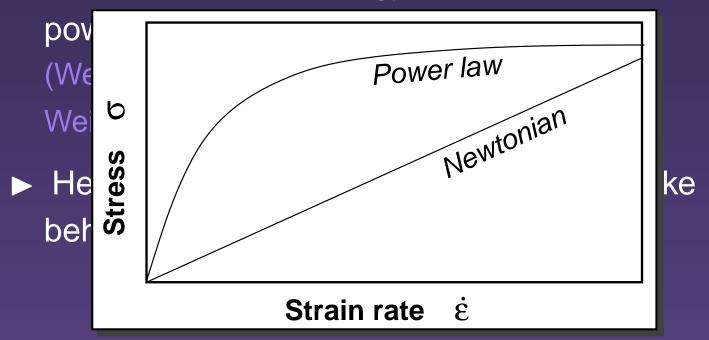


- What do we get with "simple" rheologies?
- Strongly-temperature dependent viscosity:



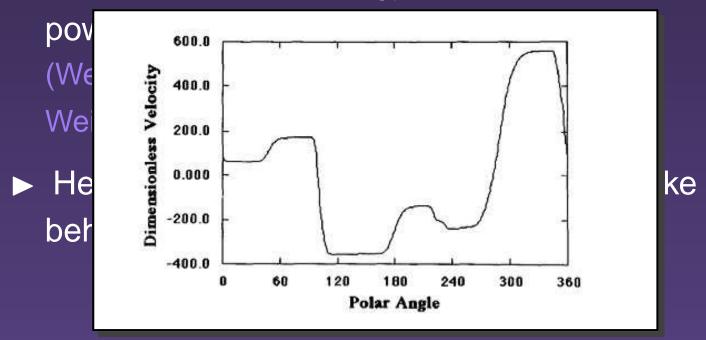
- First attempts:
 - Temperature-dependent viscosity,
 - Non-Newtonian rheology: power law: $\dot{\varepsilon} \sim \sigma^{\rm n}$. (Weinstein, *Pure Appl. Geophys.*, 1996; Weinstein and Olson, *GJI*, 1992)
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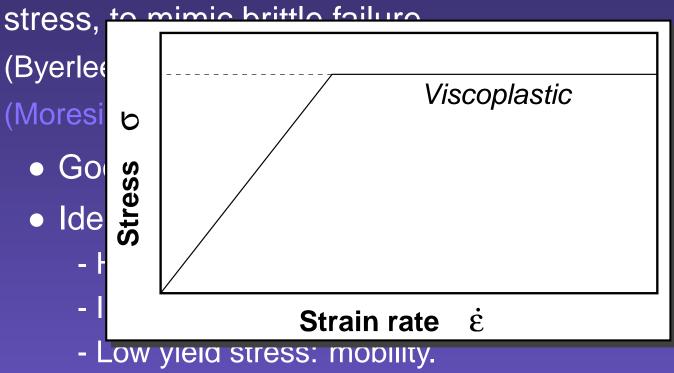
- With realistic temperature-dependency: very strong upper viscous lid.
- Power-law rheology is not enough to break this strong lid.
 (Solomatov, *Phys. Fluids*, 1995)
- Need to explicitly include yielding.

- Viscoplastic rheology: introduction of yield stress.
- Two-dimensional models with viscosity strongly dependent on temperature and depth-dependent yield stress, to mimic brittle failure
 (Byerlee's frictional law: σ_v(z) = C₀ + μ ρg z):

(Moresi and Solomatov, GJI, 1998)

- Good plate-like behavior possible.
- Identification of different regimes:
 - High yield stress: stagnant-lid.
 - Intermediate: episodic mobility.
 - Low yield stress: mobility.

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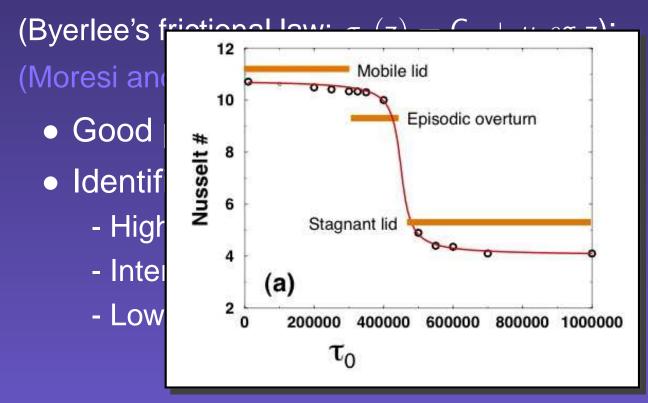


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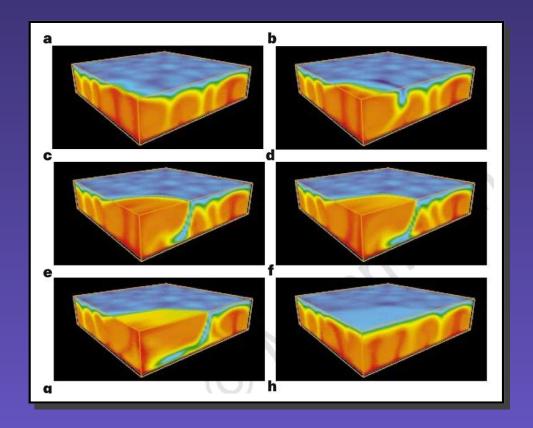
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- Three-dimensional models:
 - Trompert and Hansen, Nature, 1998:
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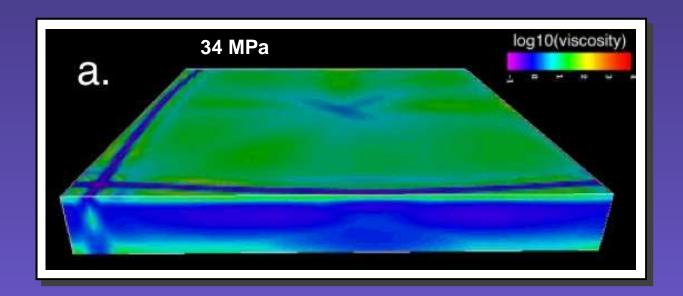
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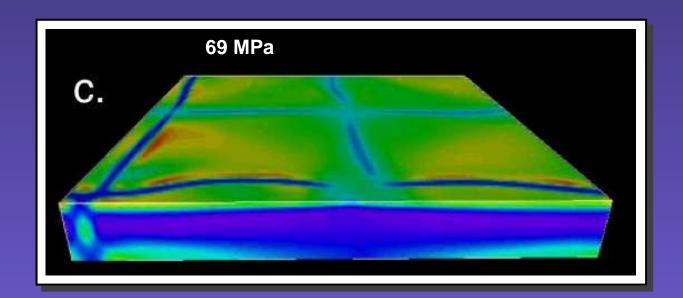
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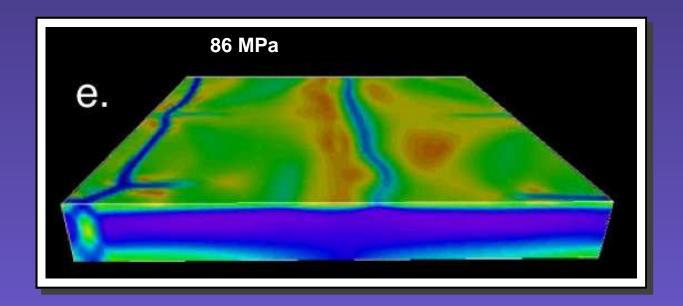
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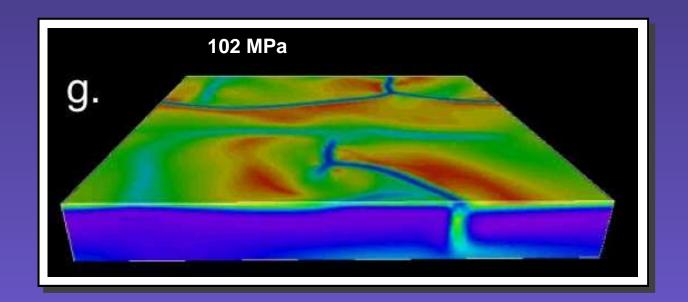
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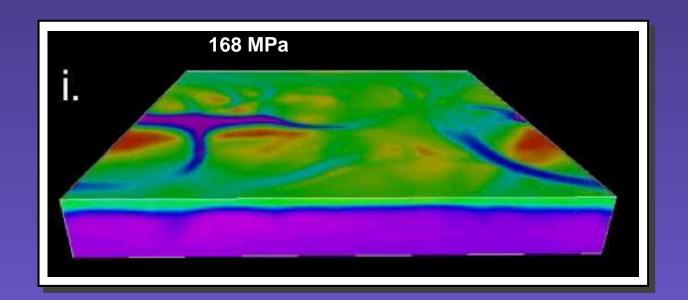
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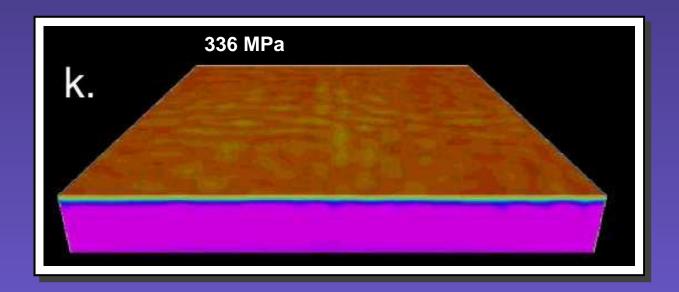
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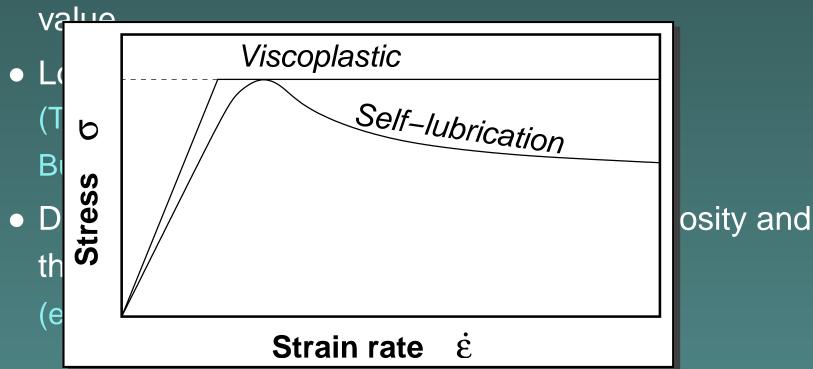


- Some problems:
 - Intra-plate deformation.
 - Low "plateness": plate boundaries are too wide.
 - In 3D: no transform faults.
 - Toroidal/Poloidal ratio too low.
 - Modelers need to use a yield stress significantly <u>lower</u> than what's given for the strength of the lithosphere by laboratory experiments on rocks: ~ 400-600 MPa (e.g. Kirby, *Rev. Geophys. Space Phys.*, 1983; Kohlstedt et al., *JGR*, 1995).

- Addition of other complexities:
 - Self-lubrication (a.k.a. self-weakening)
 (Bercovici, EPSL, 1993; Tackley, G³, 2000):
 stress decreases with strain-rate beyond a critical value.
 - Low viscosity asthenosphere.
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 - Depth-dependency of some properties: viscosity and thermal expansion.

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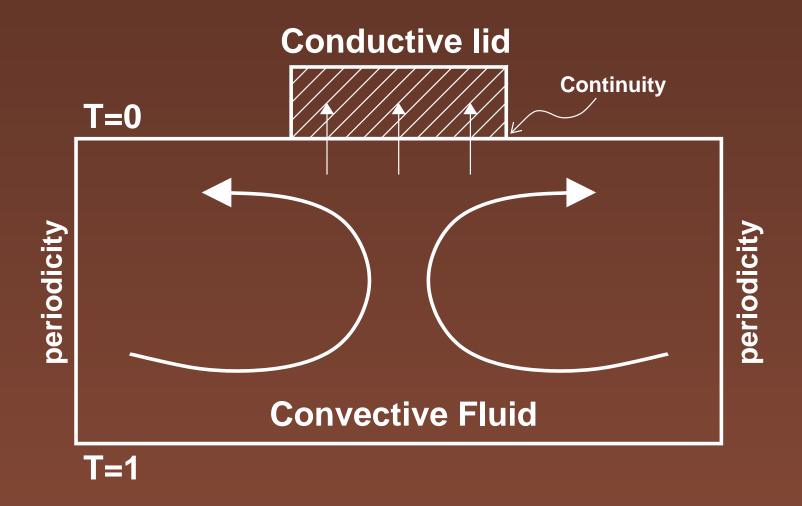
- Modelers predict <u>low</u> yield stress:
 - Plate tectonics switched off in 3D models for σ > 200 MPa.
 (Tackley, G³, 2000)
 - Good Earth-like behavior for $\sigma = 80$ MPa. (Gait and Lowman, *GJI*, 2007)
 - Initiation of subduction by small-scale convection for $\sigma = 30$ MPa.

(Solomatov, JGR, 2004)

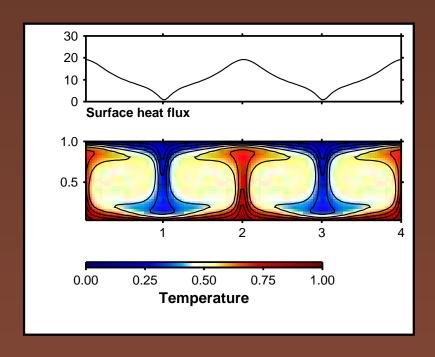
- Modelers predict <u>low</u> yield stress.
- Two directions:
 - Can we explain why the lithosphere strength is low?
 e.g. effect of water...
 - Can we add things in the models that can generate higher stresses?

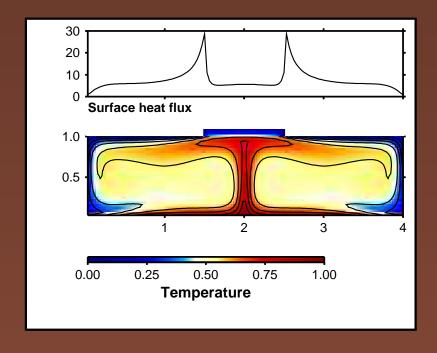
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- Two directions:
 - Can we explain why the lithosphere strength is low?
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 - Can we add things in the models that can generate higher stresses?
- ► The Earth is the only planet with plate tectonics and with continents.

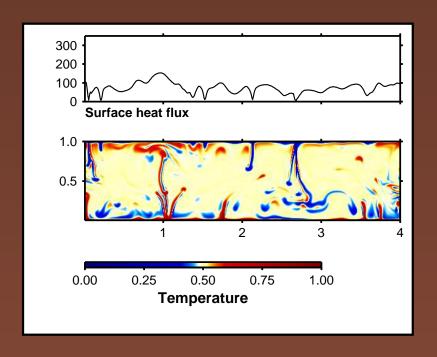


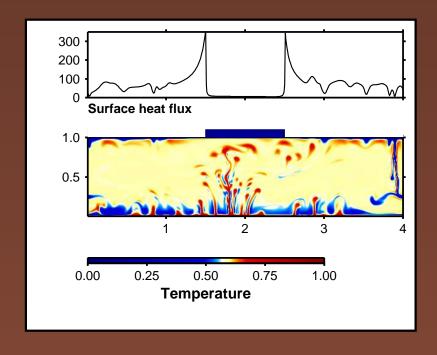
$$Ra = 10^5$$



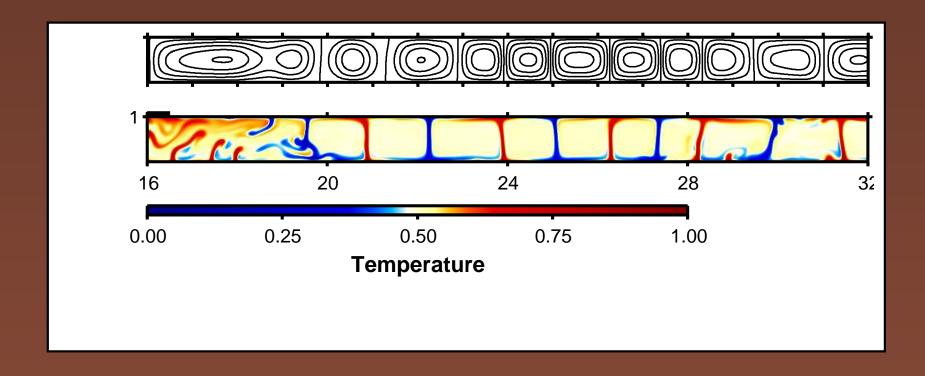


 $Ra = 10^8$

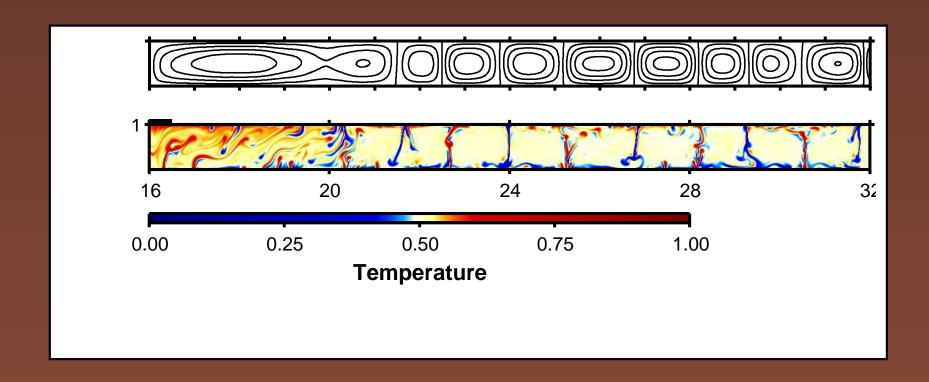




 $\mathsf{Ra} = 10^6$



$$Ra = 10^7$$



- Insulating continents increase the convective wavelength.
- This elongation increases with the Rayleigh number.

(Grigné et al., *JGR*, 2007)

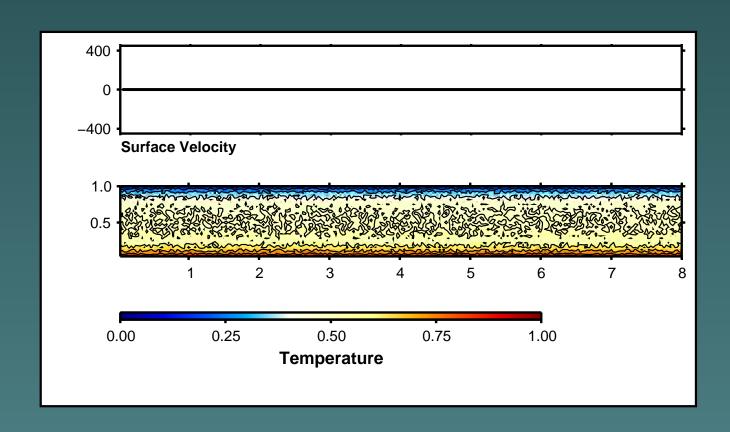
Method

- Purely ductile yielding: constant yield stress σ_y (no depth-dependency).
- Why?
 - Systematic study with reasonable amount of parameters.
 - Able to express yield stress σ_y in a simple way.
 - Whole-mantle convection: brittle part is very thin.
 - Difference with brittle-ductile is small (Tackley, G3, 2000).
- Temperature-dependent viscosity. No other complexities.
- Code: Stag3D (Tackley).

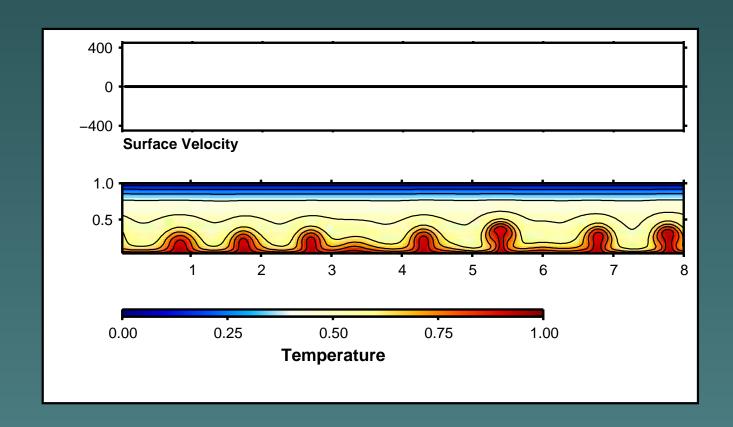
- Low σ_y (<200 MPa) needed in 3D and/or with high internal heating
 [e.g. Tackley, G³, 2000]
- \blacksquare 2D and no internal heating: can use high yield stress σ_y
- Requires large boxes
- Stable only when long wavelength is attained

- Initial: boundary layers.
- Ra = 10^6 , $\sigma_y = 10^5 (\sim 500 \text{MPa})$, $\Delta \eta = 10^5$

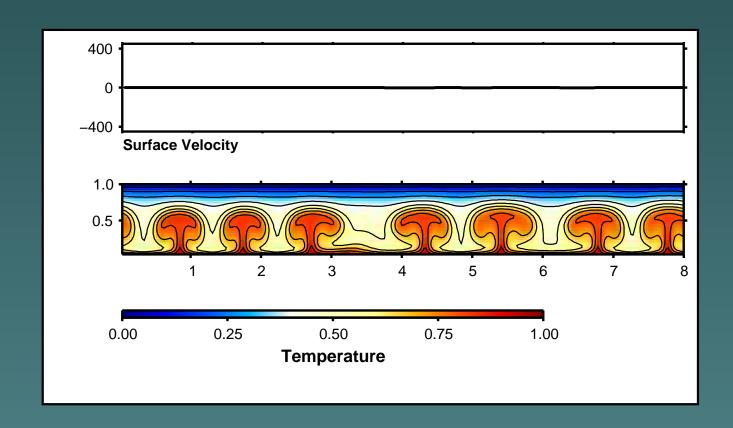
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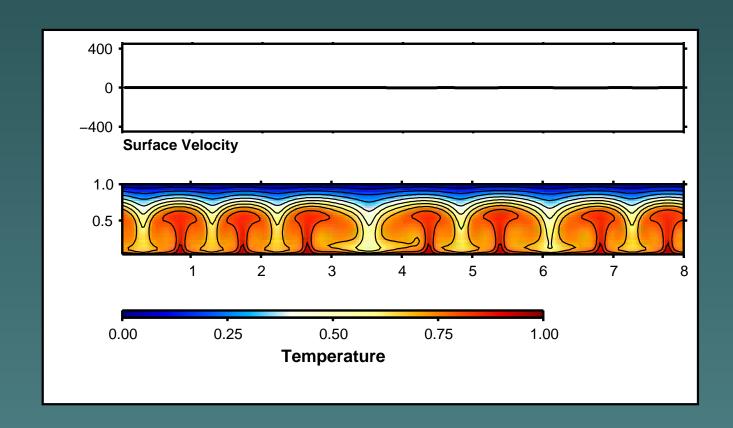
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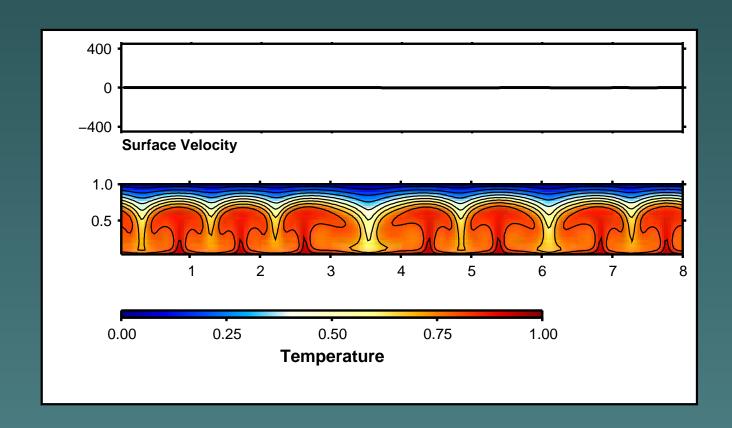
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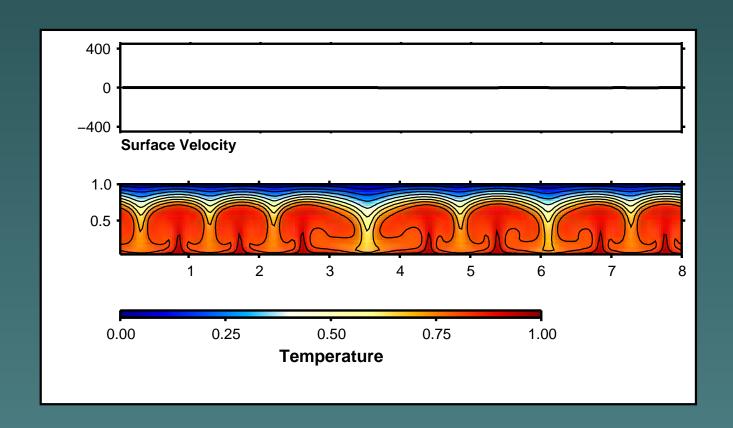
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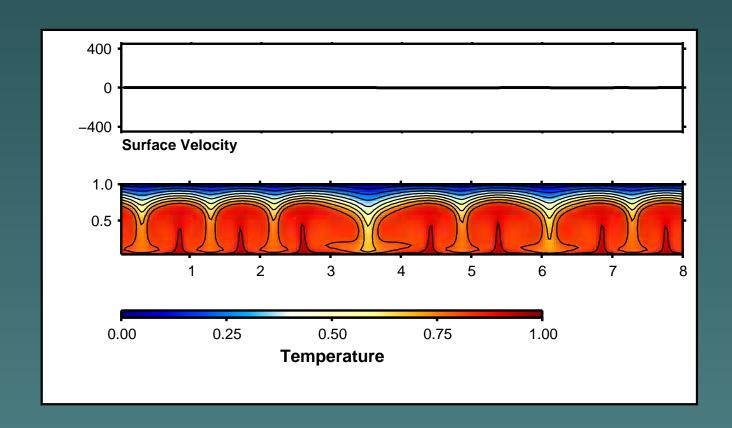
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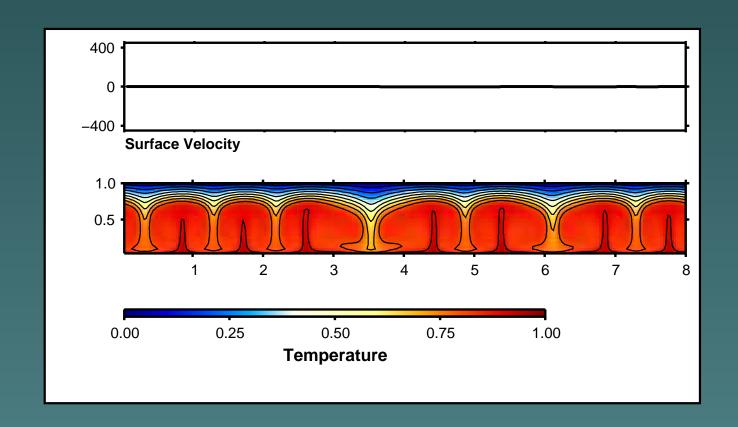
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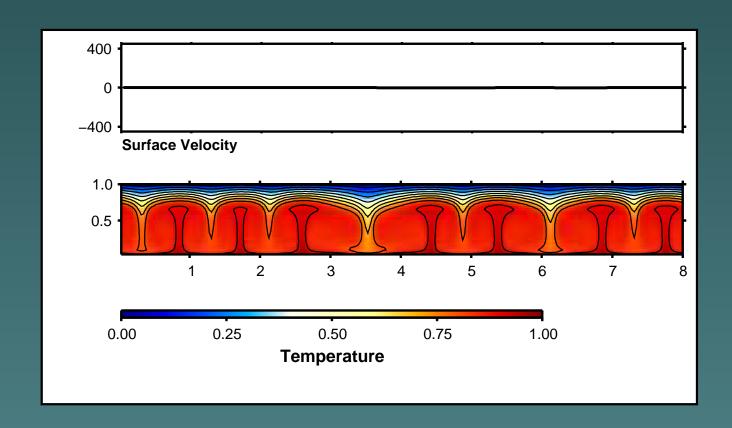
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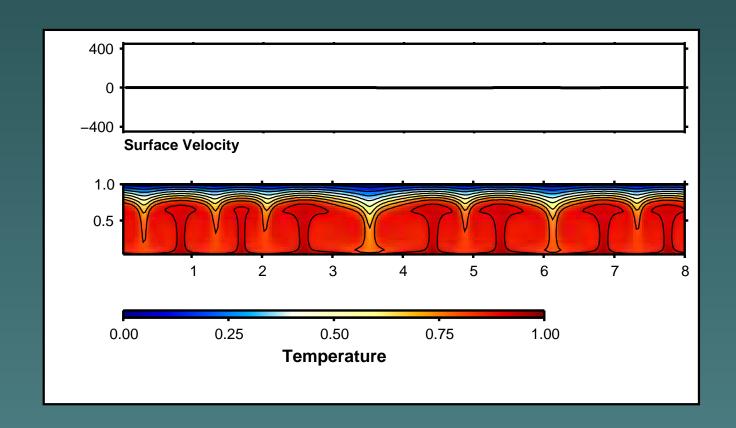
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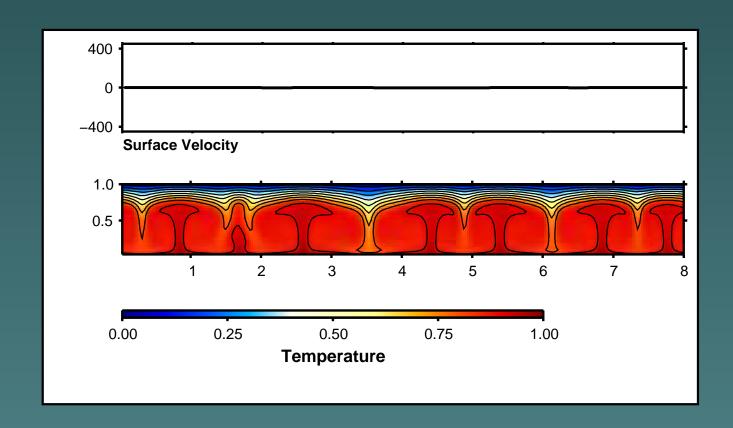
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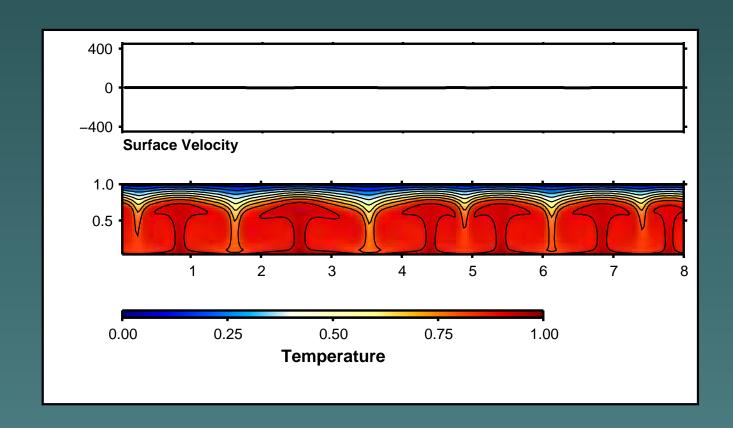
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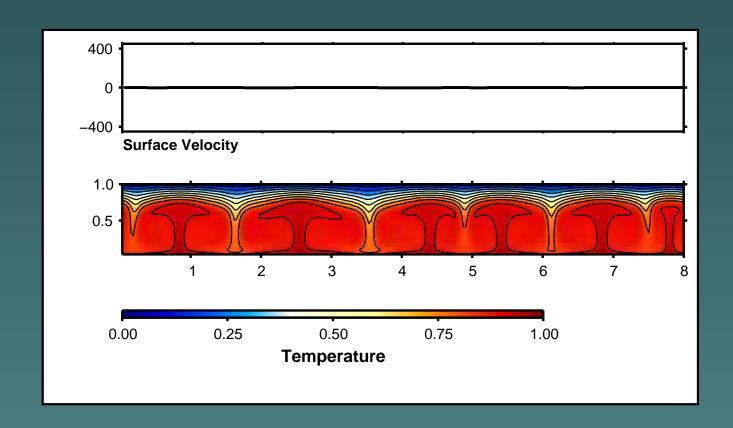
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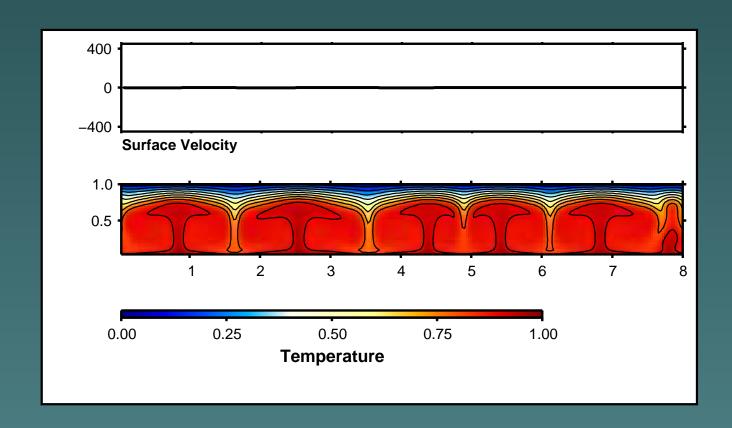
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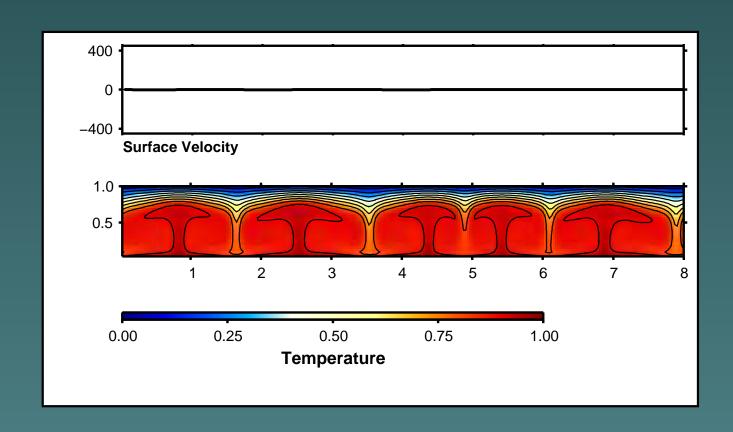
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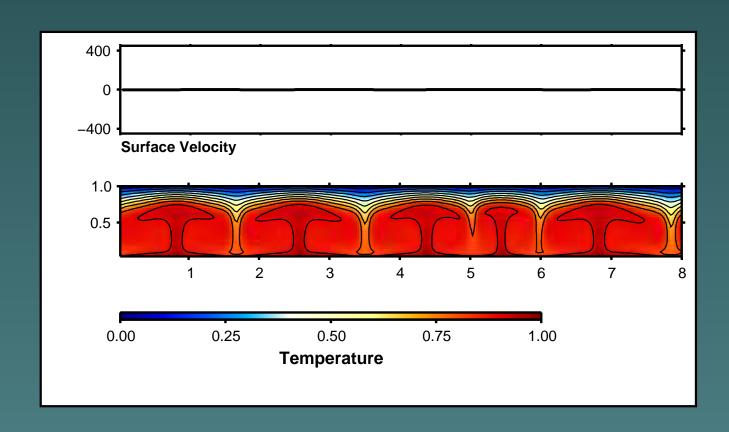
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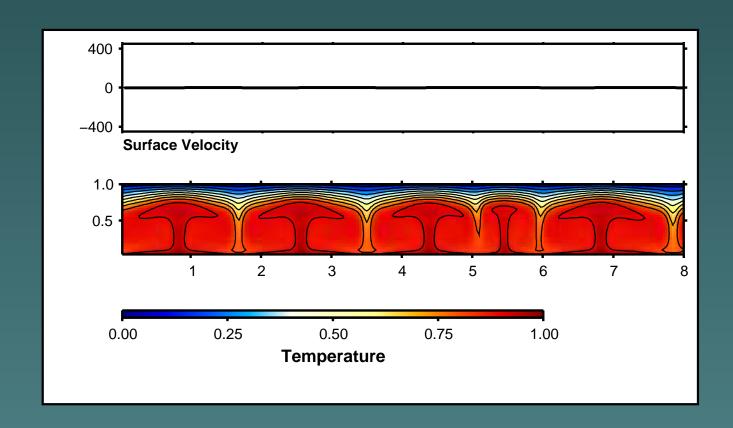
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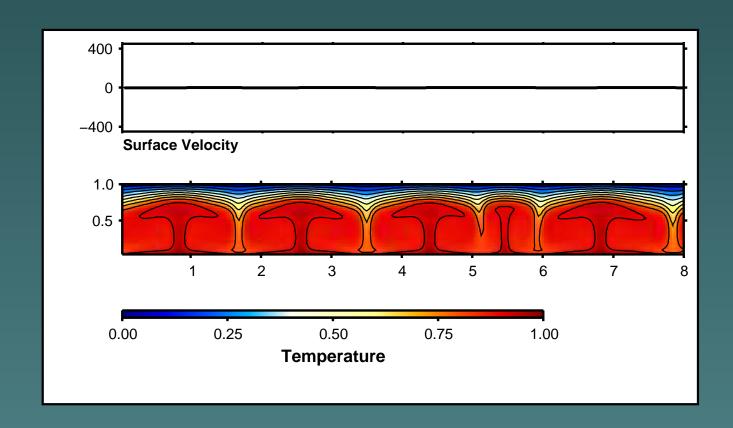
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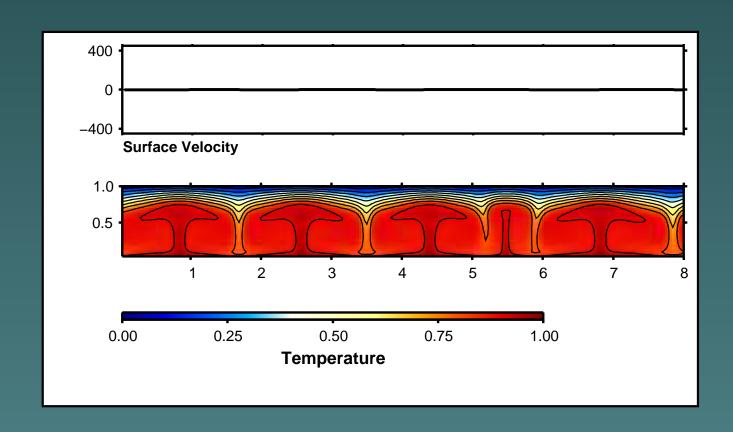
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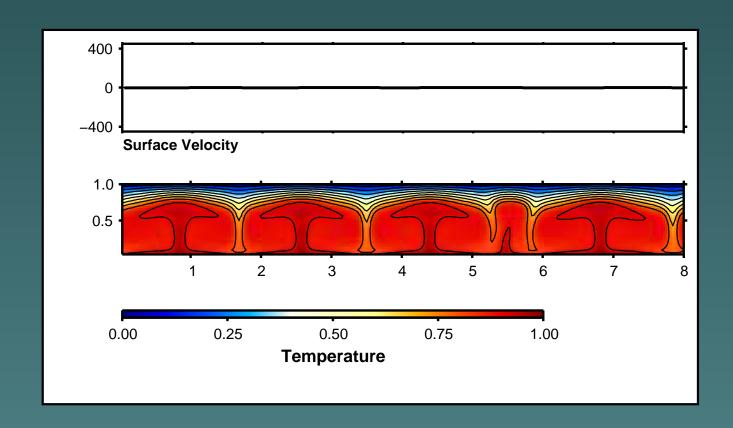
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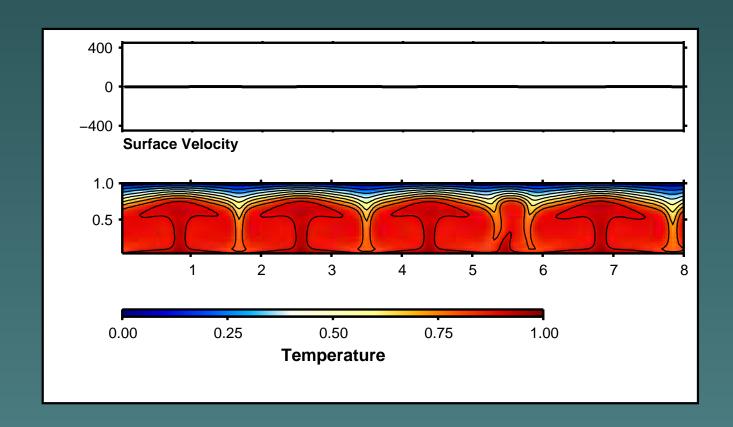
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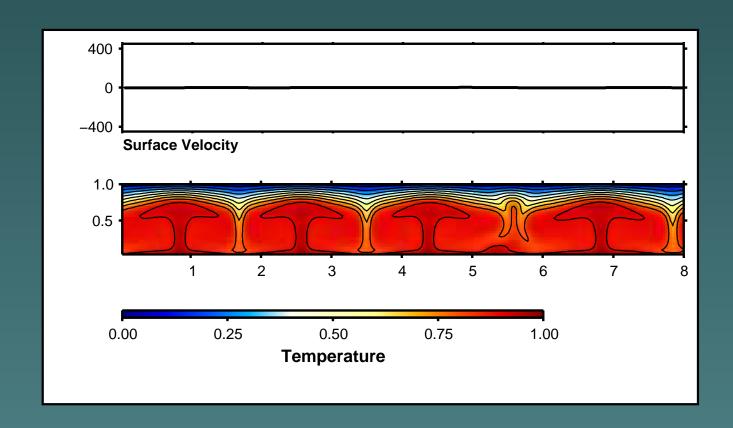
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- $\overline{lue{}}$ Ra = $10^6,~\sigma_{\mathsf{y}}=10^5(\sim500\mathsf{MPa}),~\Delta\eta=10^5$



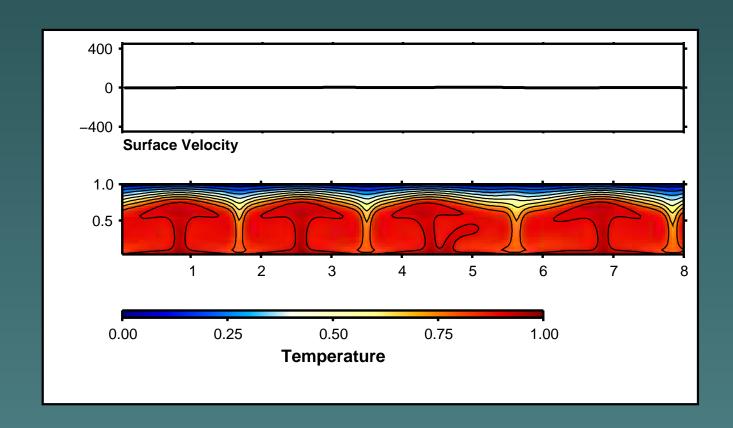
- Initial: boundary layers.
- \blacksquare Ra = 10^6 , $\sigma_{\sf y} = 10^5 (\sim 500 {\sf MPa})$, $\Delta \eta = 10^5$



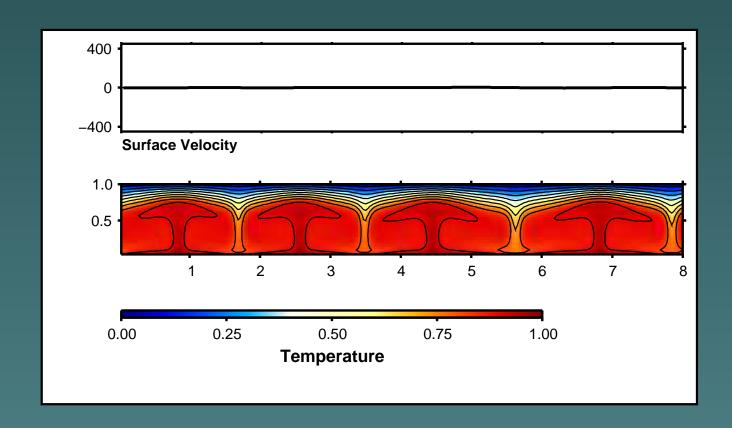
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- \blacksquare Ra = 10^6 , $\sigma_{\sf y} = 10^5 (\sim 500 {\sf MPa})$, $\Delta \eta = 10^5$



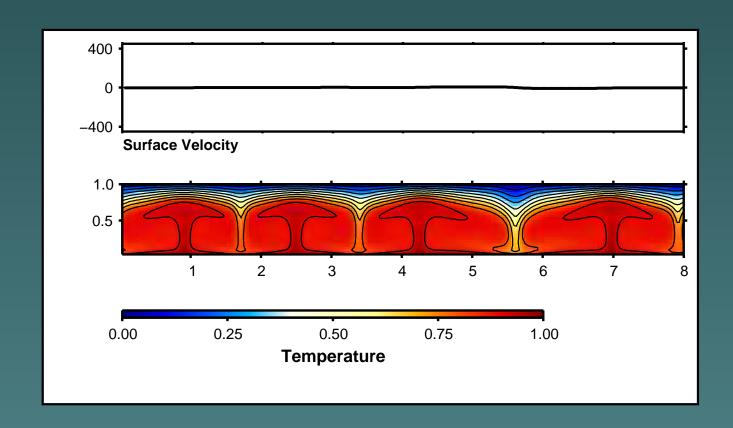
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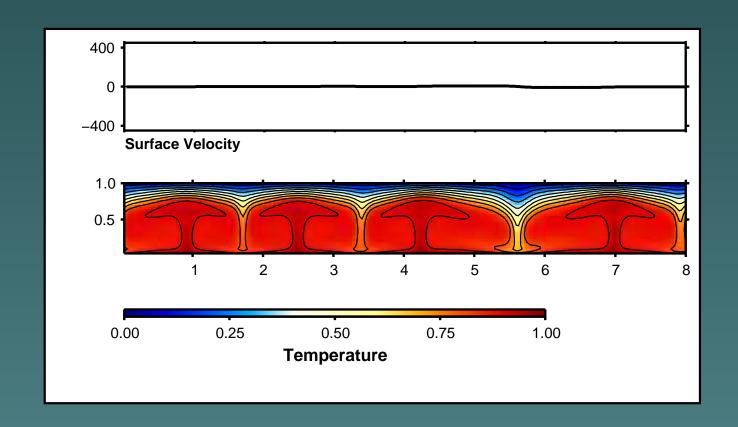
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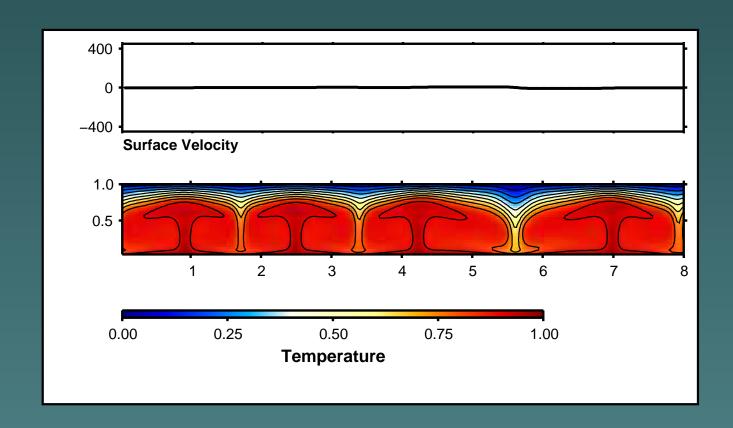
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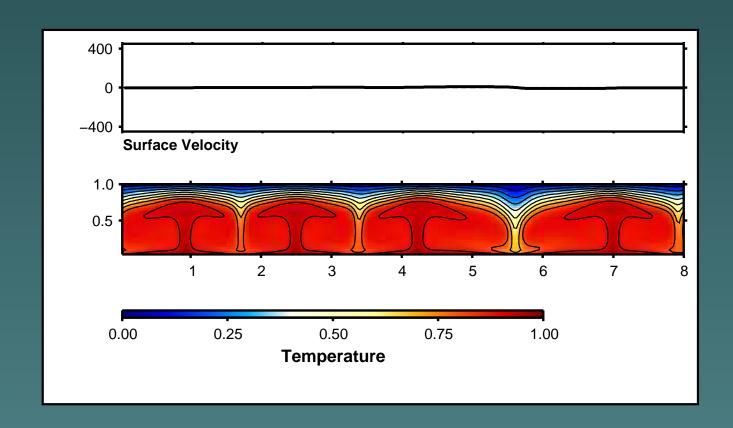
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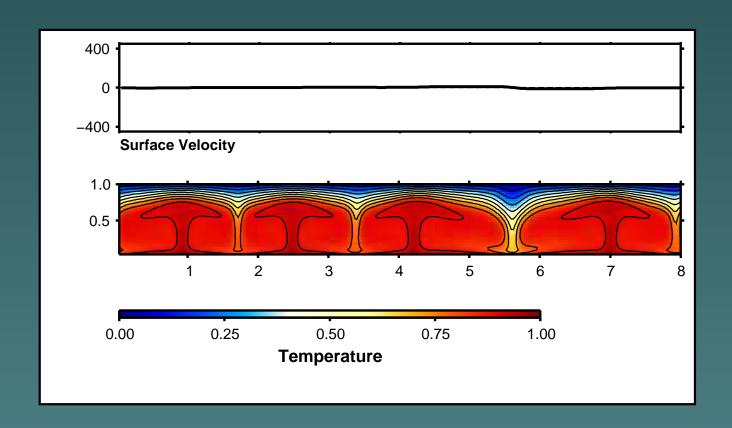
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- \blacksquare Ra = 10^6 , $\sigma_{\sf y} = 10^5 (\sim 500 {\sf MPa})$, $\Delta \eta = 10^5$



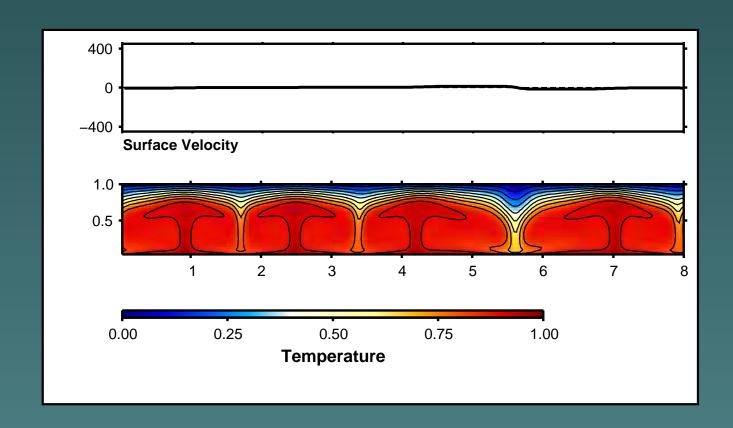
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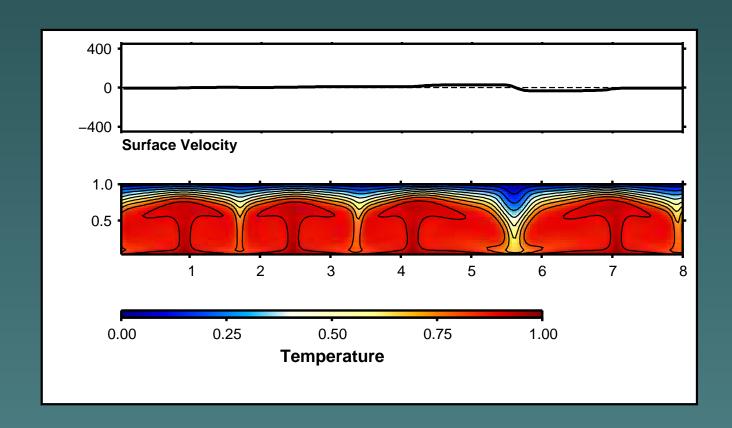
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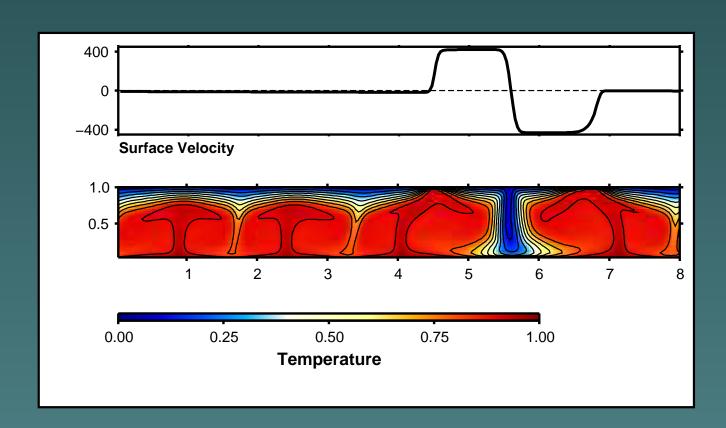
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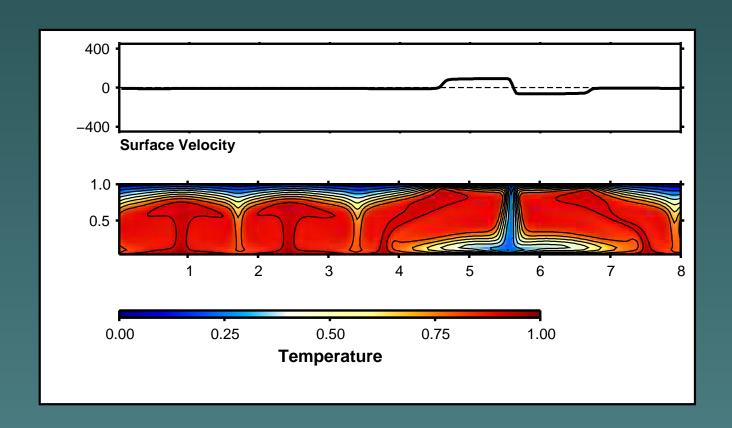
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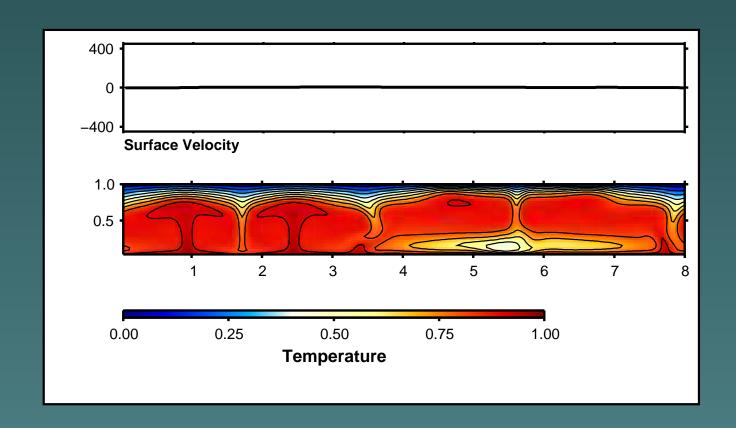
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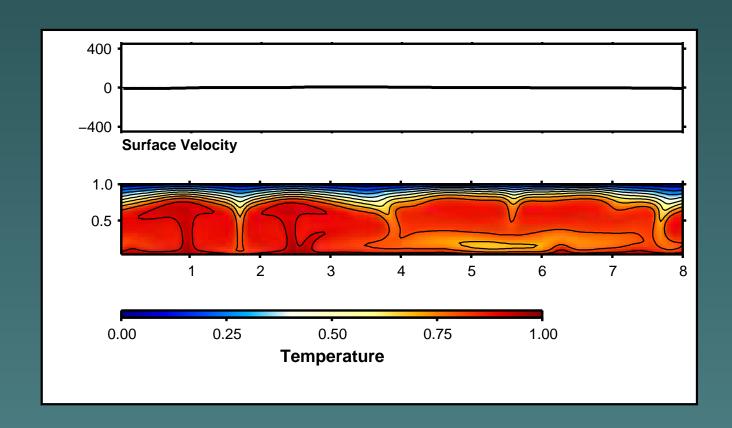
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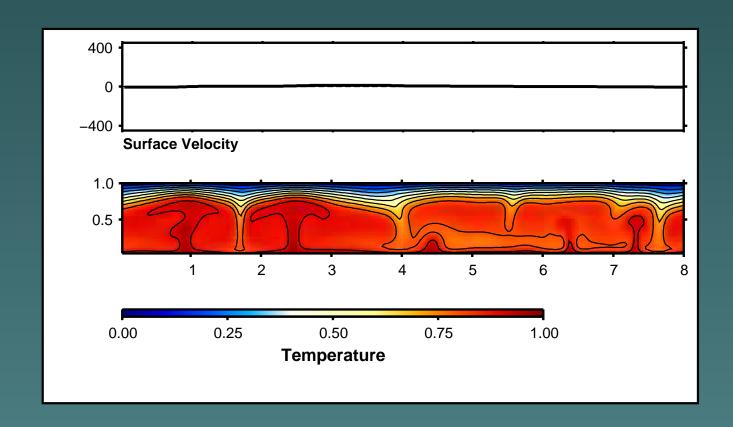
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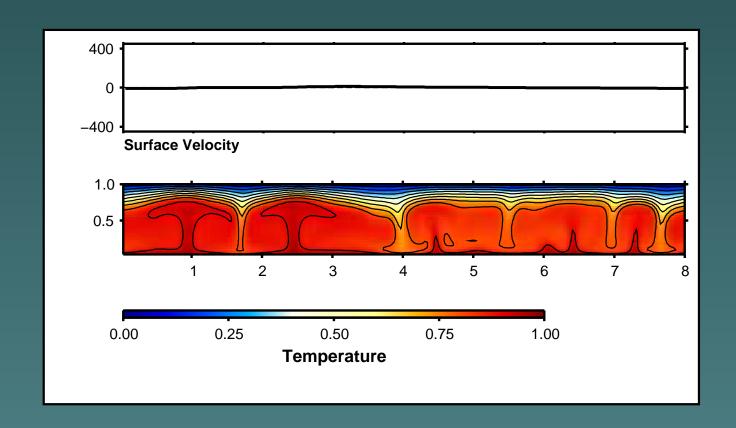
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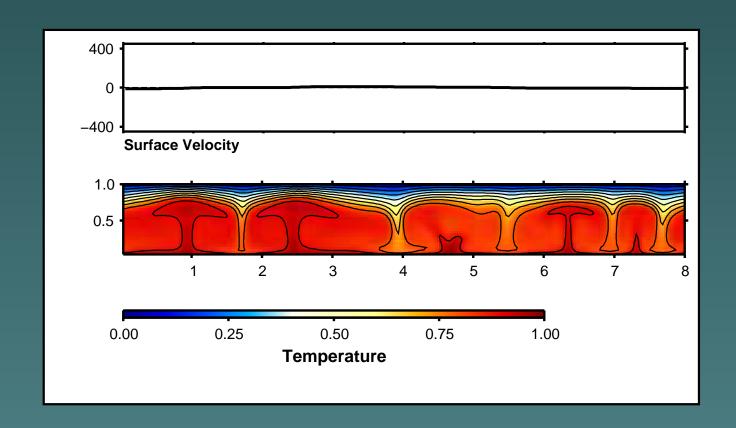
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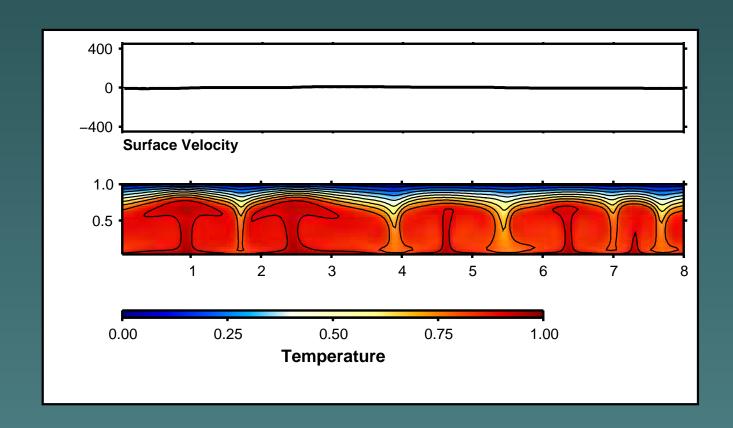
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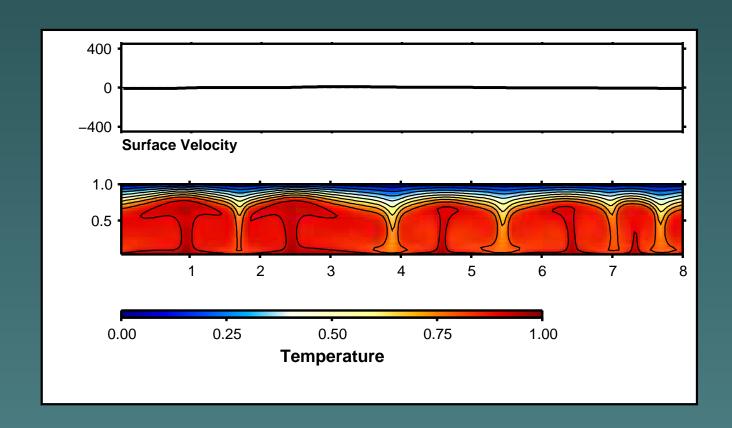
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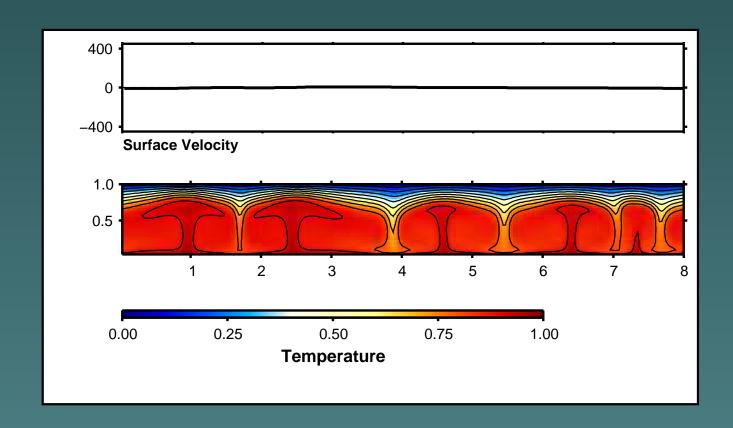
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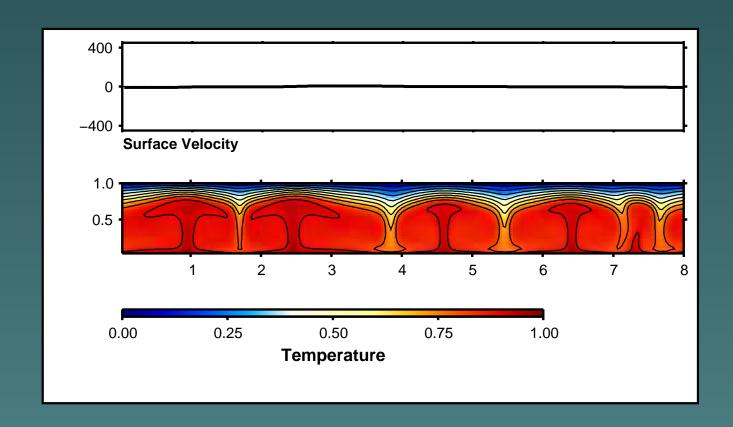
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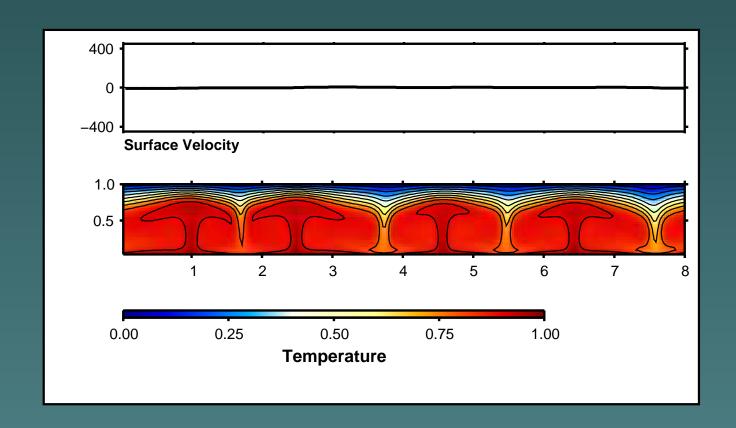
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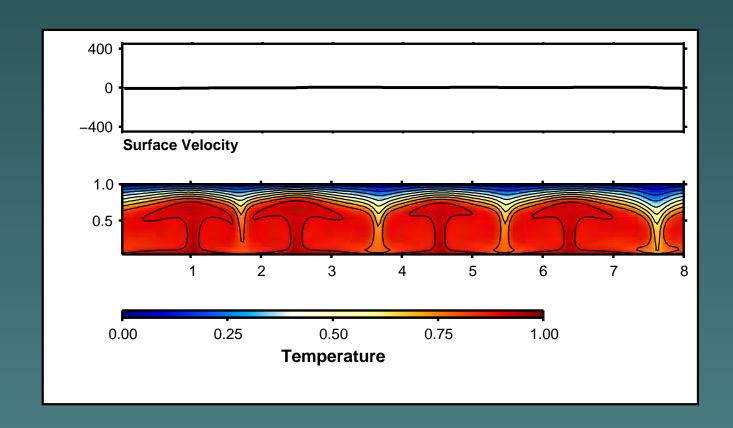
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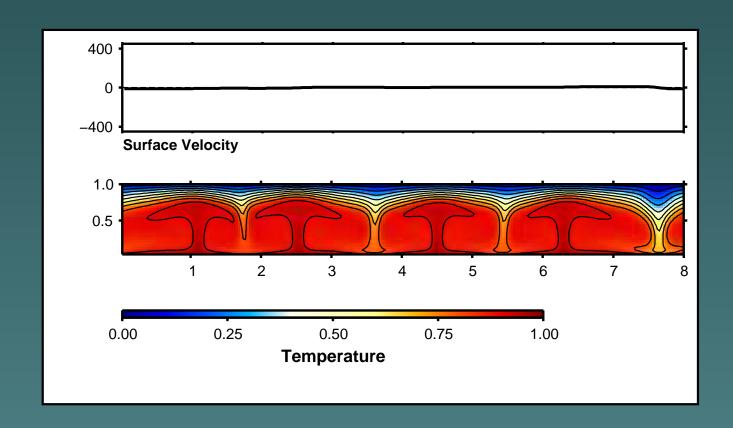
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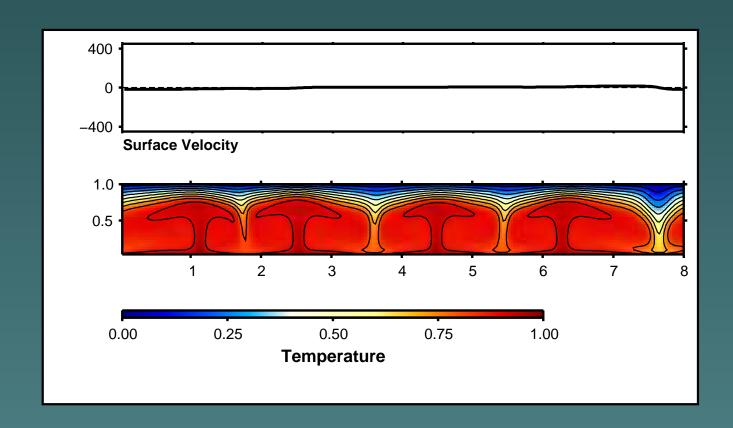
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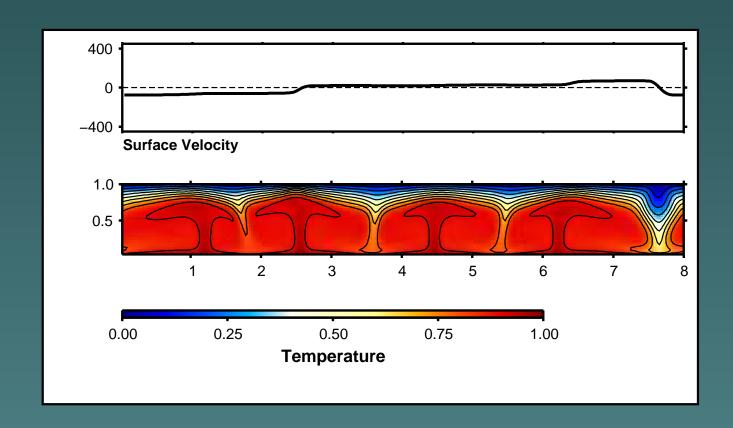
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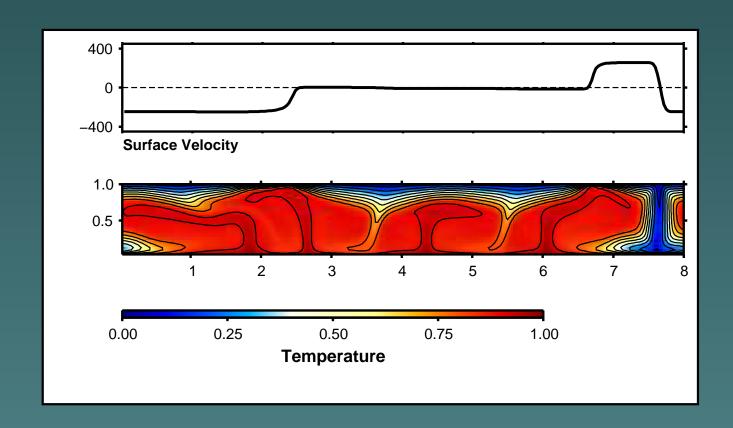
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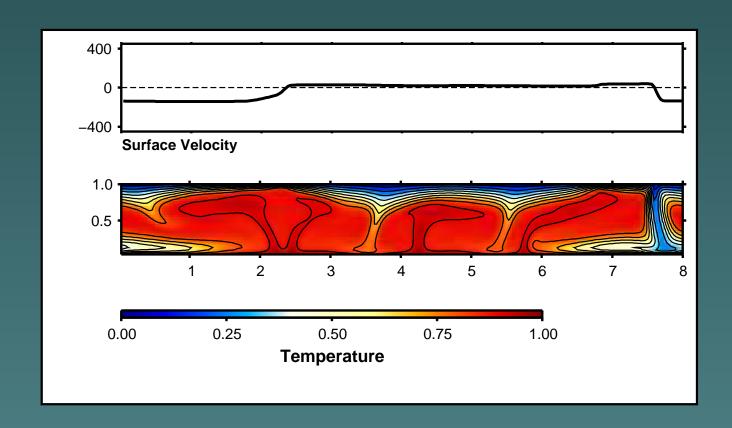
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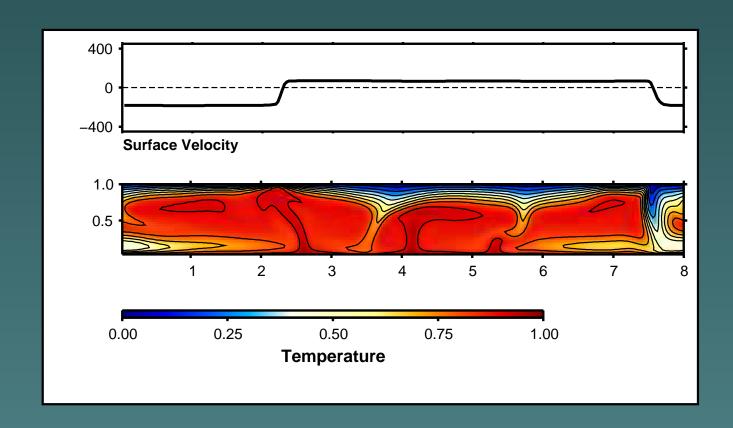
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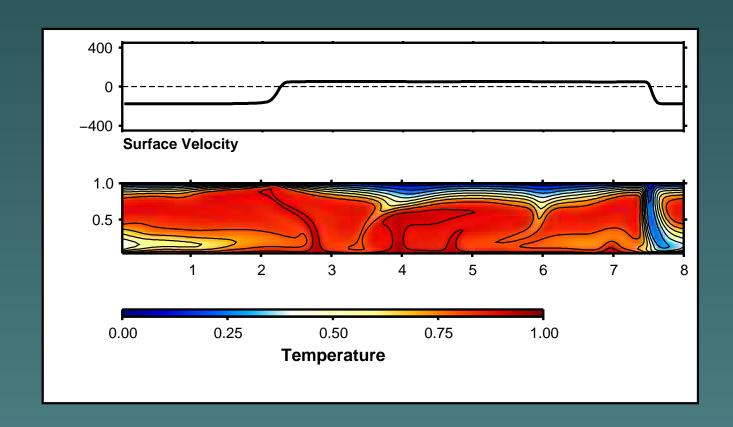
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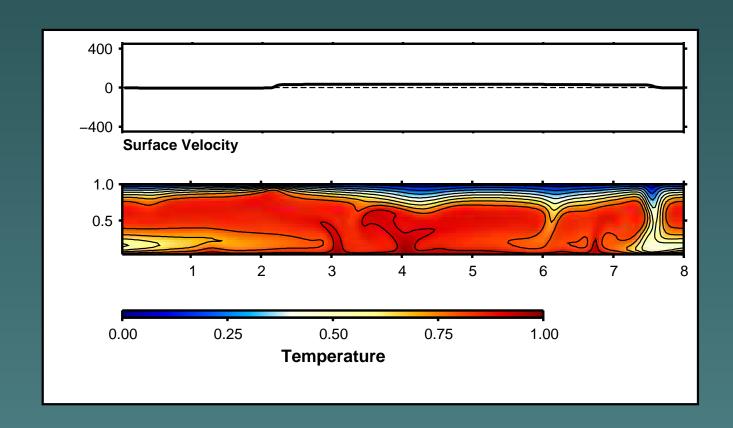
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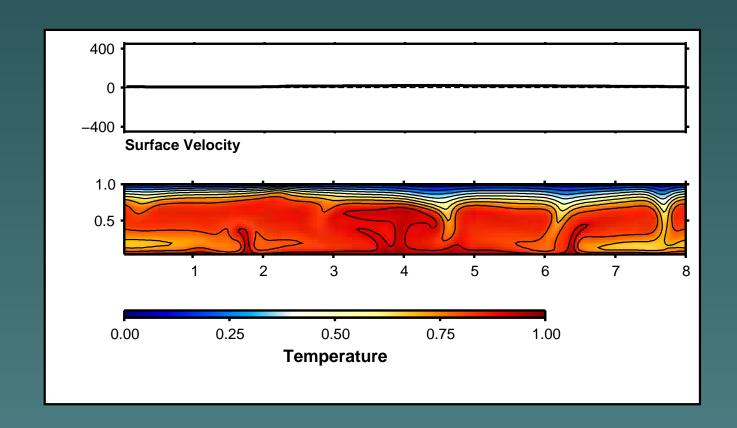
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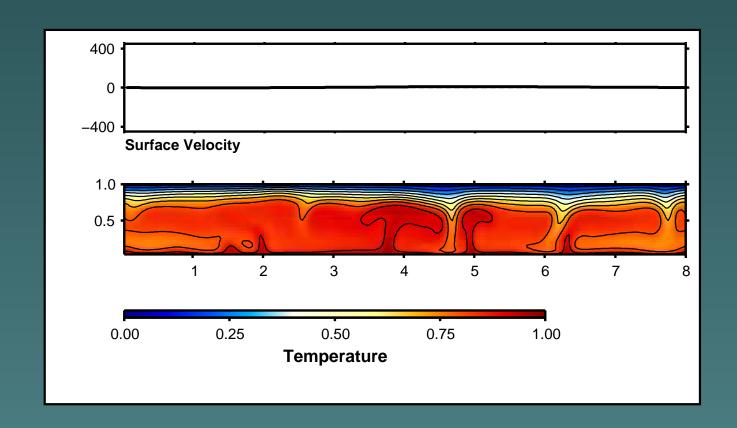
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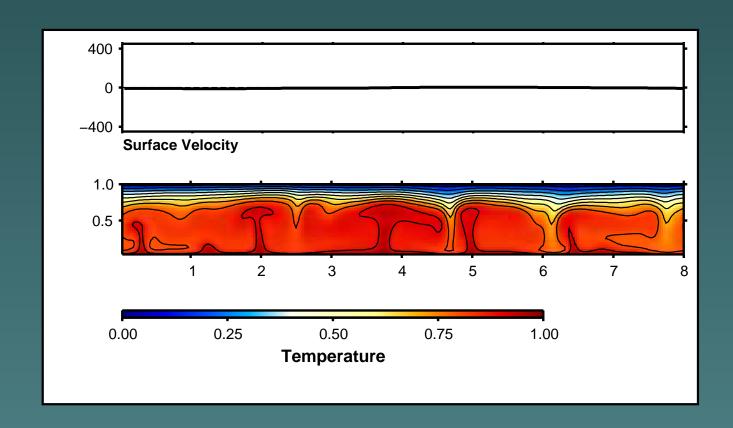
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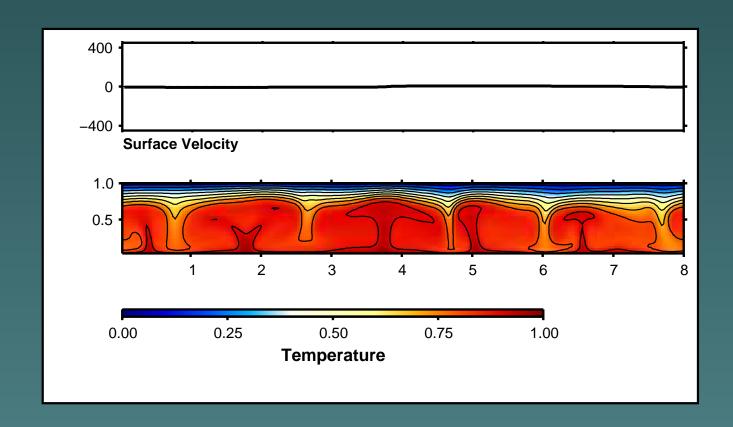
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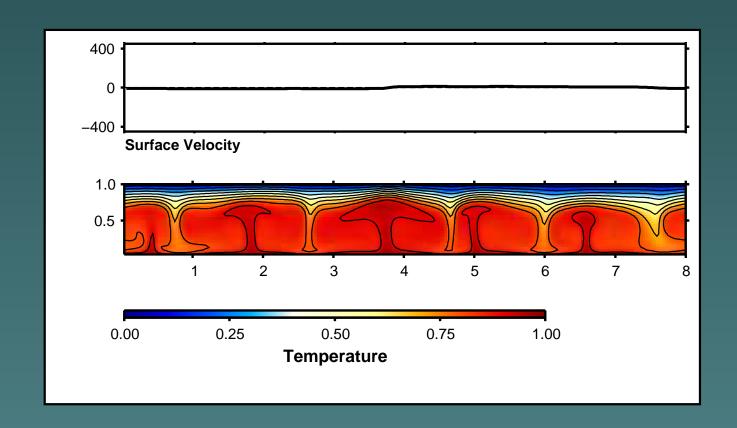
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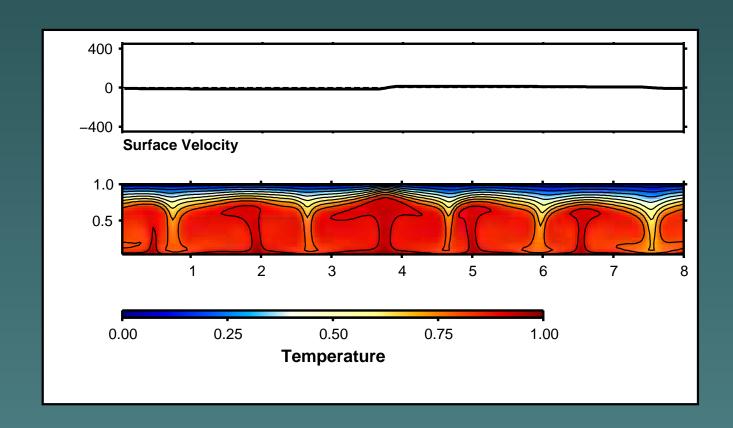
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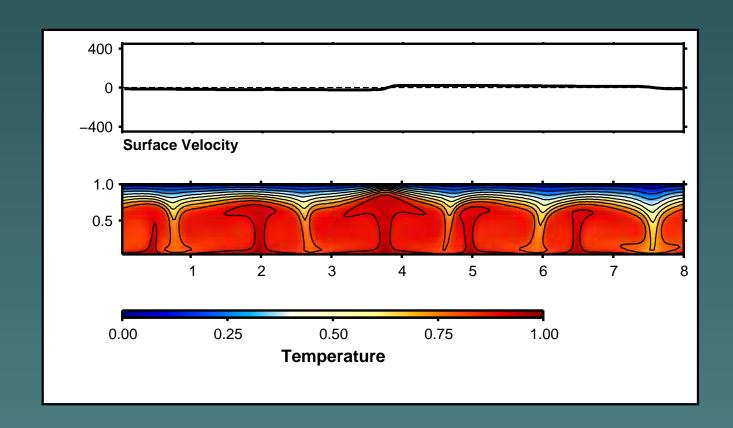
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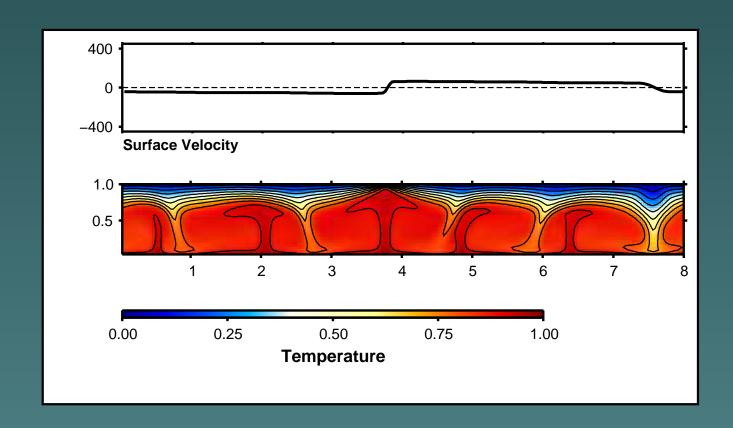
- Initial: boundary layers.
- $\overline{lue{}}$ Ra = $10^6,~\sigma_{\mathsf{y}}=10^5(\sim500\mathsf{MPa}),~\Delta\eta=10^5$



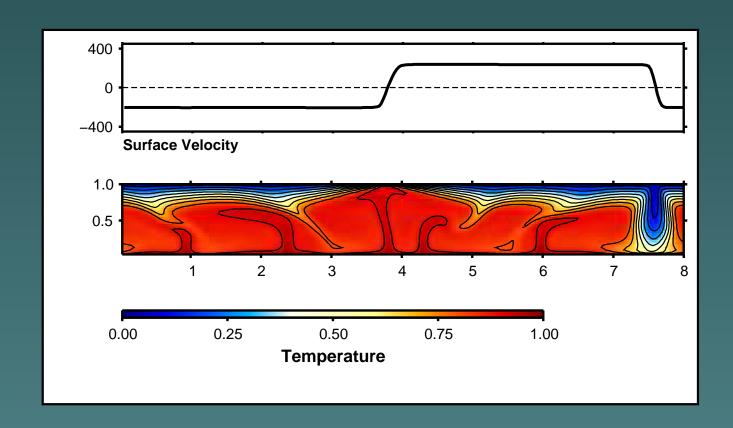
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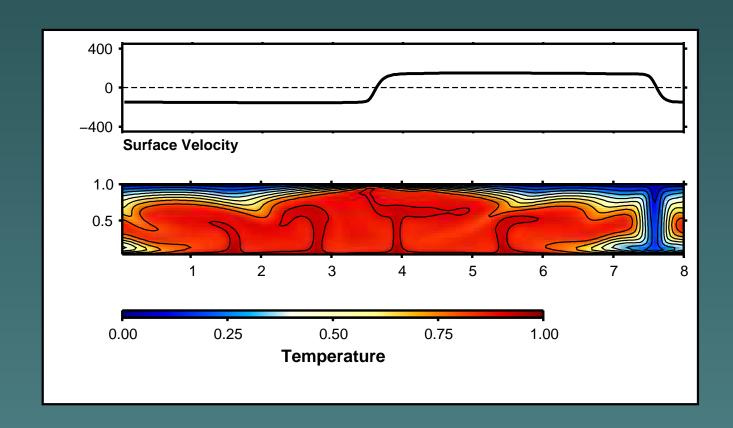
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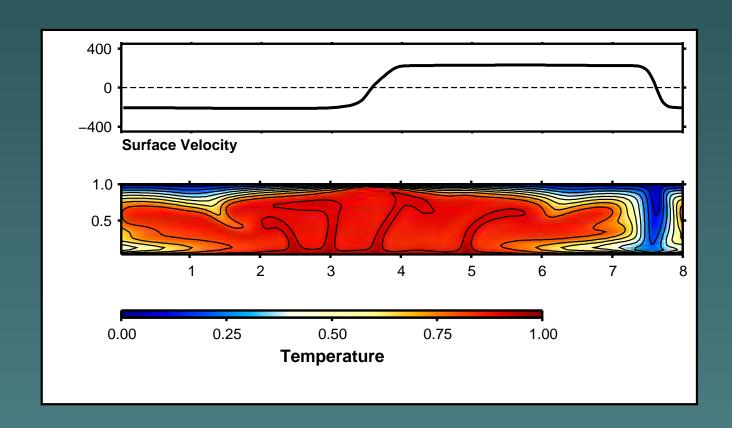
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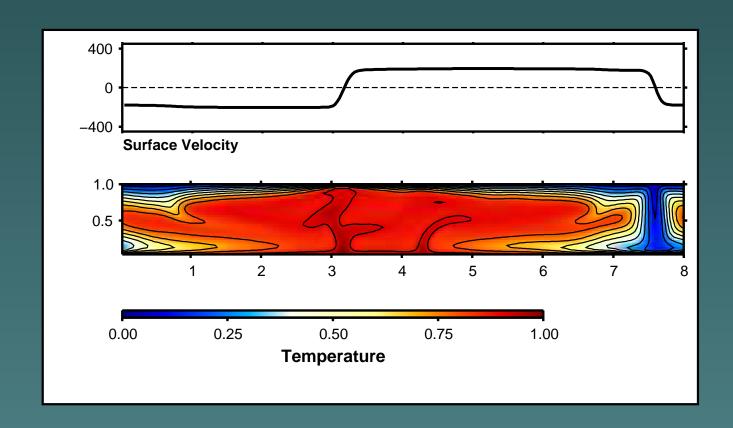
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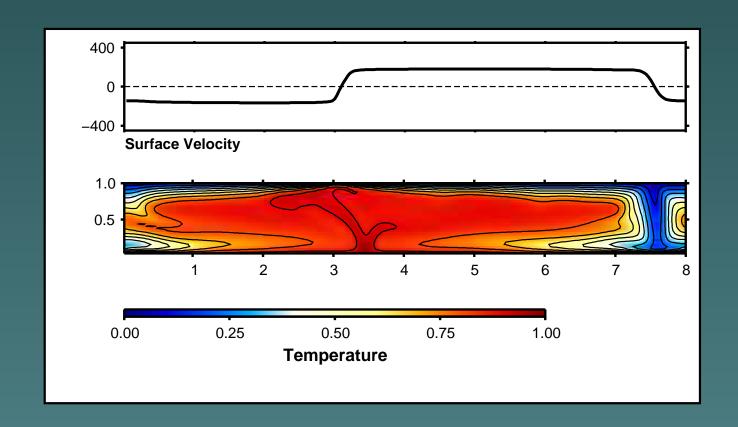
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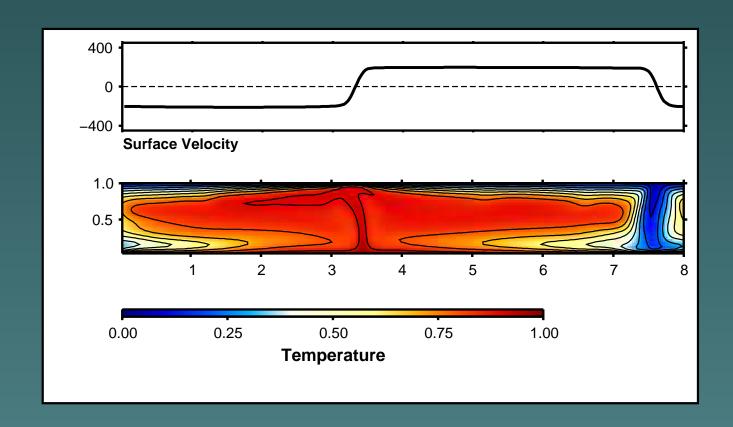
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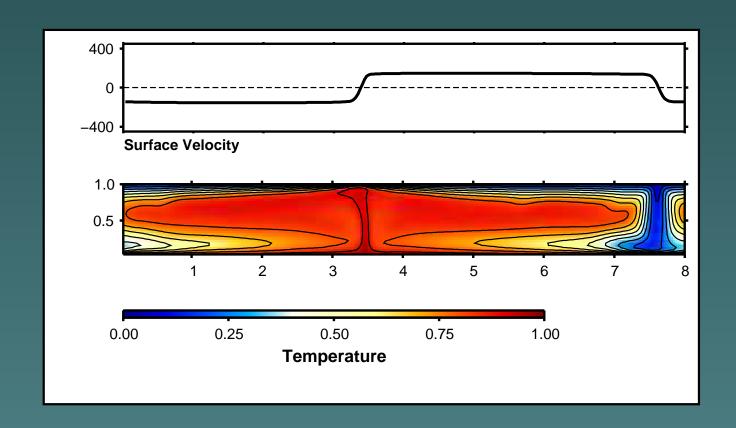
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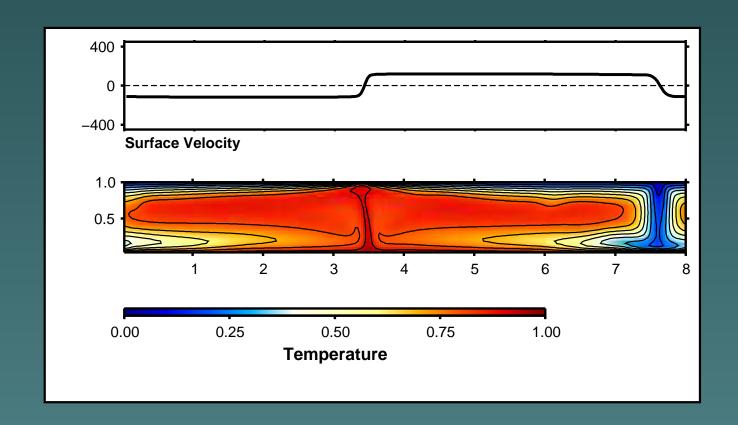
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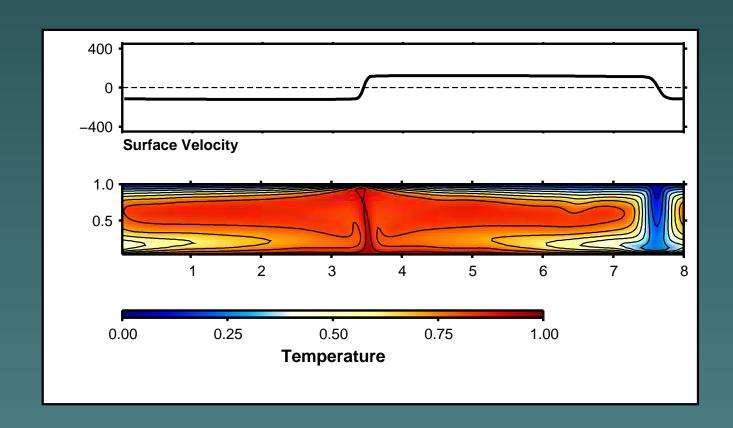
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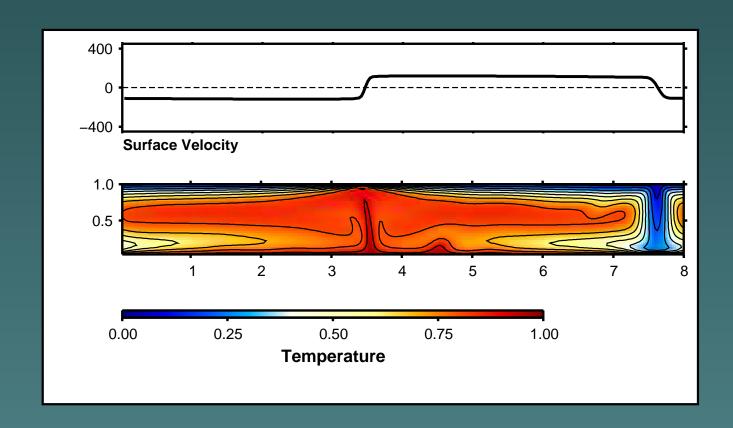
- Initial: boundary layers.
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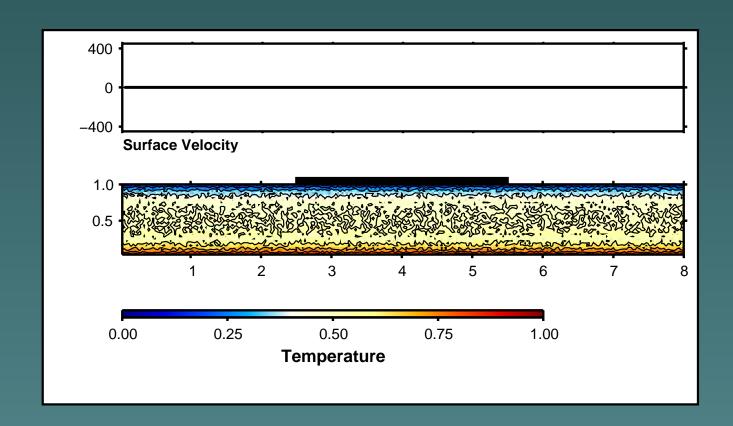


- Initial: boundary layers.
- Ra = 10^6 , $\sigma_y = 10^5 (\sim 500 \text{MPa})$, $\Delta \eta = 10^5$

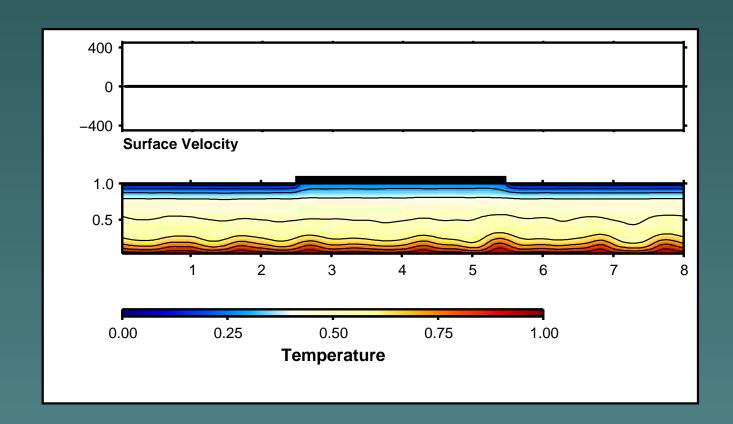


- Initial: boundary layers.
- Ra = 10^6 , $\sigma_y = 10^5$, $\Delta \eta = 10^5$ Insulating continent a=3.

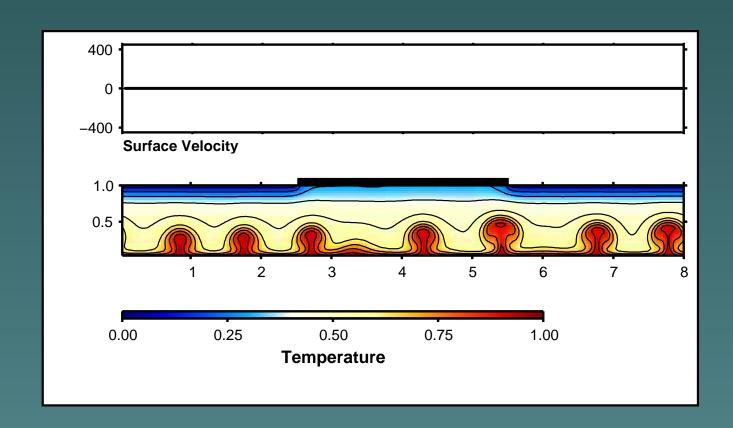
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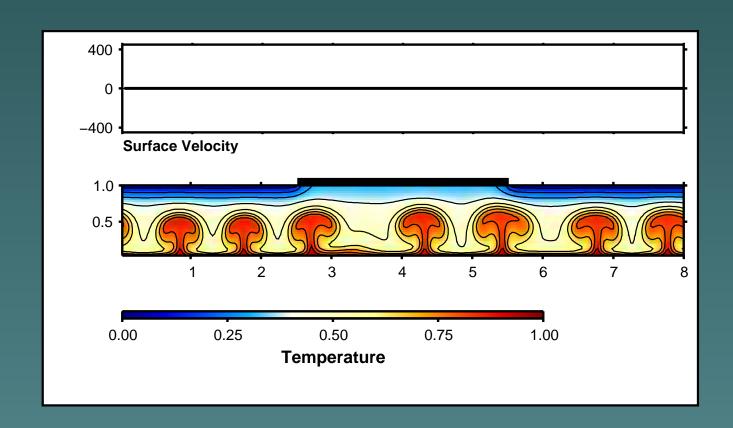
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- Ra = 10^6 , $\sigma_y = 10^5$, $\Delta \eta = 10^5$ Insulating continent a=3.



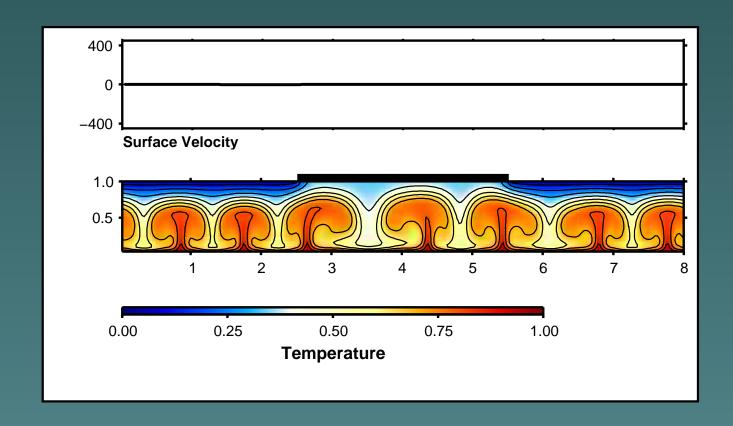
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- Ra = 10^6 , $\sigma_y = 10^5$, $\Delta \eta = 10^5$ Insulating continent a=3.



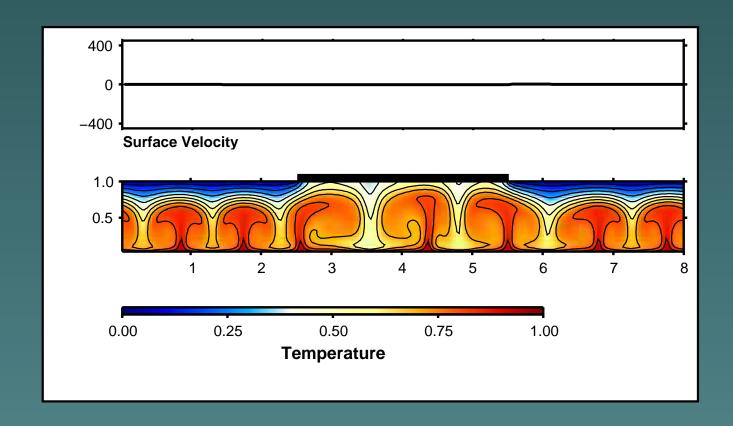
- Initial: boundary layers.
- Ra = 10^6 , $\sigma_y = 10^5$, $\Delta \eta = 10^5$ Insulating continent a=3.



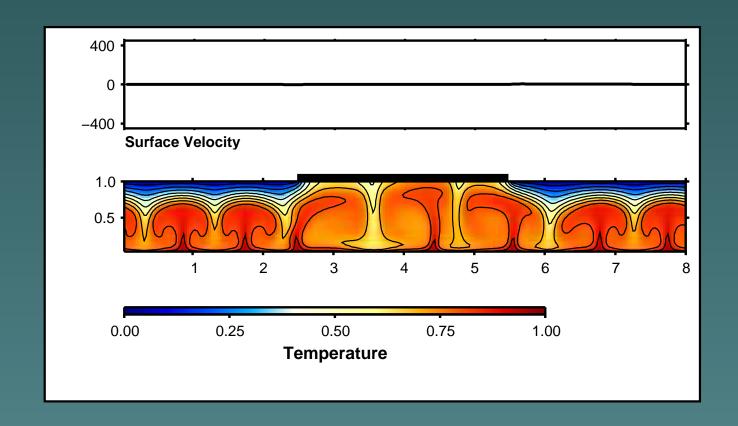
- Initial: boundary layers.
- Ra = 10^6 , $\sigma_y = 10^5$, $\Delta \eta = 10^5$ Insulating continent a=3.



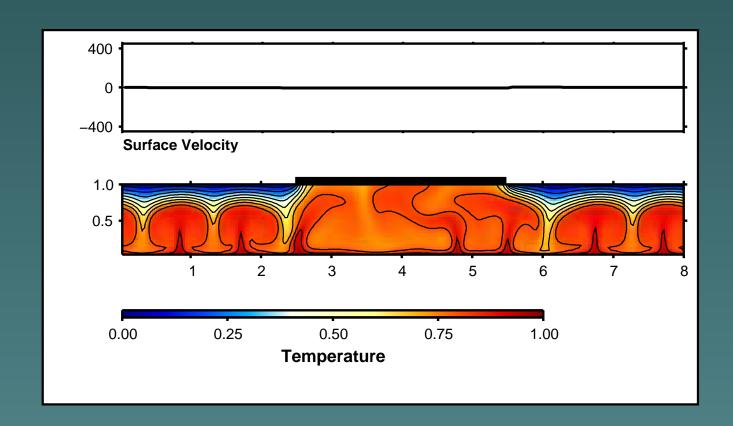
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- Ra = 10^6 , $\sigma_y = 10^5$, $\Delta \eta = 10^5$ Insulating continent a=3.



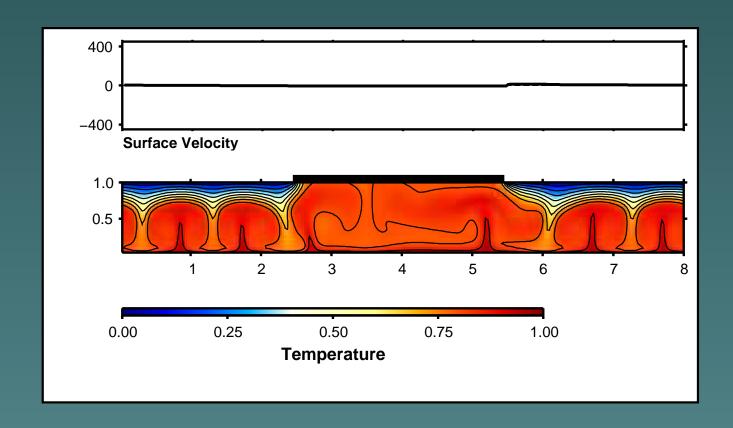
- Initial: boundary layers.
- Ra = 10^6 , $\sigma_y = 10^5$, $\Delta \eta = 10^5$ Insulating continent a=3.



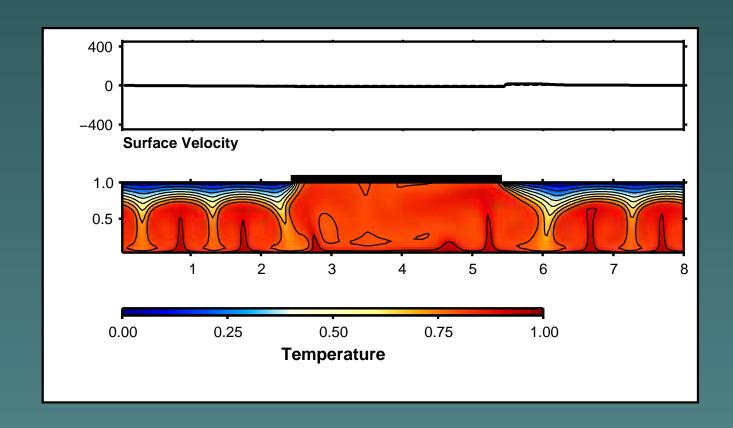
- Initial: boundary layers.
- Ra = 10^6 , $\sigma_y = 10^5$, $\Delta \eta = 10^5$ Insulating continent a=3.



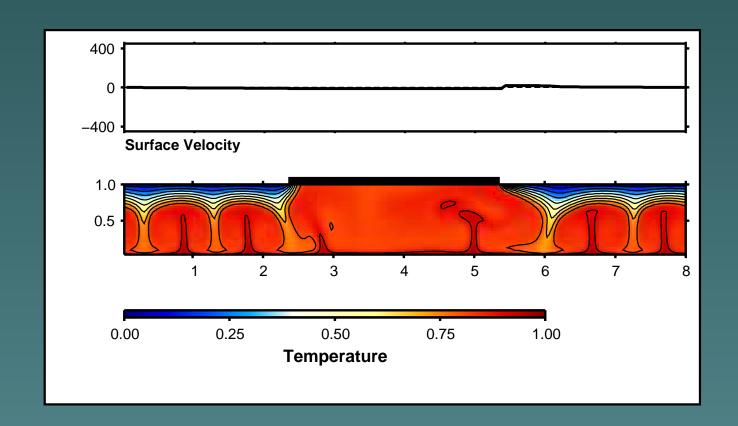
- Initial: boundary layers.
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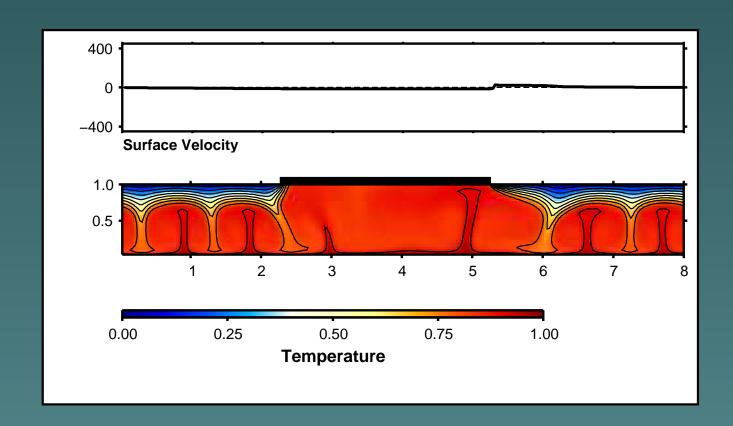
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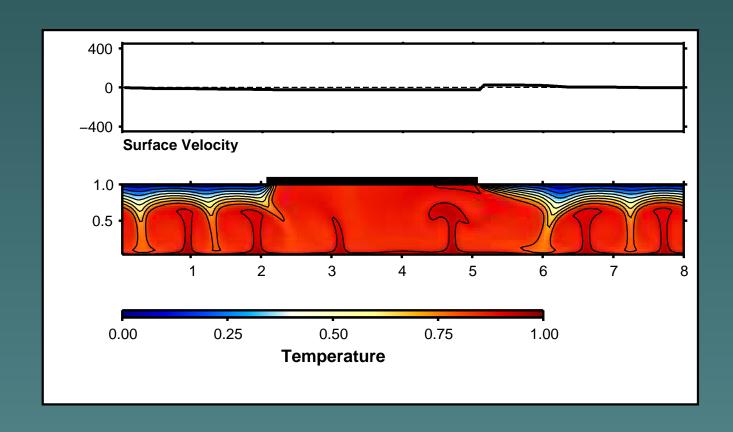
- Initial: boundary layers.
- Ra = 10^6 , $\sigma_y = 10^5$, $\Delta \eta = 10^5$ Insulating continent a=3.



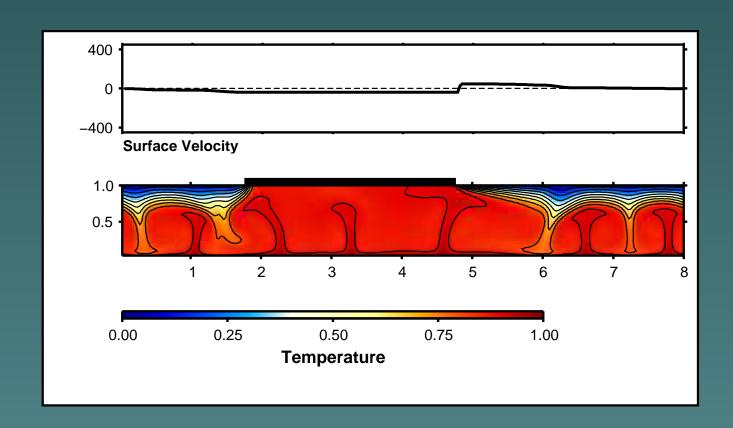
- Initial: boundary layers.
- Ra = 10^6 , $\sigma_y = 10^5$, $\Delta \eta = 10^5$ Insulating continent a=3.



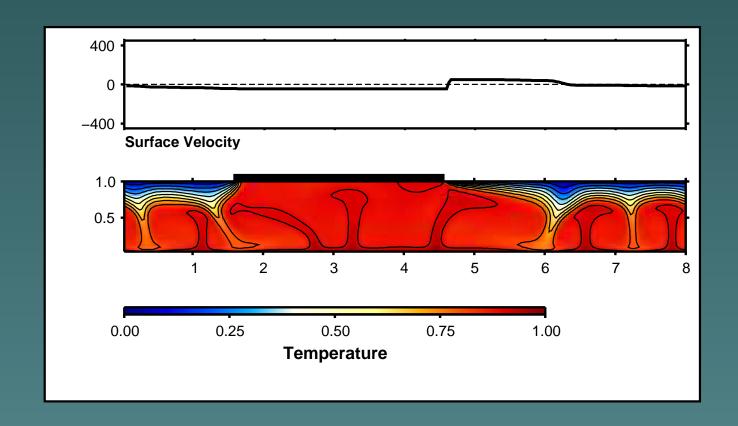
- Initial: boundary layers.
- Ra = 10^6 , $\sigma_y = 10^5$, $\Delta \eta = 10^5$ Insulating continent a=3.



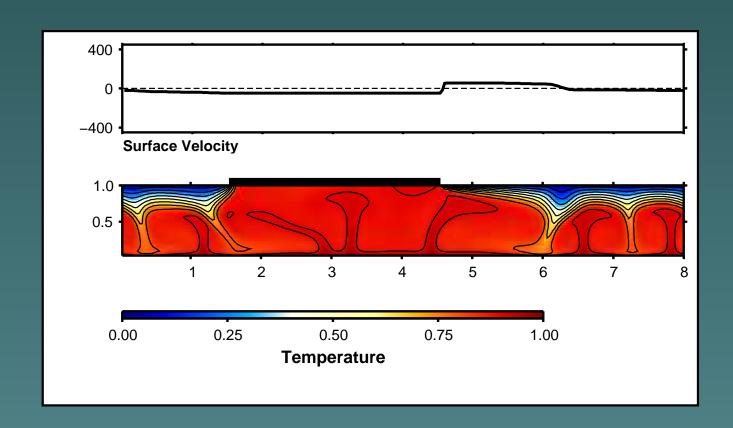
- Initial: boundary layers.
- Ra = 10^6 , $\sigma_y = 10^5$, $\Delta \eta = 10^5$ Insulating continent a=3.



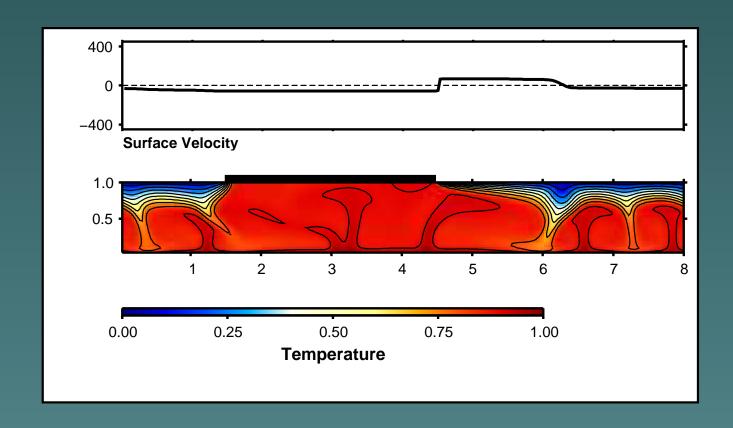
- Initial: boundary layers.
- Ra = 10^6 , $\sigma_y = 10^5$, $\Delta \eta = 10^5$ Insulating continent a=3.



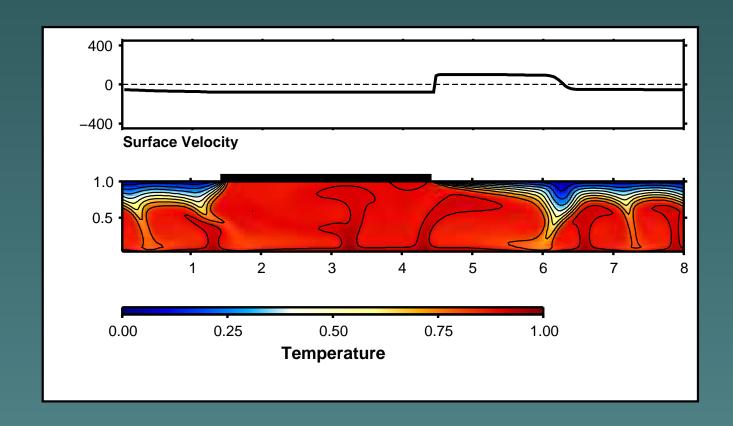
- Initial: boundary layers.
- Ra = 10^6 , $\sigma_y = 10^5$, $\Delta \eta = 10^5$ Insulating continent a=3.



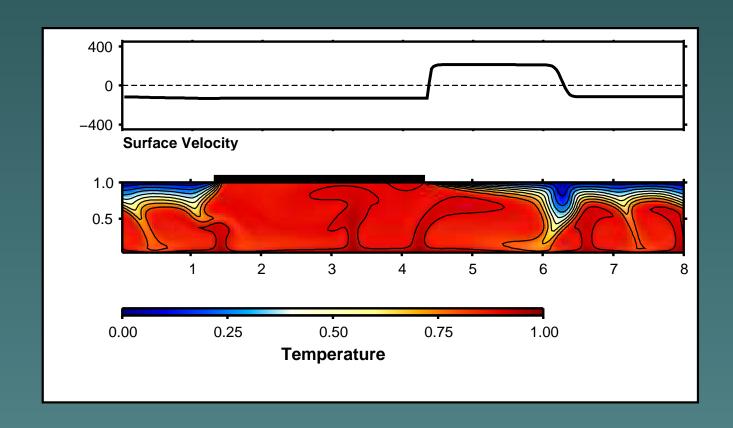
- Initial: boundary layers.
- Ra = 10^6 , $\sigma_y = 10^5$, $\Delta \eta = 10^5$ Insulating continent a=3.



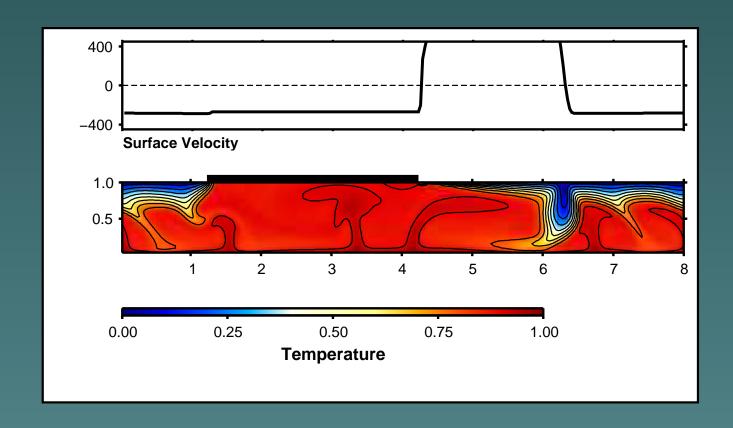
- Initial: boundary layers.
- Ra = 10^6 , $\sigma_y = 10^5$, $\Delta \eta = 10^5$ Insulating continent a=3.



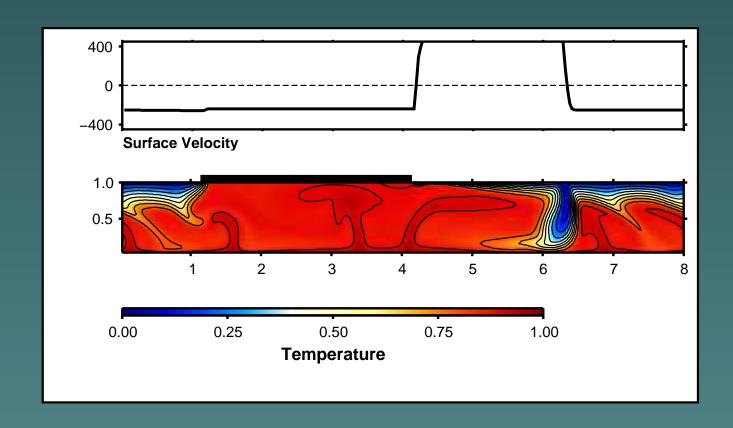
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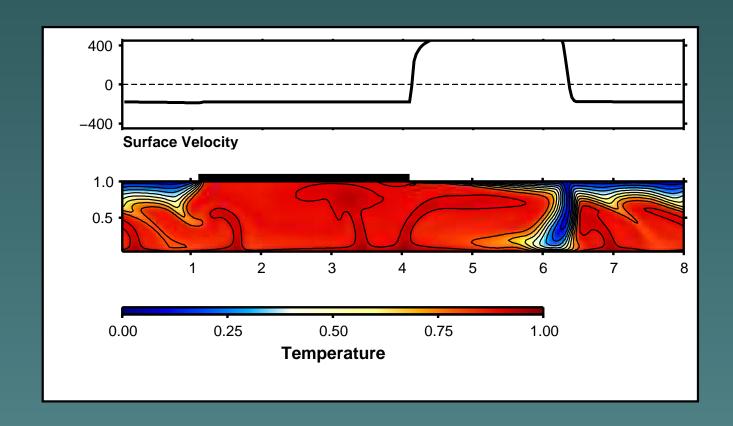
- Initial: boundary layers.
- Ra = 10^6 , $\sigma_y = 10^5$, $\Delta \eta = 10^5$ Insulating continent a=3.



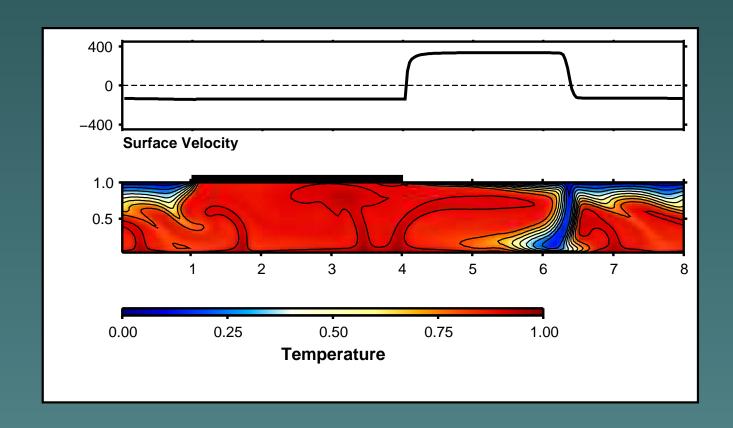
- Initial: boundary layers.
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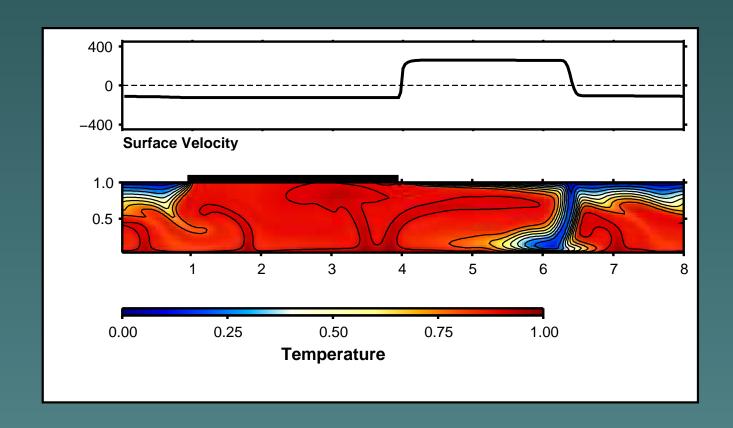
- Initial: boundary layers.
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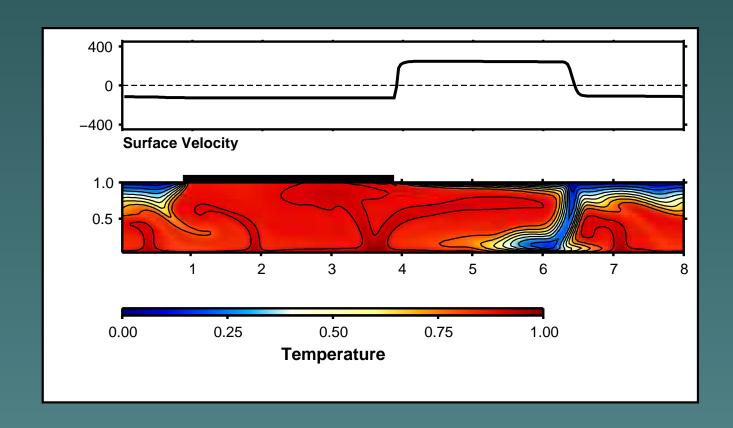
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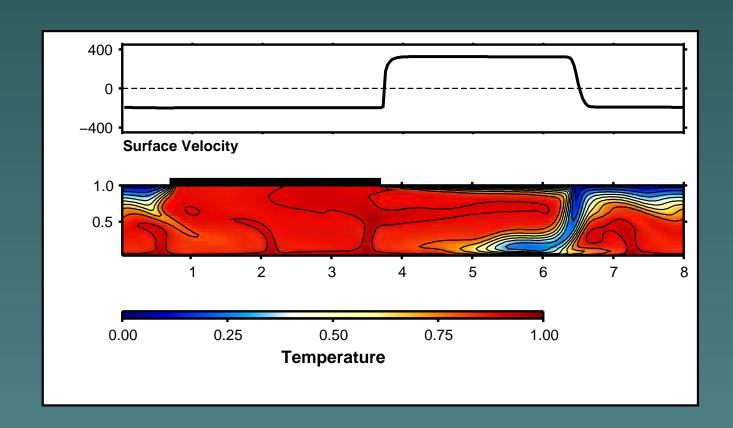
- Initial: boundary layers.
- Ra = 10^6 , $\sigma_y = 10^5$, $\Delta \eta = 10^5$ Insulating continent a=3.



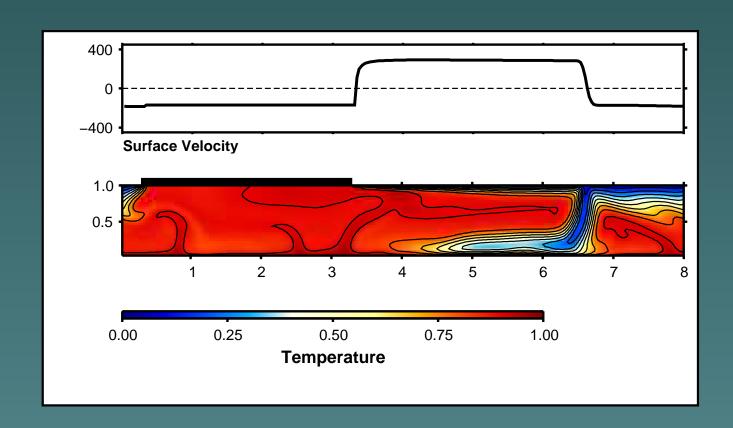
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- Ra = 10^6 , $\sigma_y = 10^5$, $\Delta \eta = 10^5$ Insulating continent a=3.



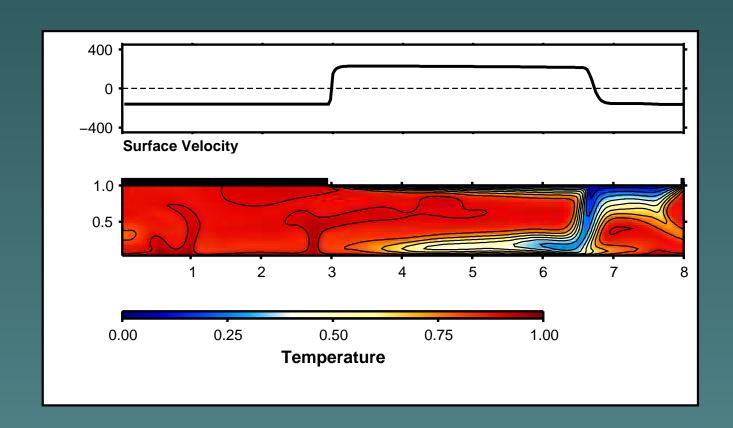
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- Ra = 10^6 , $\sigma_y = 10^5$, $\Delta \eta = 10^5$ Insulating continent a=3.



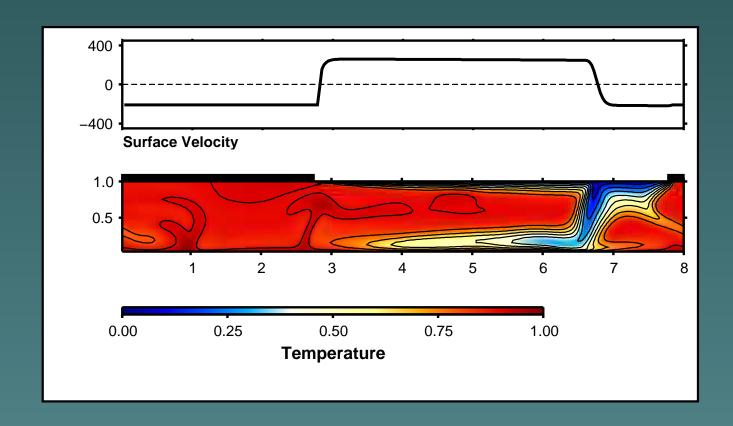
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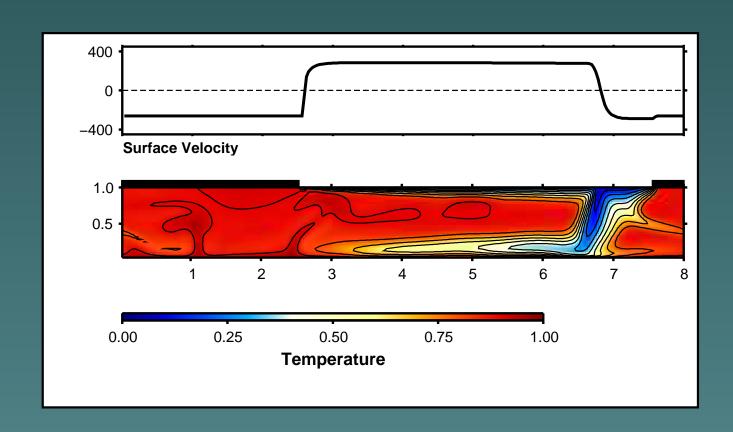
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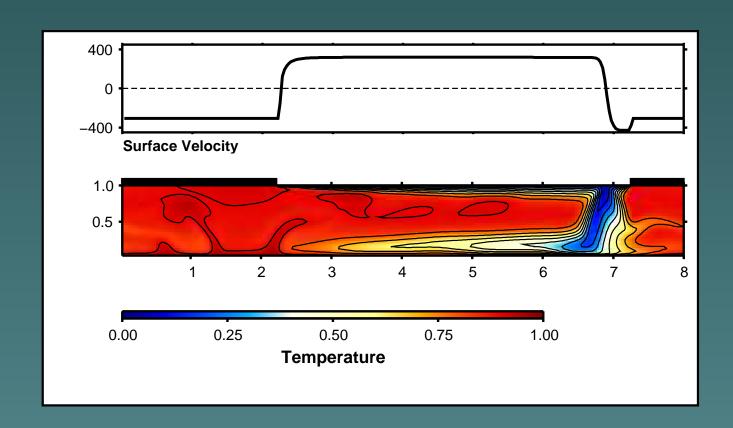
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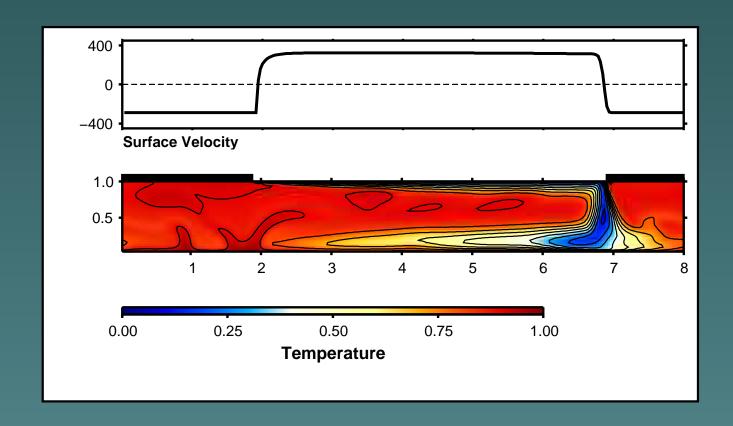
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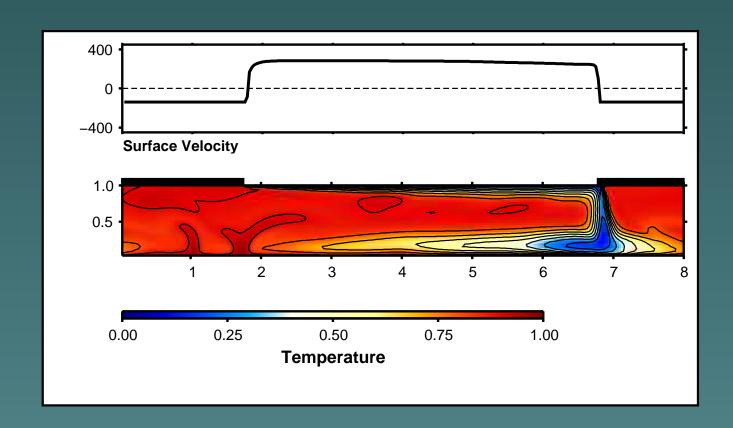
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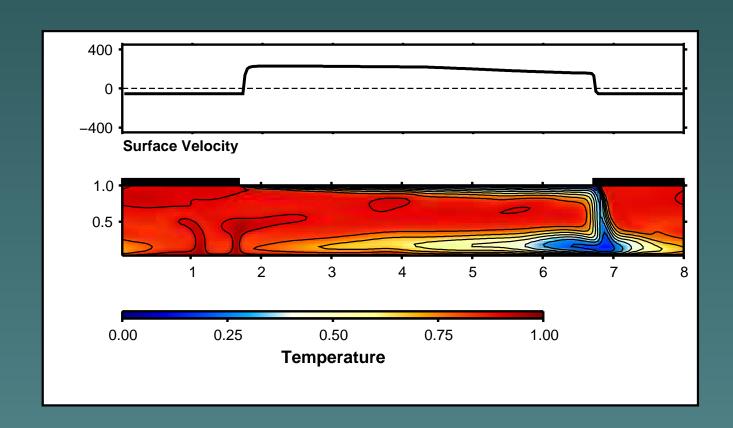
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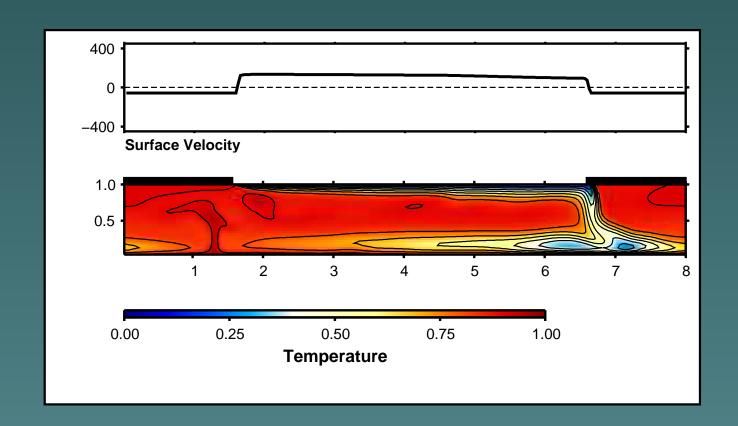
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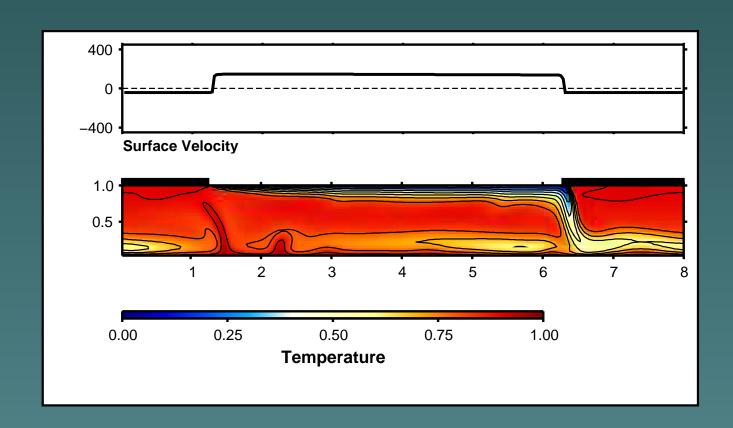
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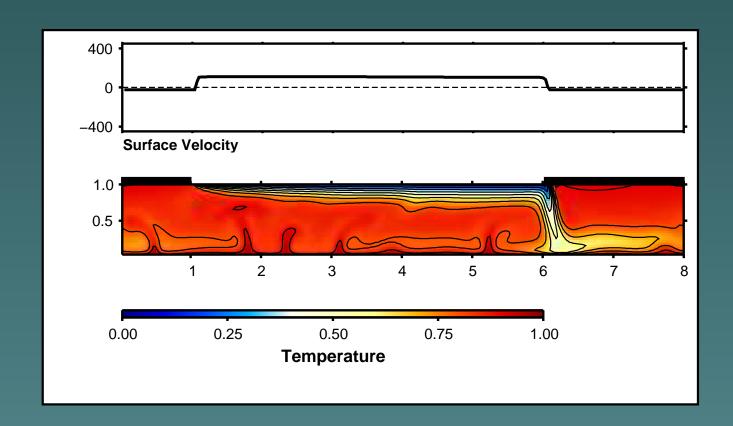
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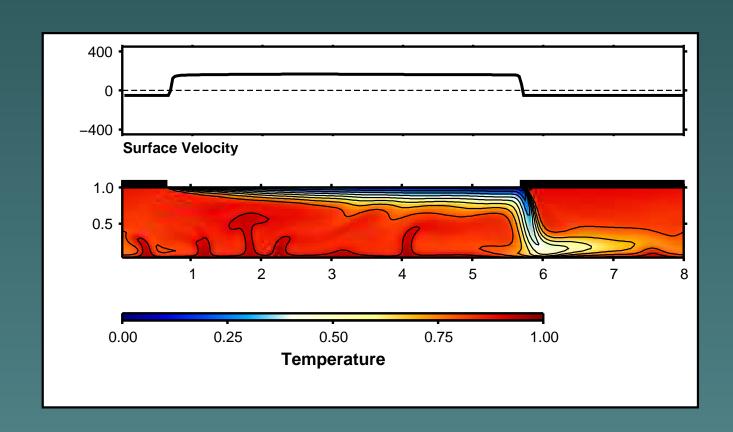
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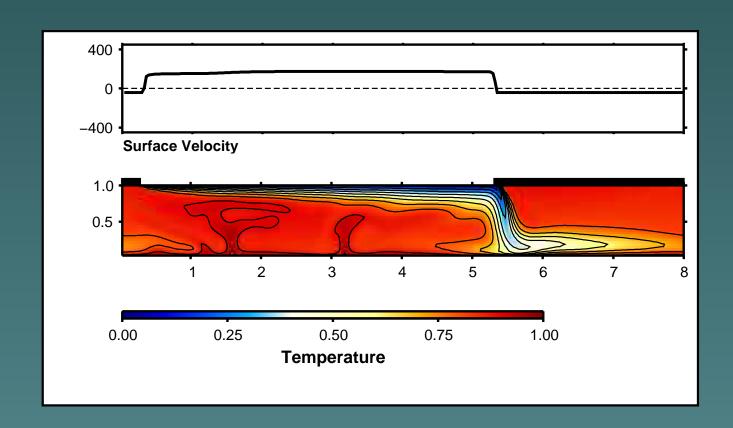
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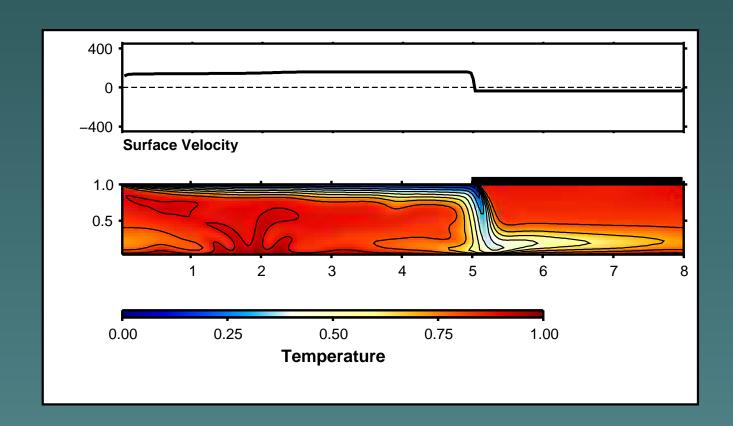
- Initial: boundary layers.
- Ra = 10^6 , $\sigma_y = 10^5$, $\Delta \eta = 10^5$ Insulating continent a=3.



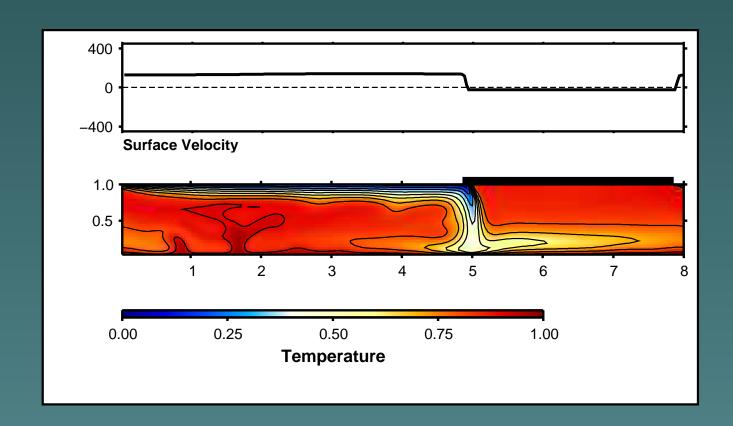
- Initial: boundary layers.
- Ra = 10^6 , $\sigma_y = 10^5$, $\Delta \eta = 10^5$ Insulating continent a=3.



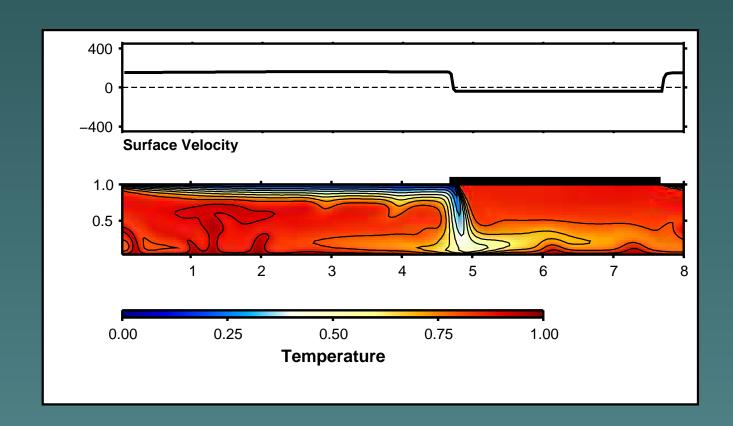
- Initial: boundary layers.
- Ra = 10^6 , $\sigma_y = 10^5$, $\Delta \eta = 10^5$ Insulating continent a=3.



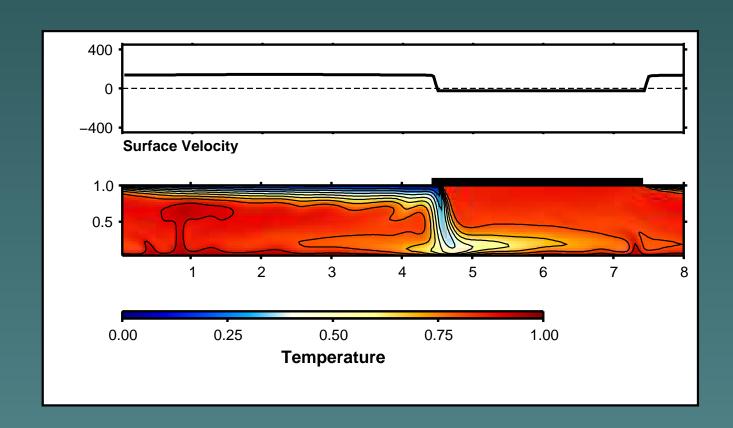
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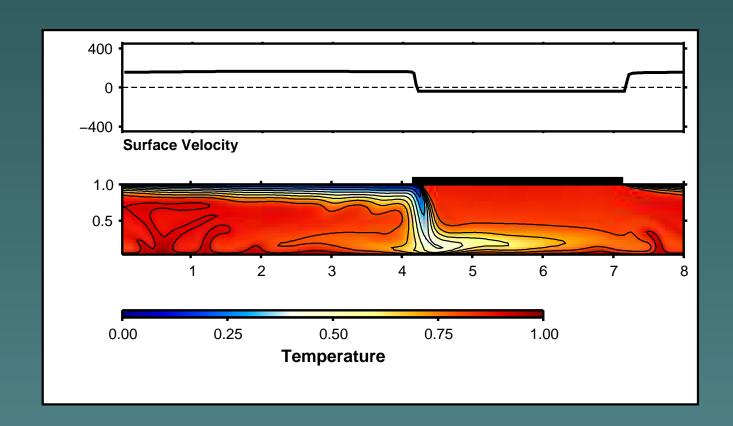
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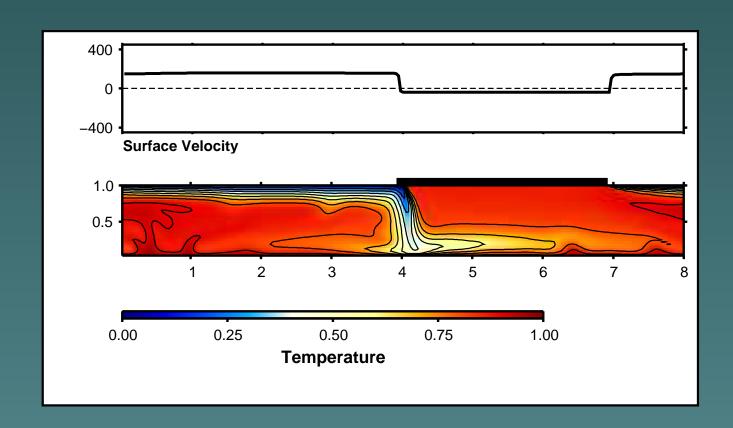
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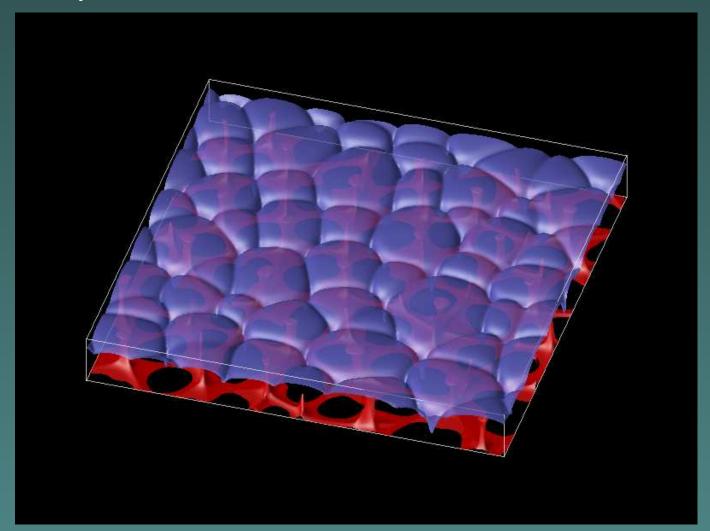


- Initial: boundary layers.
- Ra = 10^6 , $\sigma_y = 10^5$, $\Delta \eta = 10^5$ Insulating continent a=3.



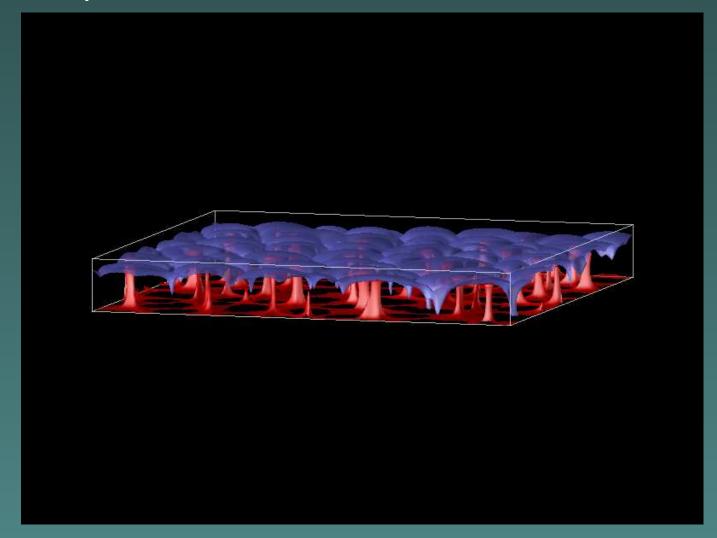
3D models

$${
m Ra}=10^6$$
 $\sigma_{
m y}=10^5$ Red: T=0.95 - Blue: T=0.7

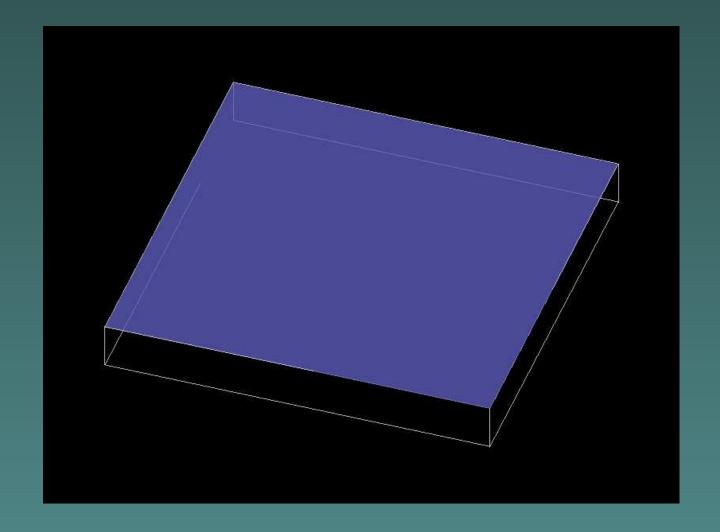


3D models

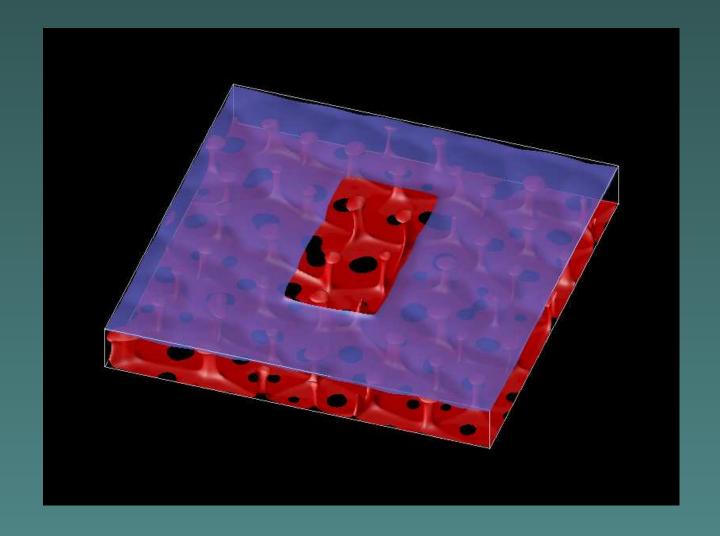
 ${\sf Ra}=10^6$ $\sigma_{\sf y}=10^5$ Red: T=0.95 - Blue: T=0.7



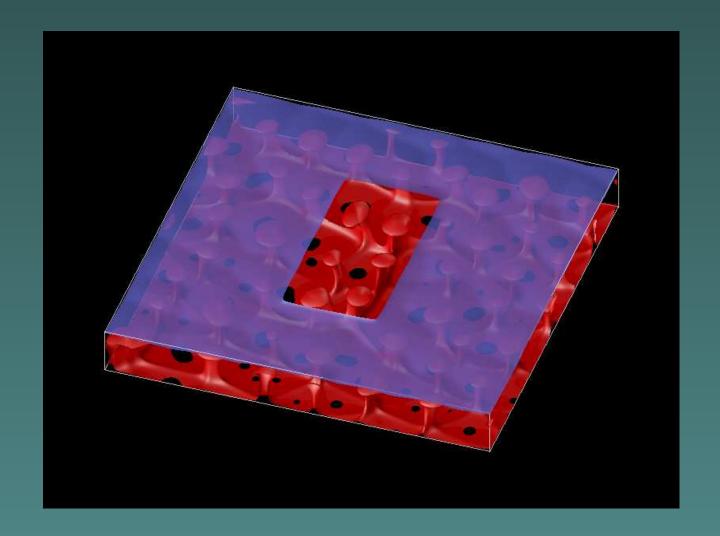
$${
m Ra}=10^6$$
 $\sigma_{
m y}=10^5$ Red: T=0.8 - Blue: T=0.2



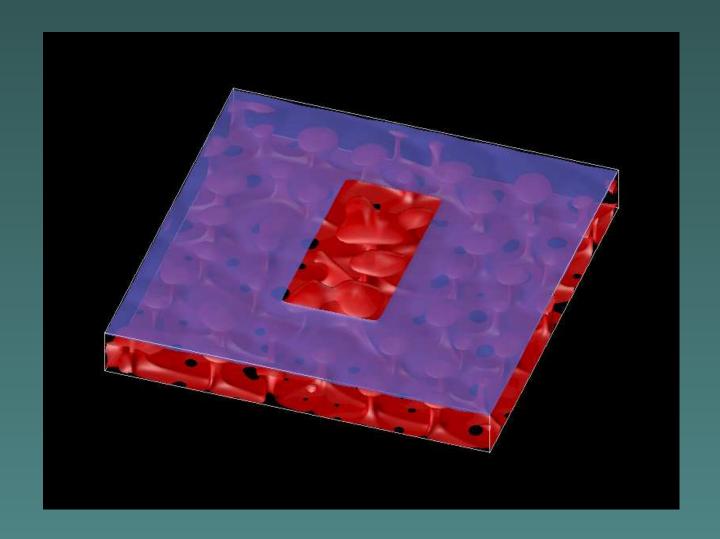
$${
m Ra}=10^6$$
 $\sigma_{
m y}=10^5$ Red: T=0.8 - Blue: T=0.2



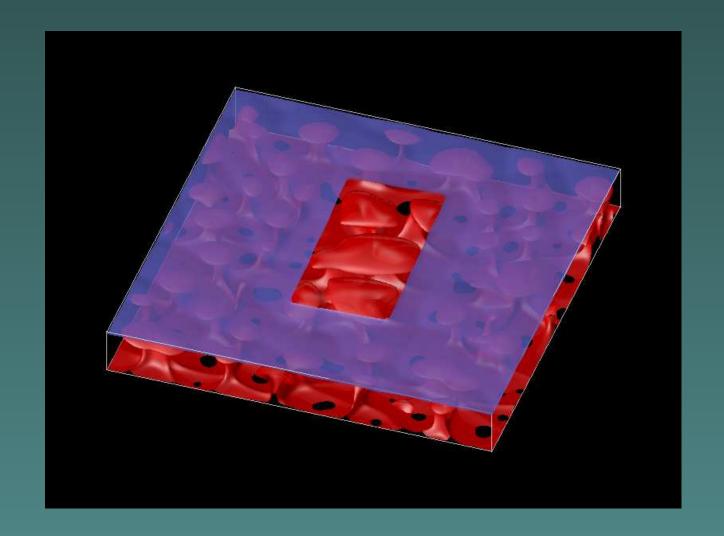
$${
m Ra}=10^6$$
 $\sigma_{
m y}=10^5$ Red: T=0.8 - Blue: T=0.2



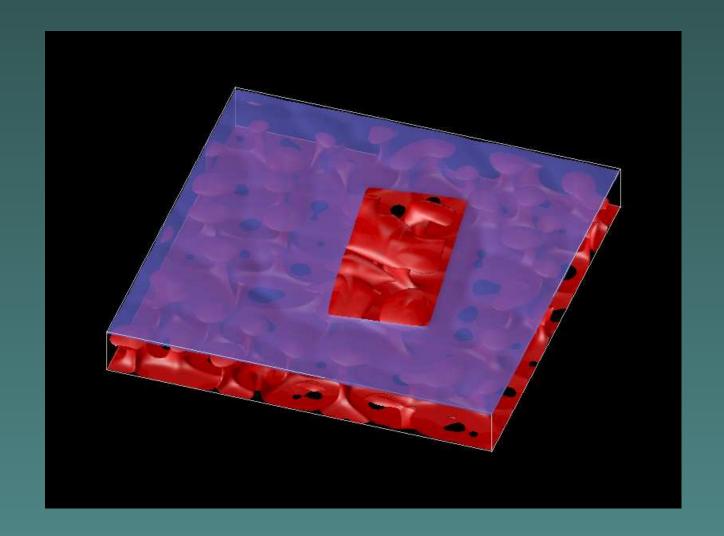
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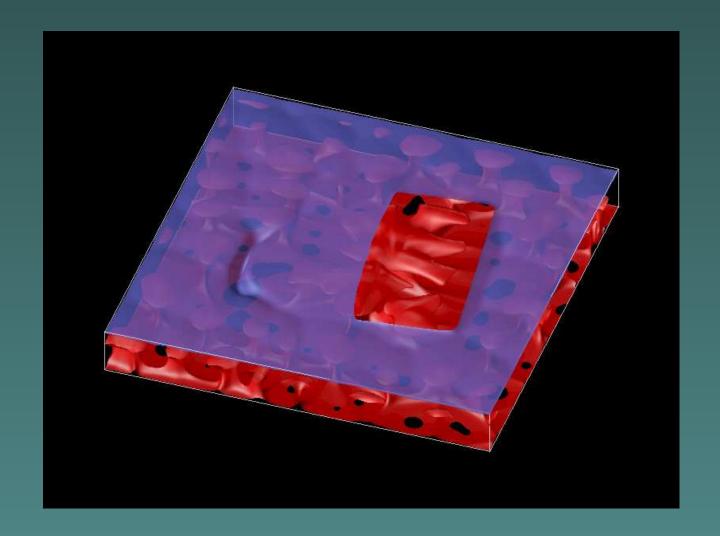
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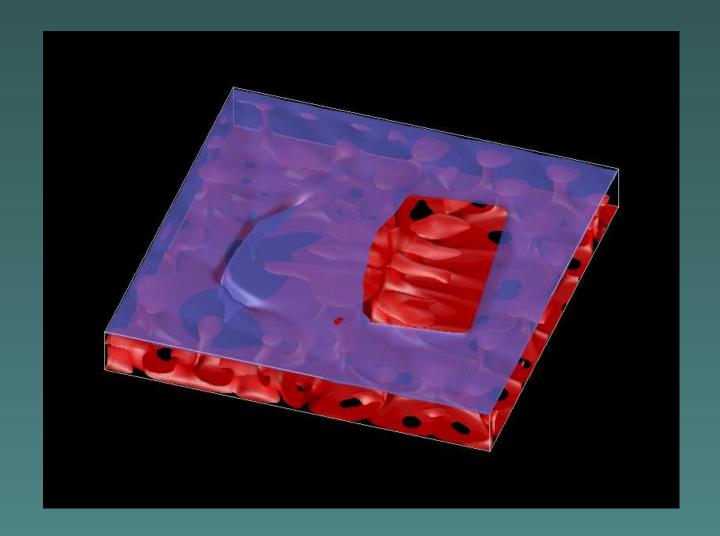
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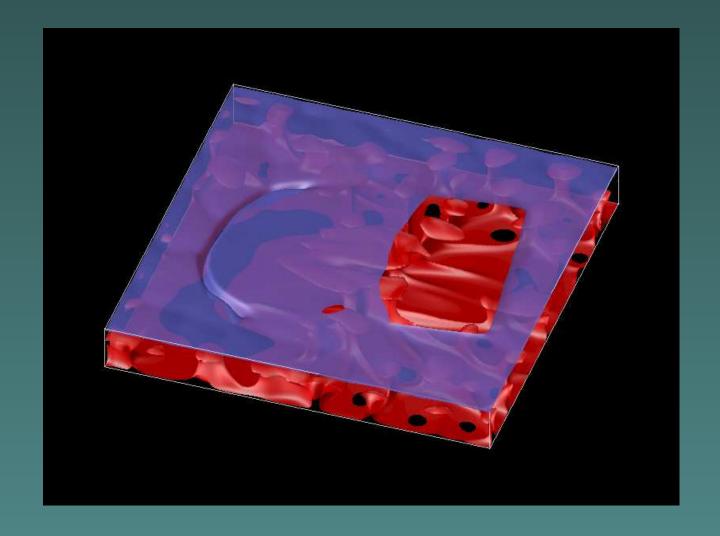
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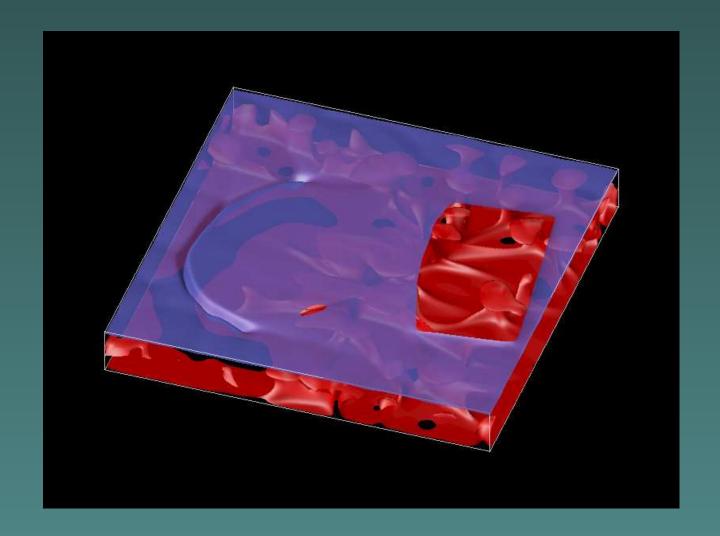
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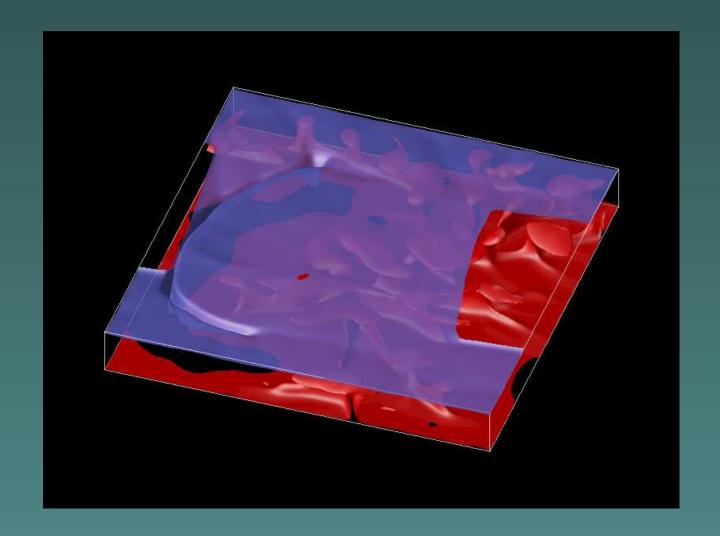
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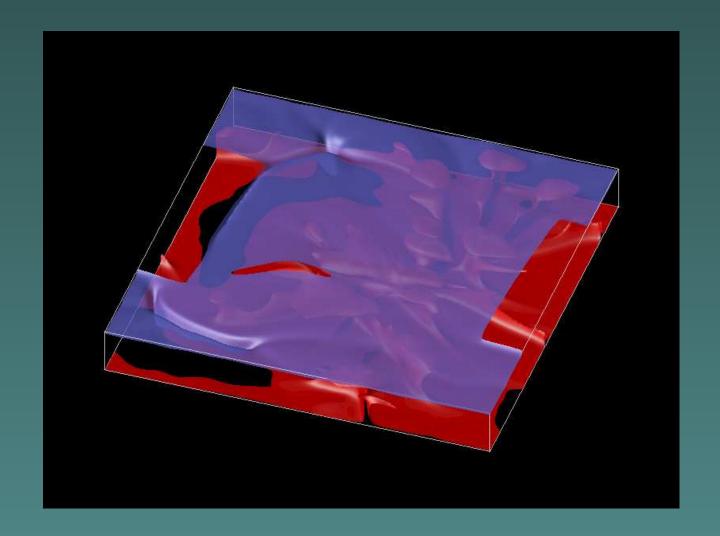
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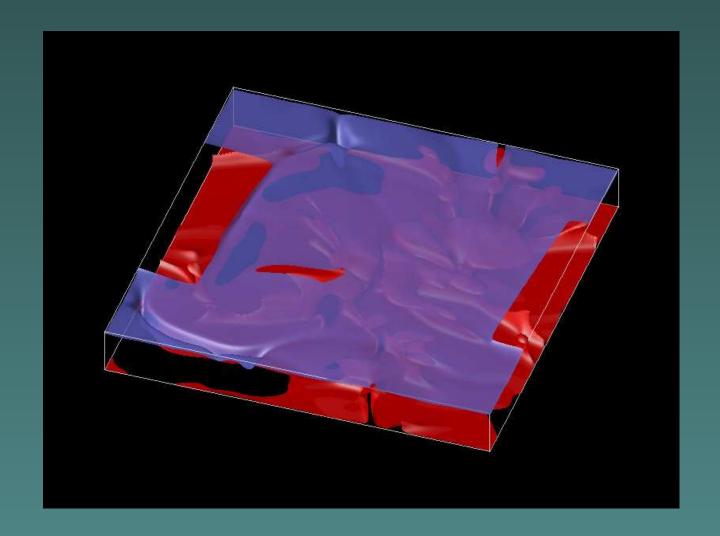
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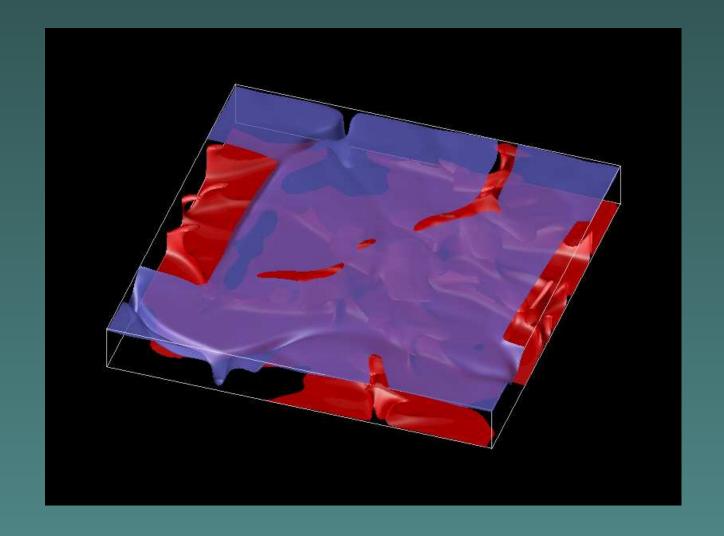
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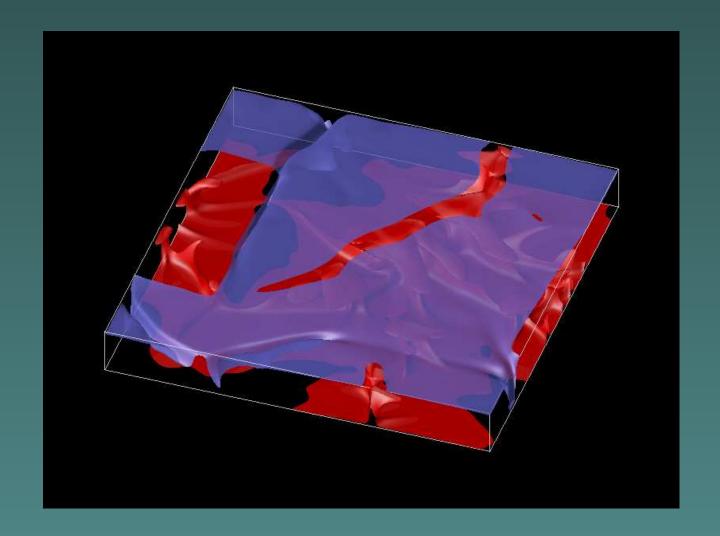
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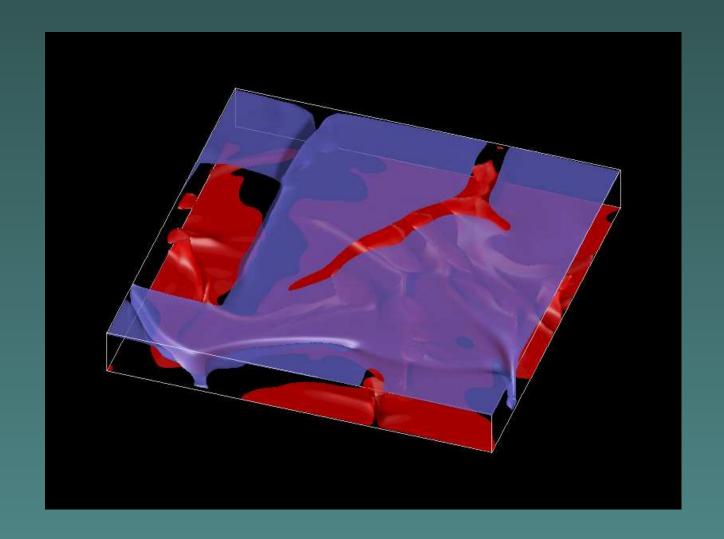
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m y}=10^5$ Red: T=0.8 - Blue: T=0.2



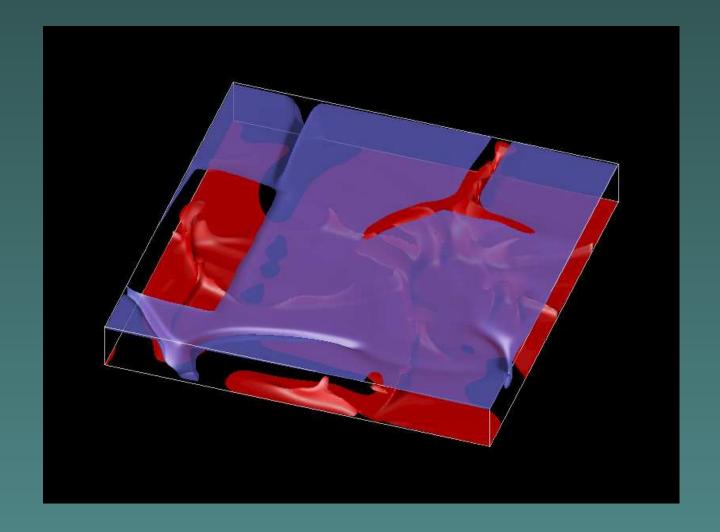
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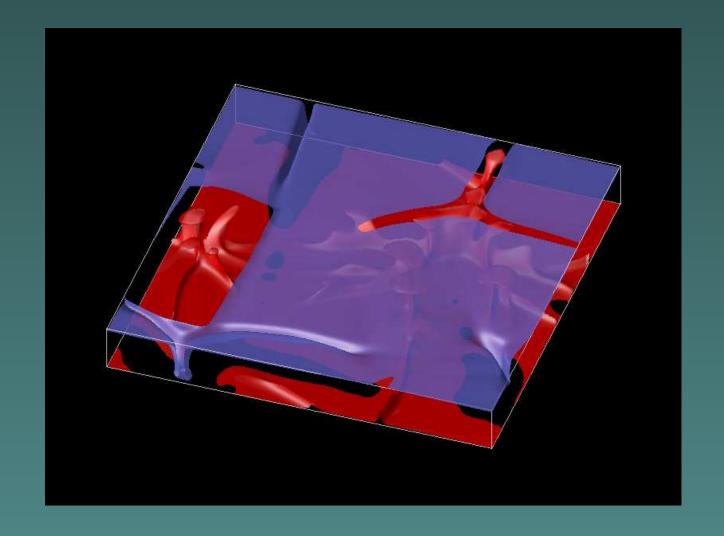
$${
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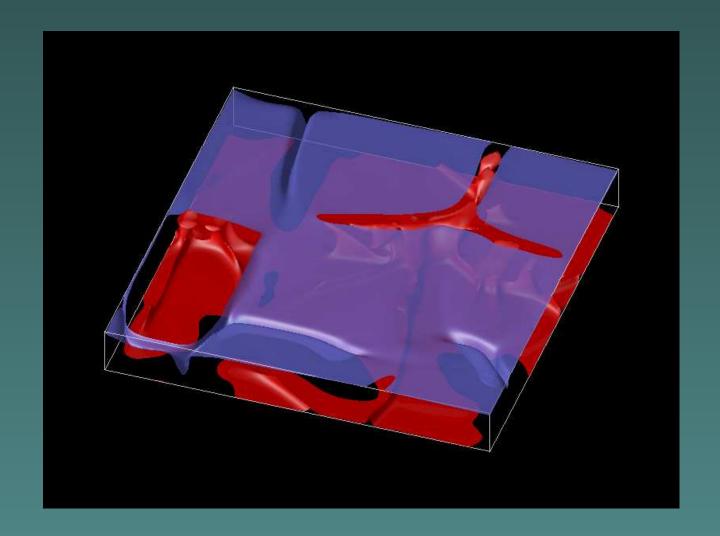
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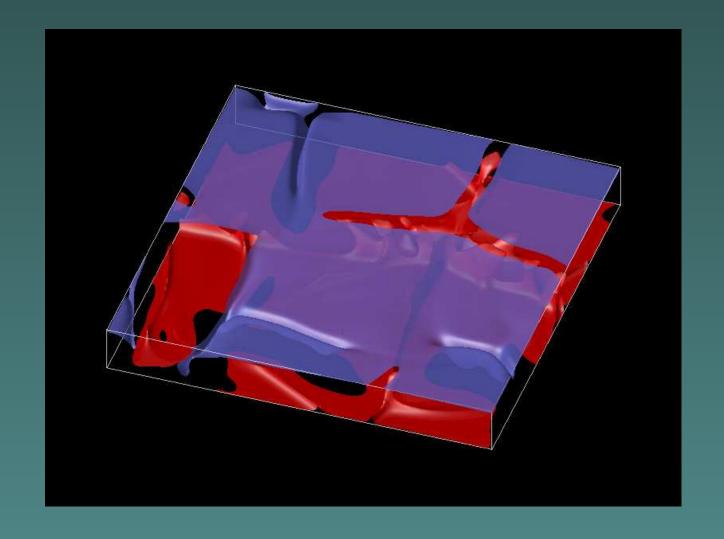
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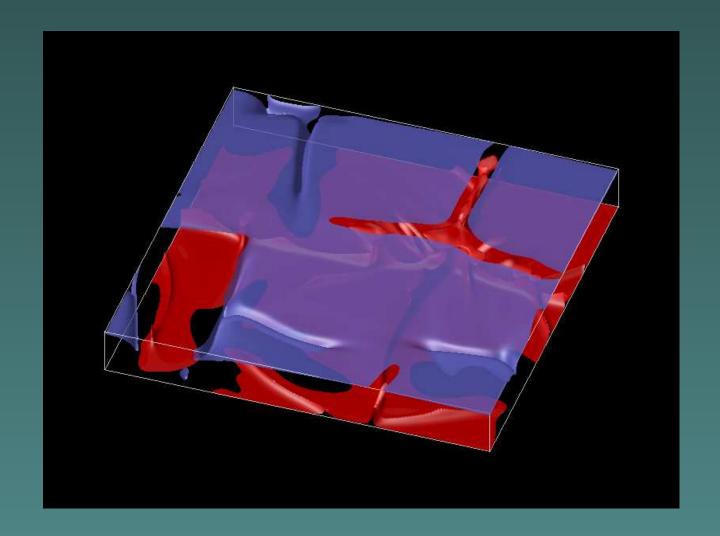
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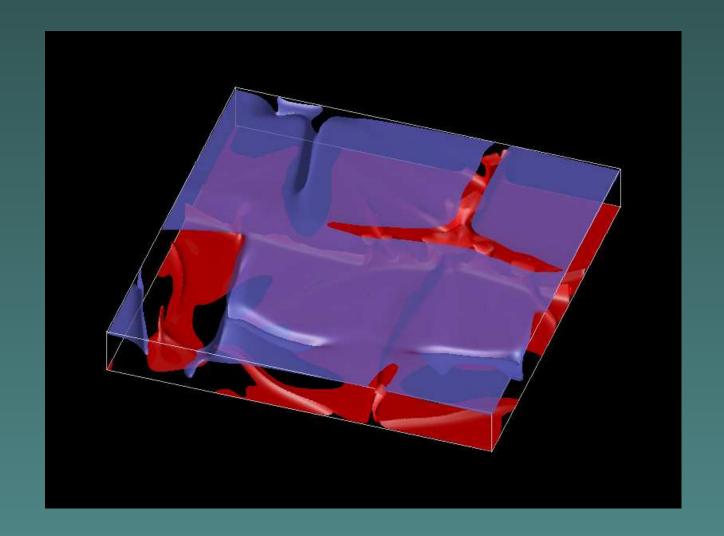
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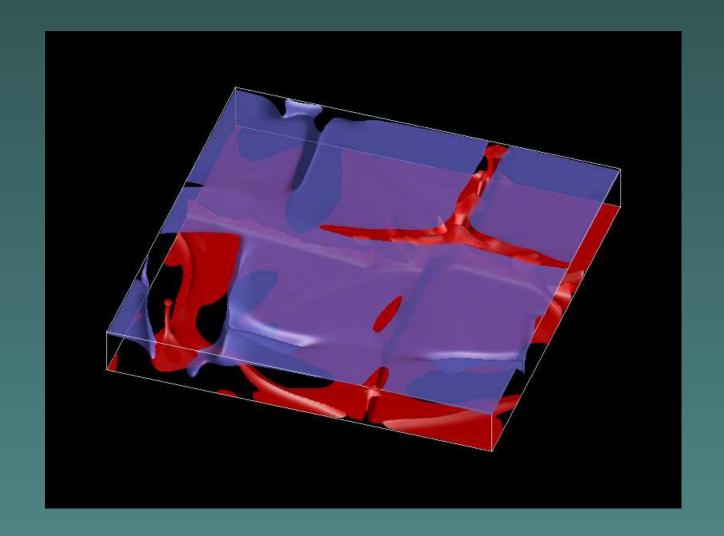
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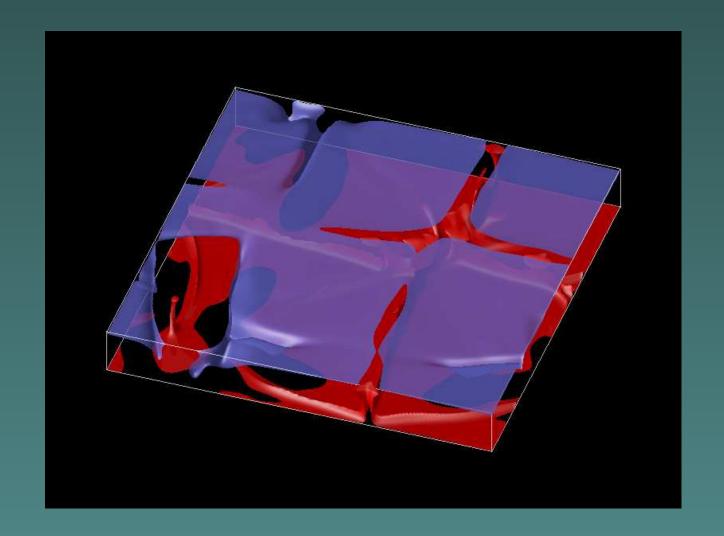
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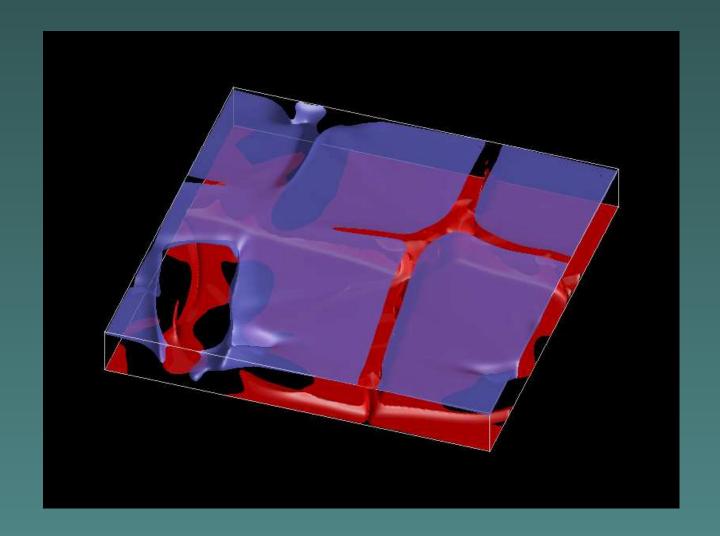
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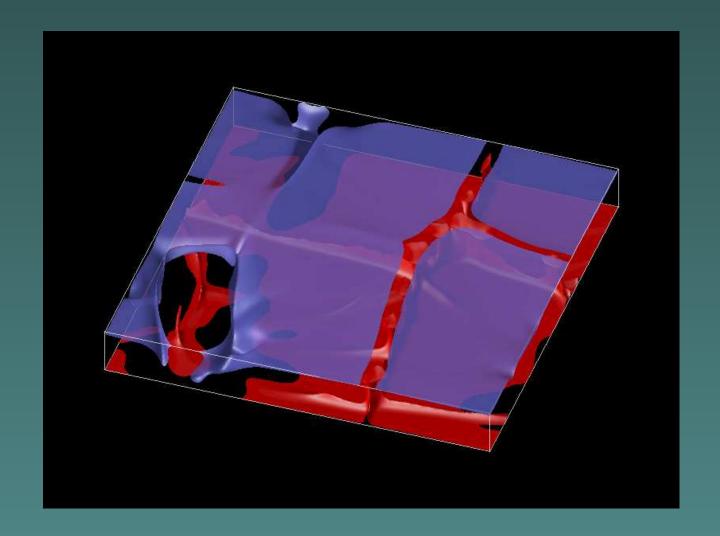
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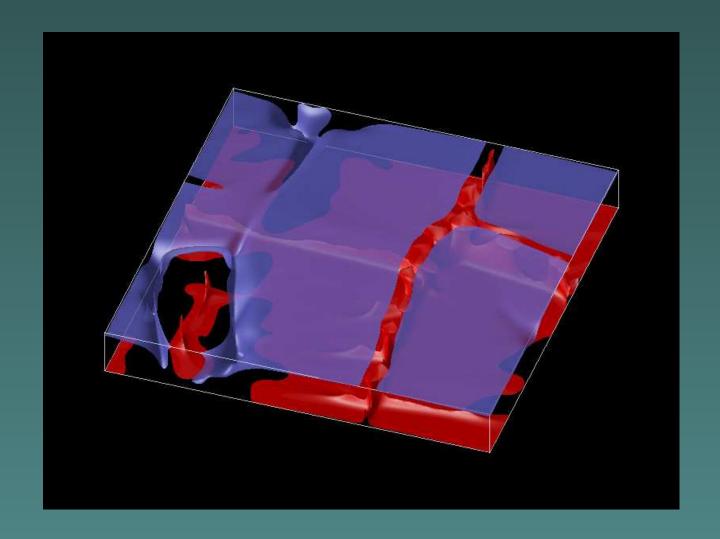
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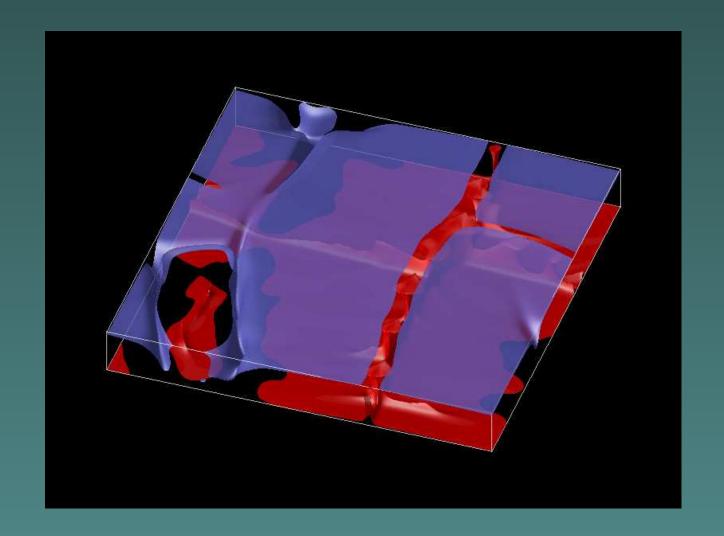
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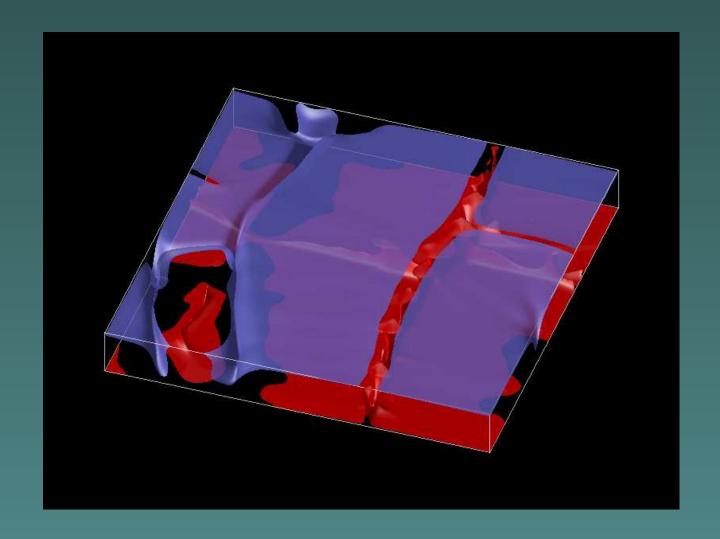
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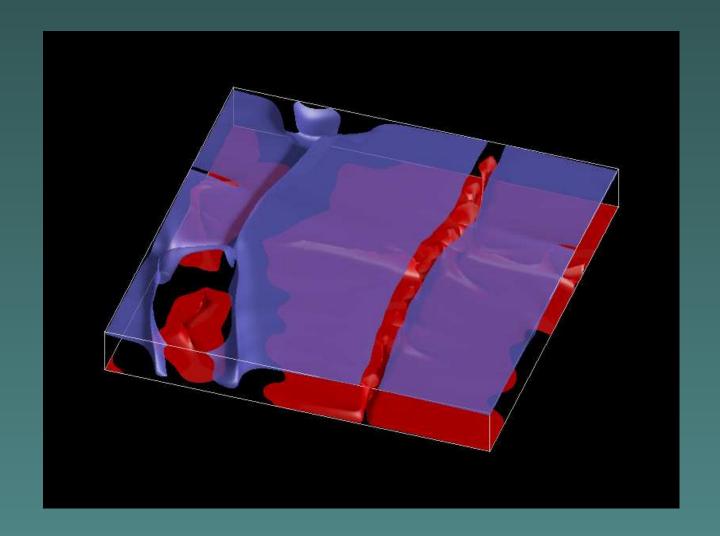
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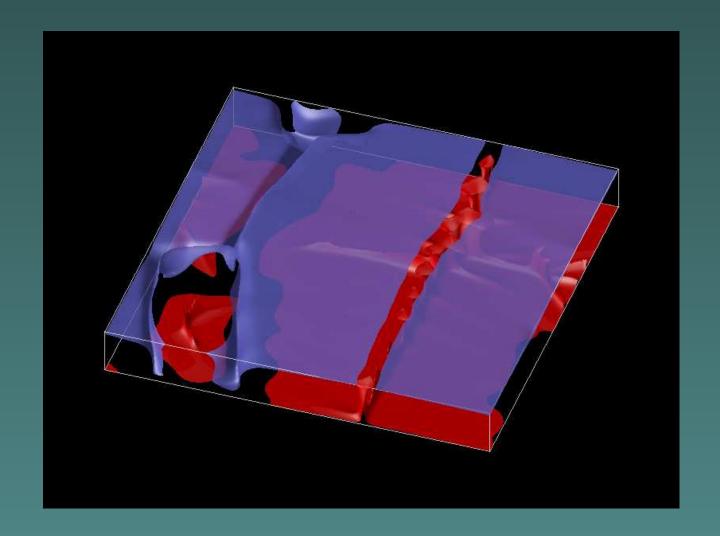
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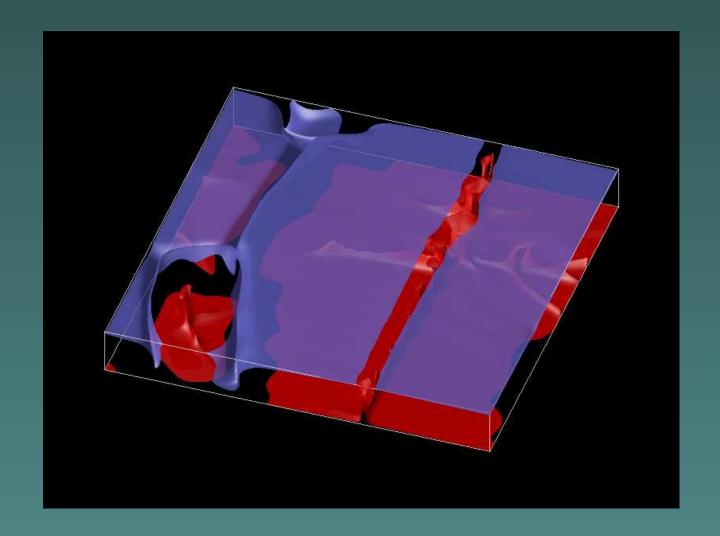
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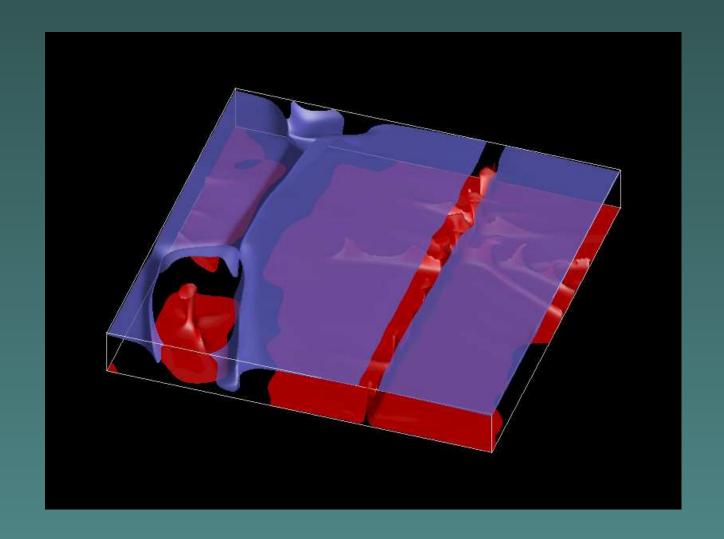
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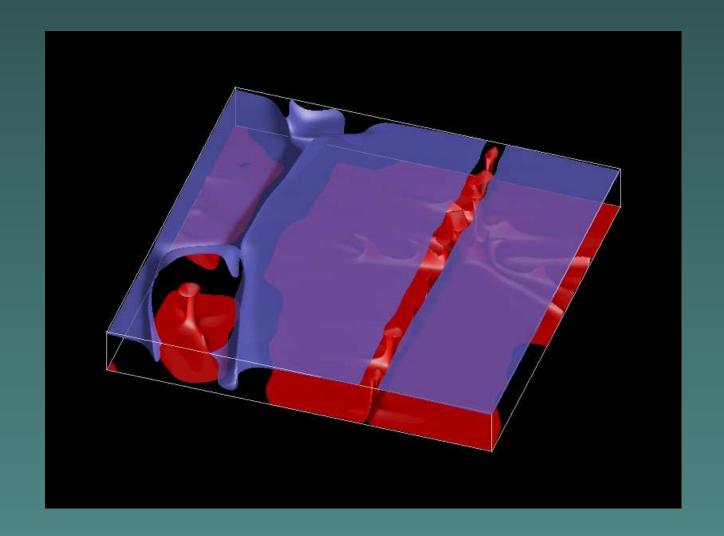
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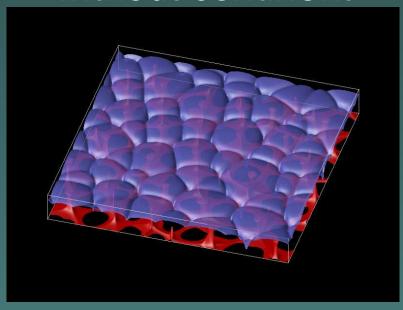


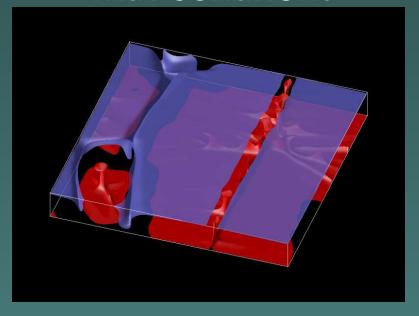
$${
m Ra}=10^6$$
 $\sigma_{
m y}=10^5$ Red: T=0.8 - Blue: T=0.2



3D models

without continent



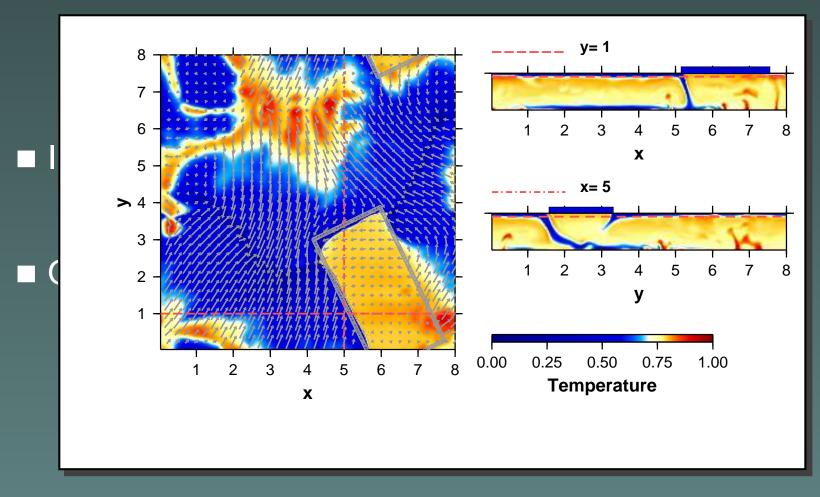


First summary - Effect of continents

- In 2D:
 - Plate tectonics occurs sooner.
 - More stable.
- In 3D:
 - One can use higher yield stress.
- One-sided subduction zones.

First summary - Effect of continents

■ In 2D:



First summary - Effect of continents

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Thermal evolution

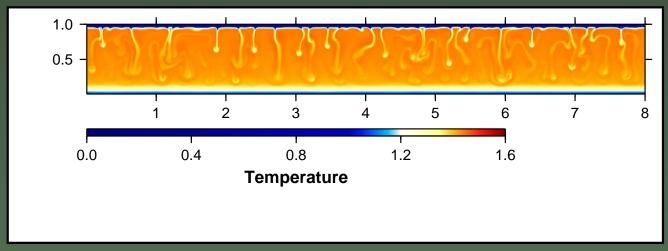
- Computations in 2D at different Rayleigh numbers and internal heating rates chosen to represent different ages of the Earth's thermal history
- \blacksquare Ages up to t = 2 Gy
- Internal heating:
 - Mantle always depleted (early formation of continents).
 - Radioactive decay.
- Rayleigh number:
 - Linear increase of T_{CMB} with age: 100 K/Gy.

Thermal evolution

Computations in 2D at different Rayleigh numbers and internal heating rates chosen to represent different ages of the Earth's thermal history

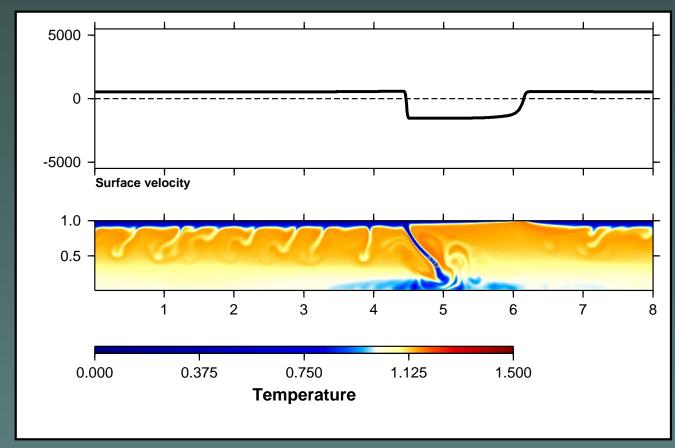
Age t (Gy)	T_b (K)	H (μ W.m $^{-3}$)	$\eta(T_b)$ (Pa.s)	Ra^*	H^*
0.0	1973	$1.59.10^{-2}$	10^{22}	7.10^{6}	22
0.5	1998	$1.76.10^{-2}$	$8.5.10^{21}$	8.10^{6}	24
1.0	2023	$1.97.10^{-2}$	$7.2.10^{21}$	$9.5.10^{6}$	27
1.5	2048	$2.24.10^{-2}$	$6.2.10^{21}$	$1.1.10^{7}$	30
2.0	2073	$2.59.10^{-2}$	$5.3.10^{21}$	$1.3.10^7$	34

$${
m Ra} = 1.1.10^7 \quad {
m H} = 30 \ ({
m age} = 1.5 \ {
m Gy}) \qquad \sigma_{
m y} = 3.5.10^5 \ (196 \ {
m MPa})$$

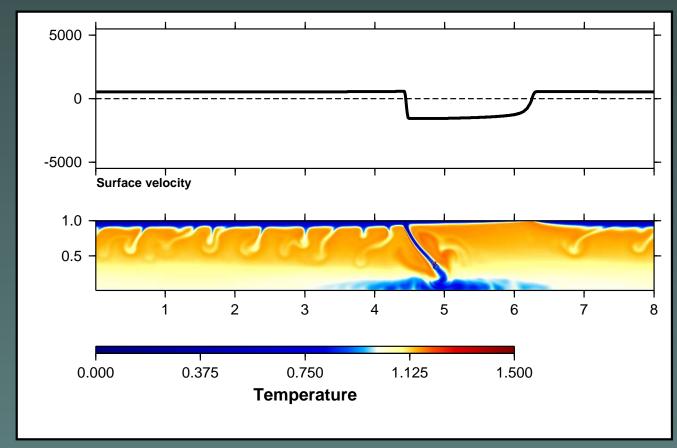


- Stagnant lid regime.
- Negative heat flux at the CMB.

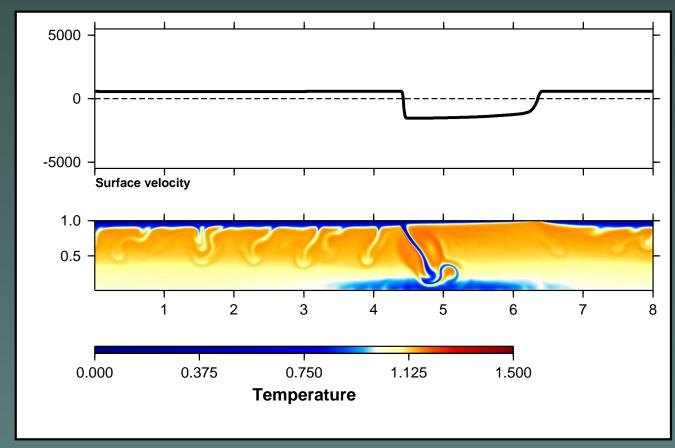
$${\sf Ra} = 7.10^6 \quad {\sf H} = 23 \; ({\sf present}) \qquad \sigma_{\sf y} = 2.10^5 \; (175 \; {\sf MPa})$$



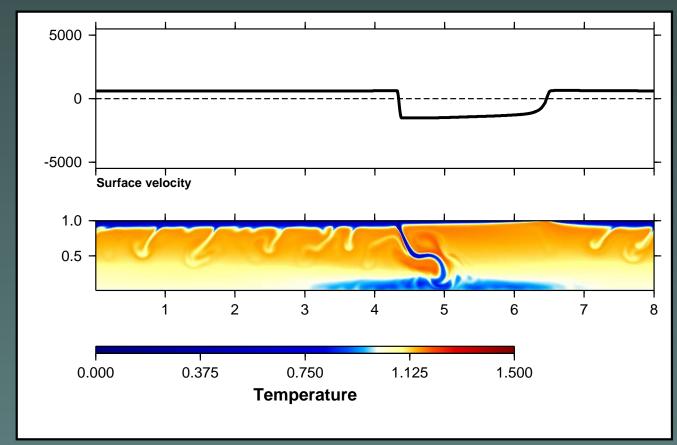
$${\sf Ra} = 7.10^6 \quad {\sf H} = 23 \; ({\sf present}) \qquad \sigma_{\sf y} = 2.10^5 \; (175 \; {\sf MPa})$$



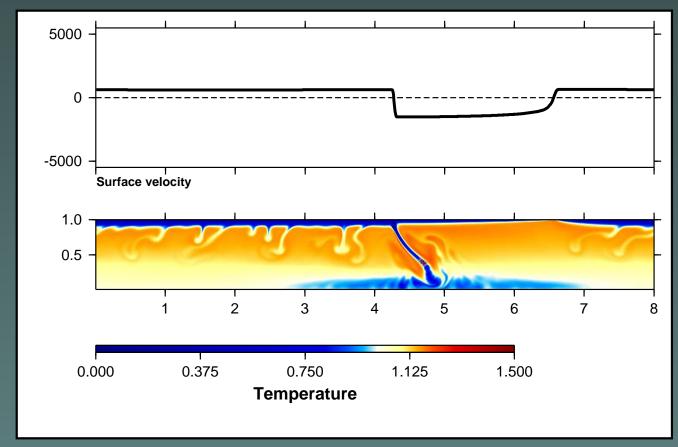
$${\sf Ra} = 7.10^6 \quad {\sf H} = 23 \; ({\sf present}) \qquad \sigma_{\sf y} = 2.10^5 \; (175 \; {\sf MPa})$$



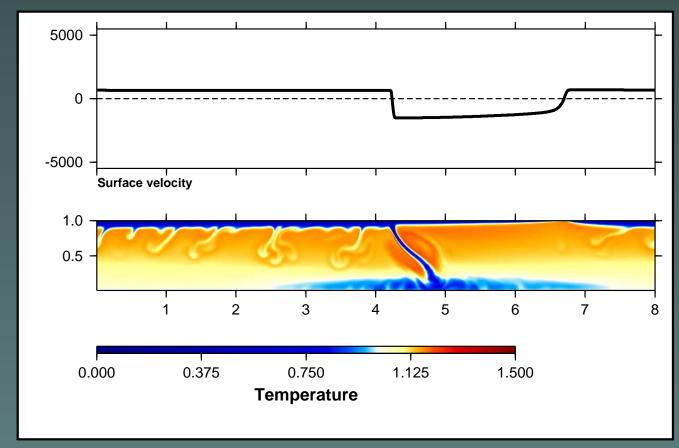
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m present}) \qquad \sigma_{
m y} = 2.10^5 \; (175 \; {
m MPa})$$



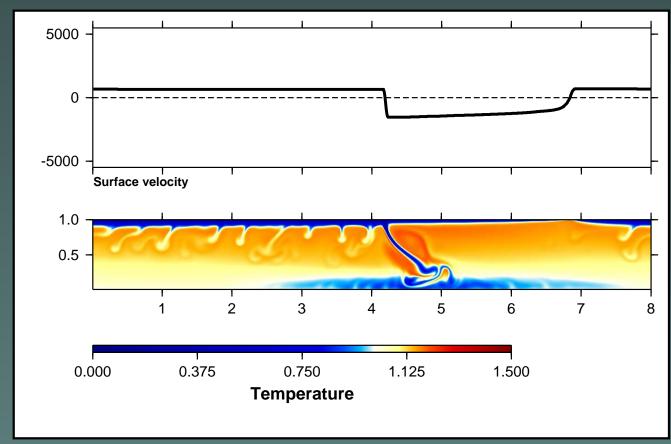
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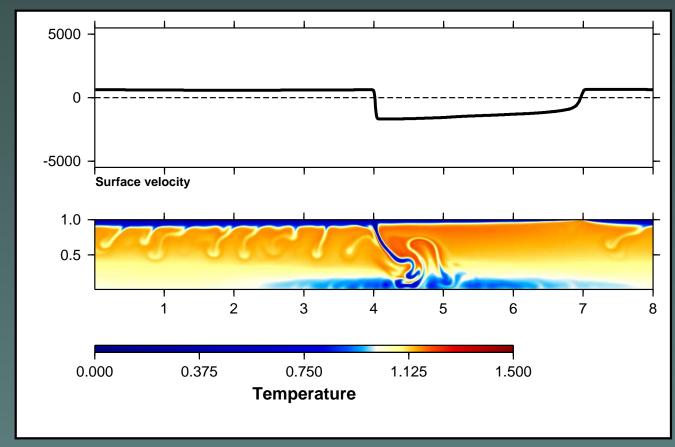
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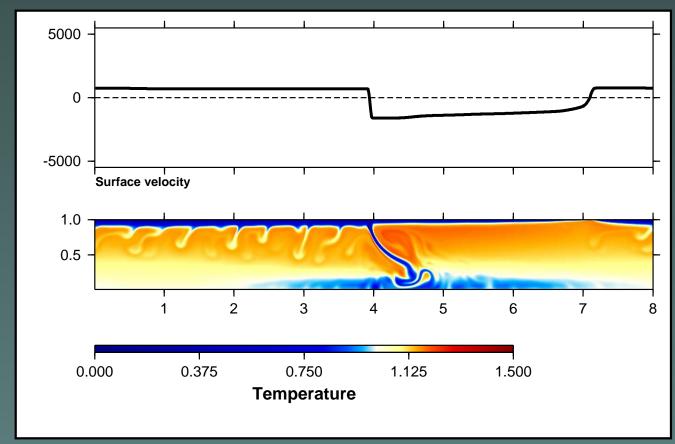
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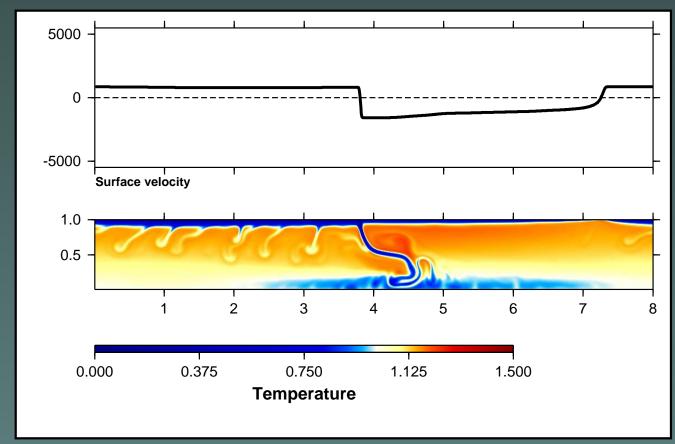
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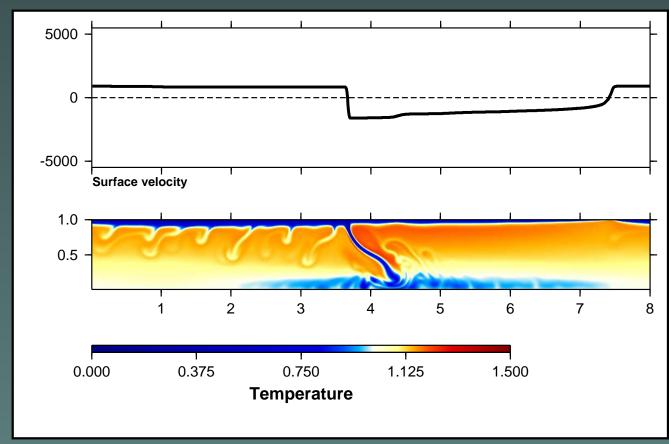
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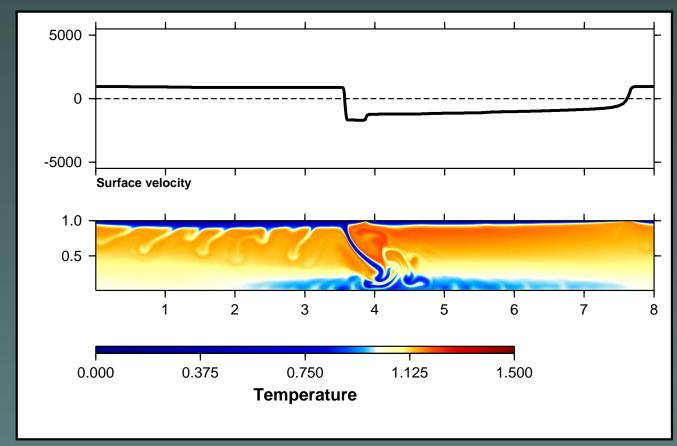
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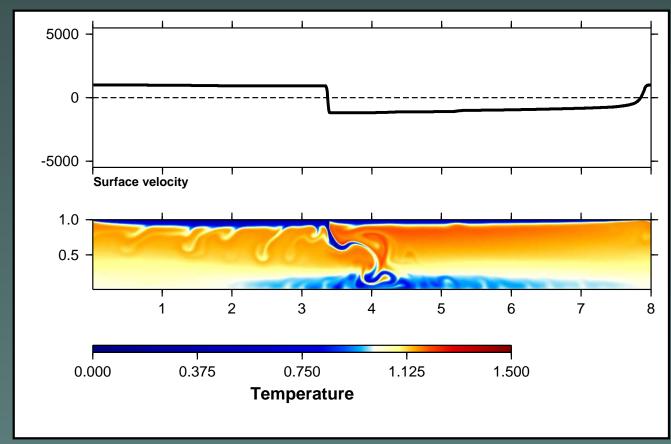
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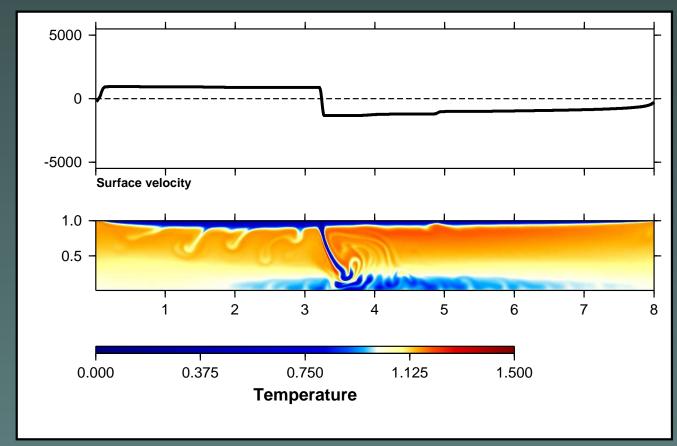
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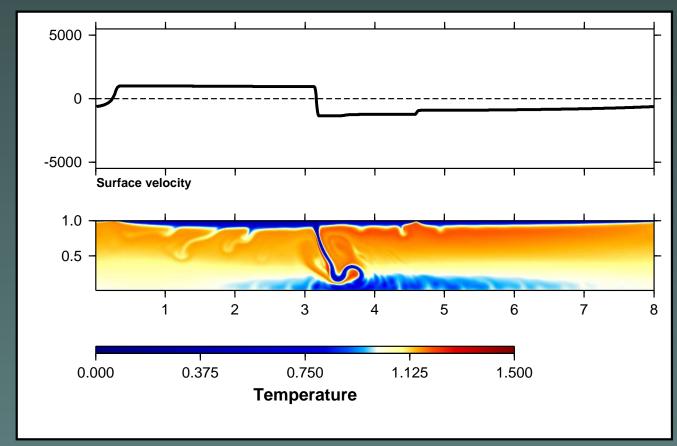
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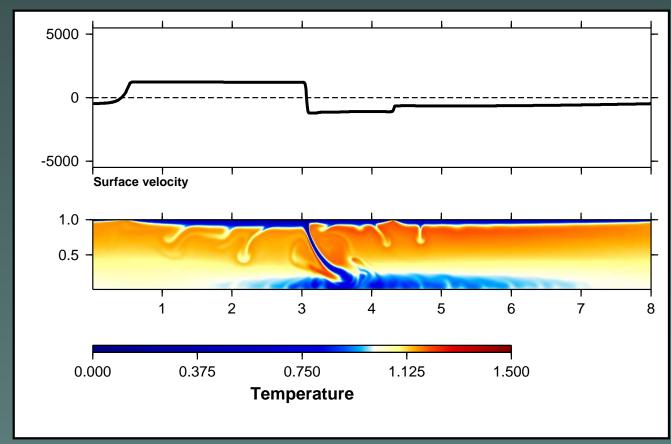
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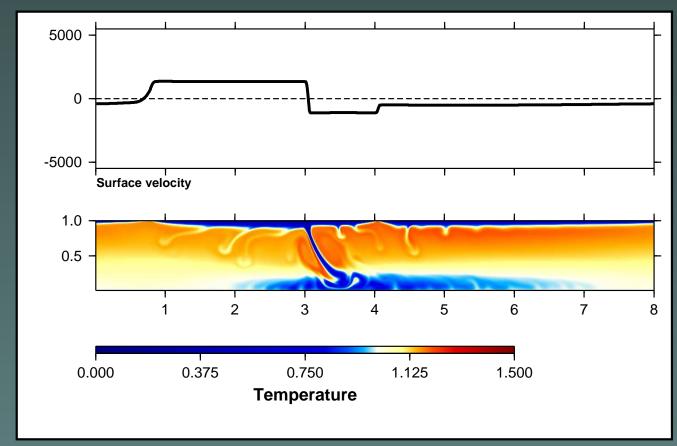
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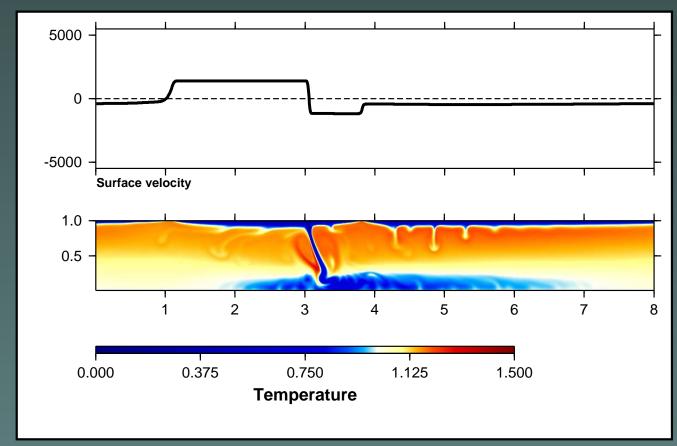
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m MPa})$$



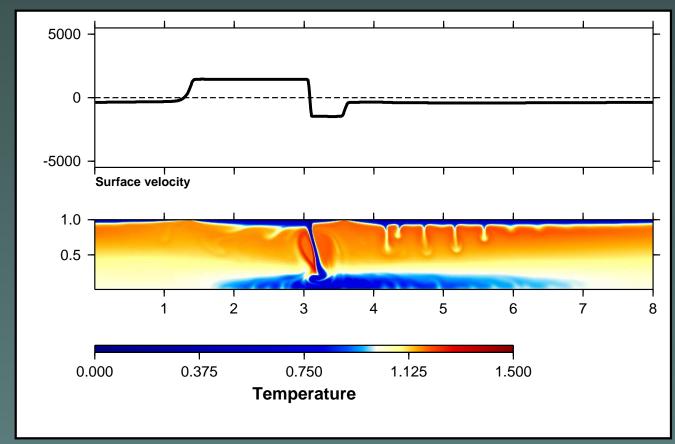
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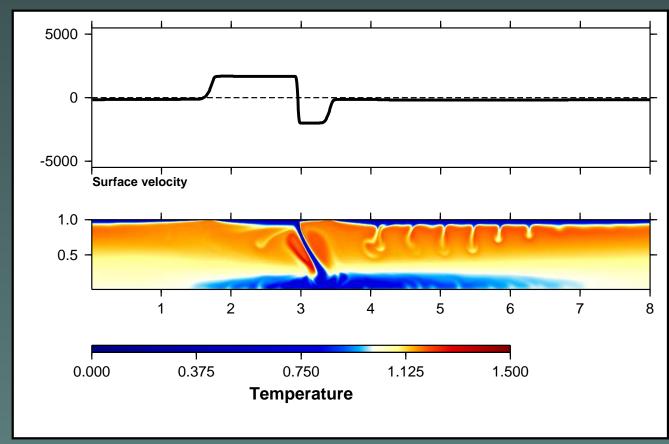
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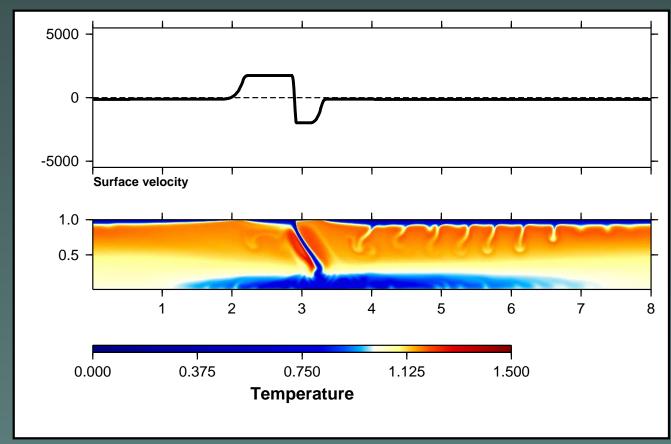
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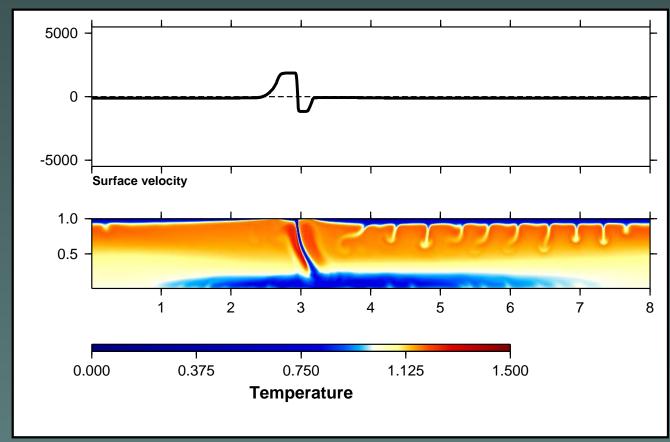
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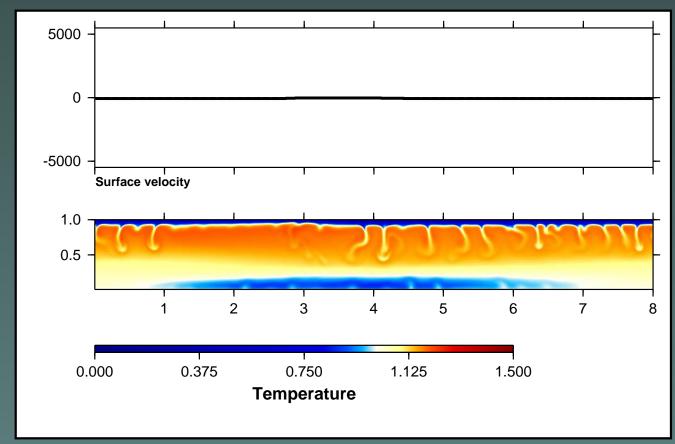
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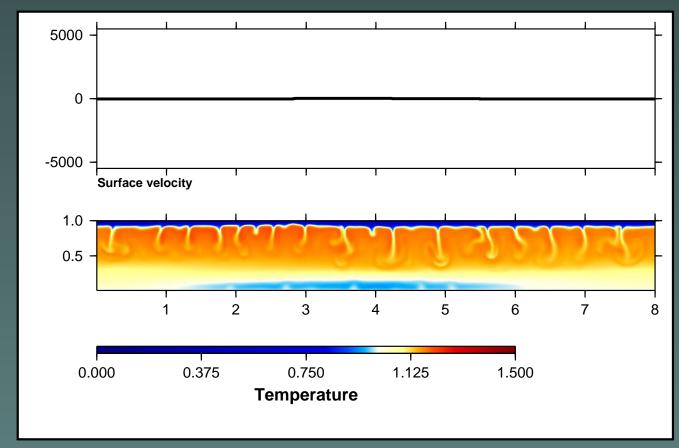
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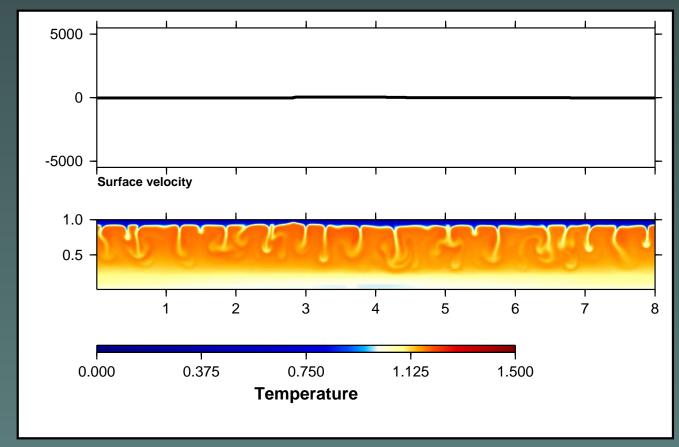
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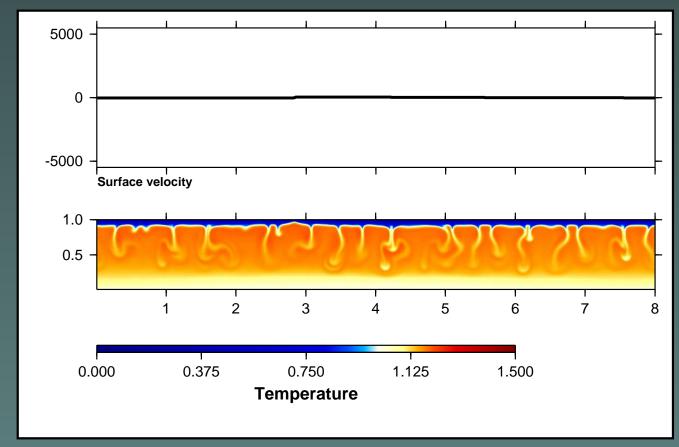
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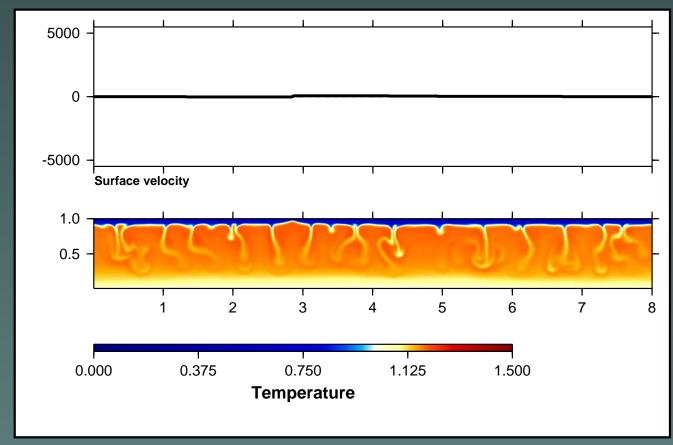
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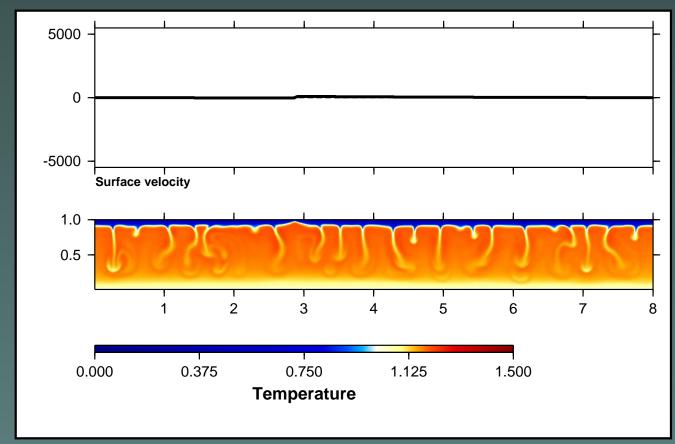
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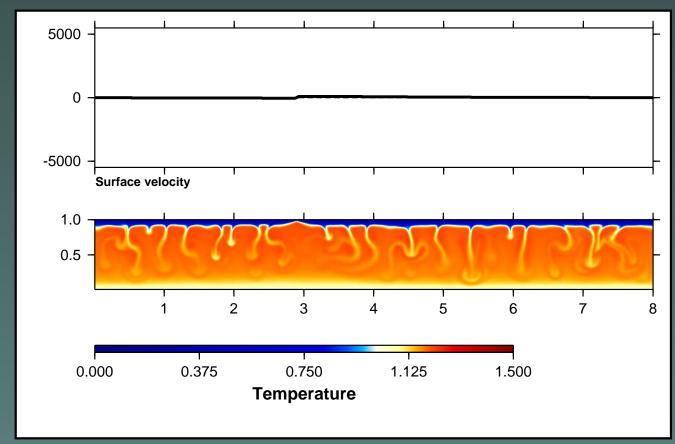
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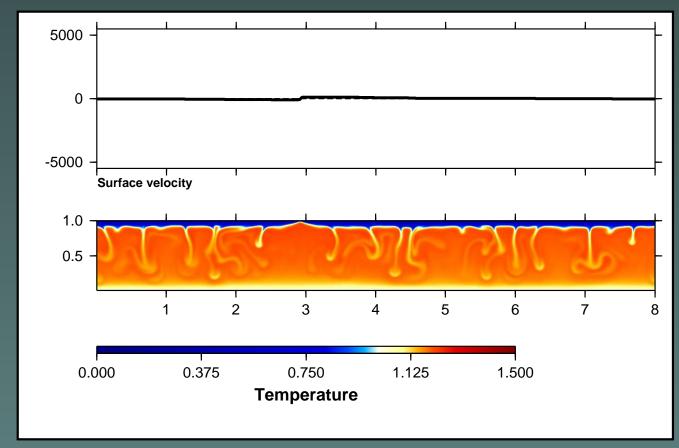
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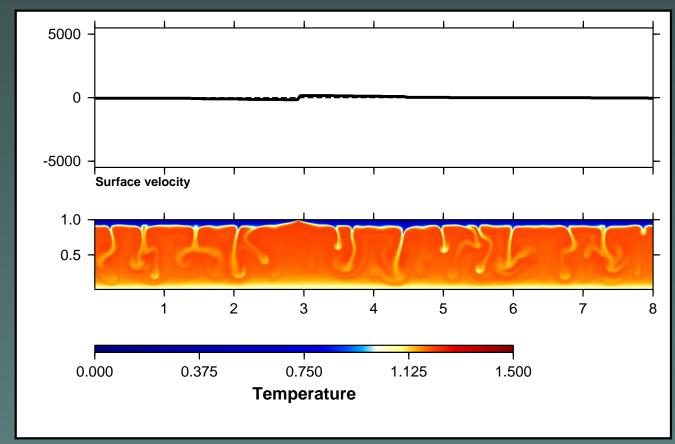
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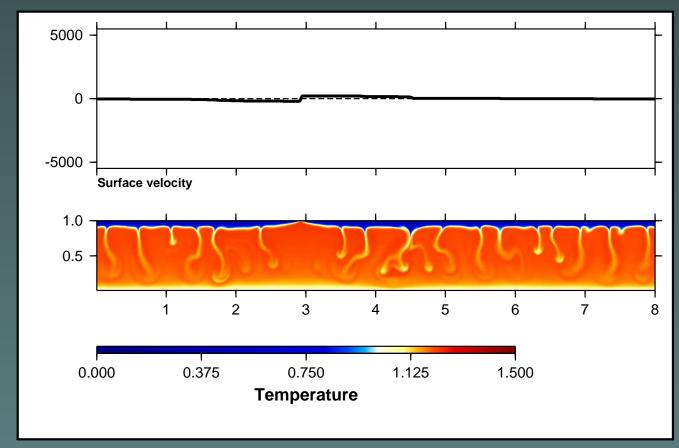
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m present}) \qquad \sigma_{
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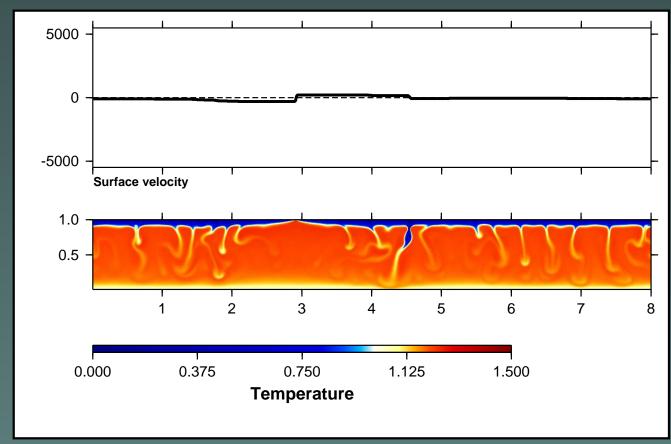
$$Ra = 7.10^6$$
 $H = 23$ (present) $\sigma_y = 2.10^5$ (175 MPa)



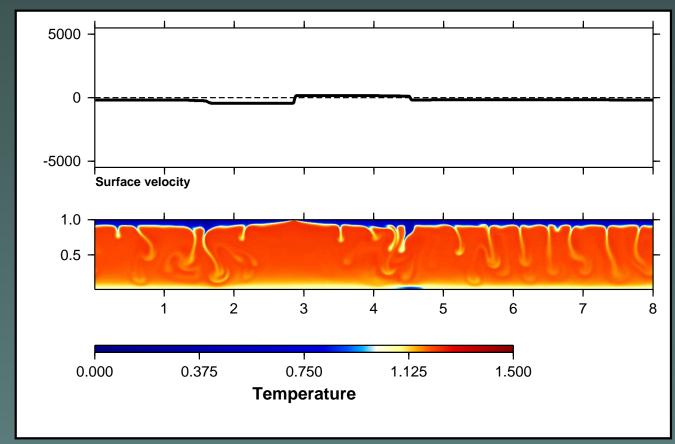
$${\sf Ra} = 7.10^6 \quad {\sf H} = 23 \; ({\sf present}) \qquad \sigma_{\sf y} = 2.10^5 \; (175 \; {\sf MPa})$$



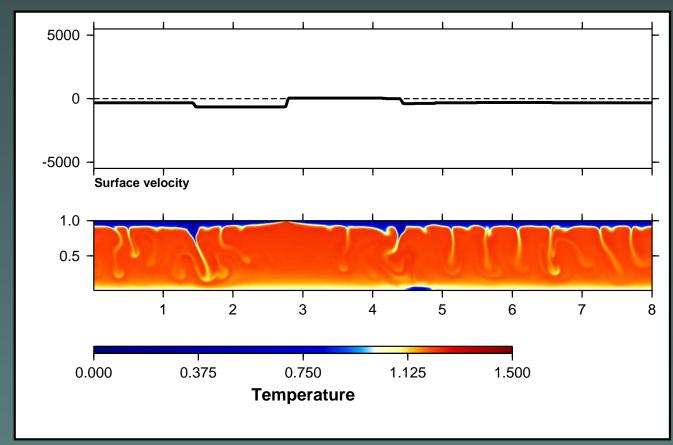
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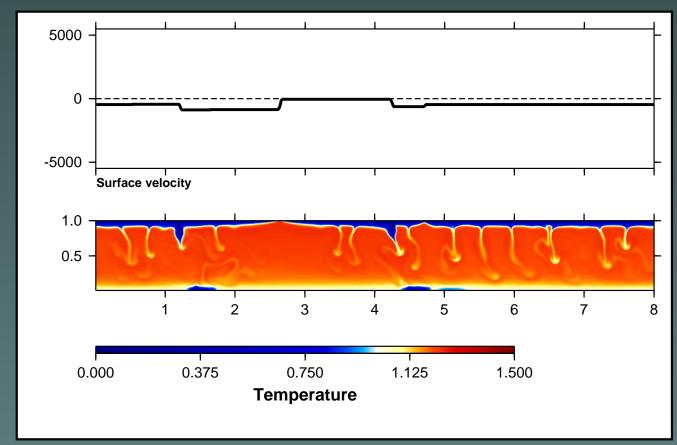
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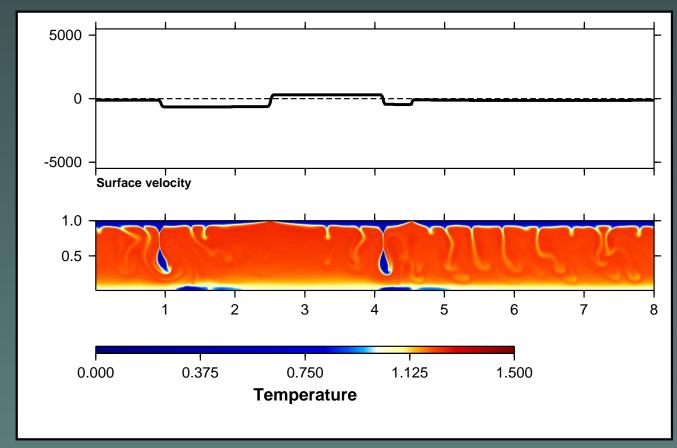
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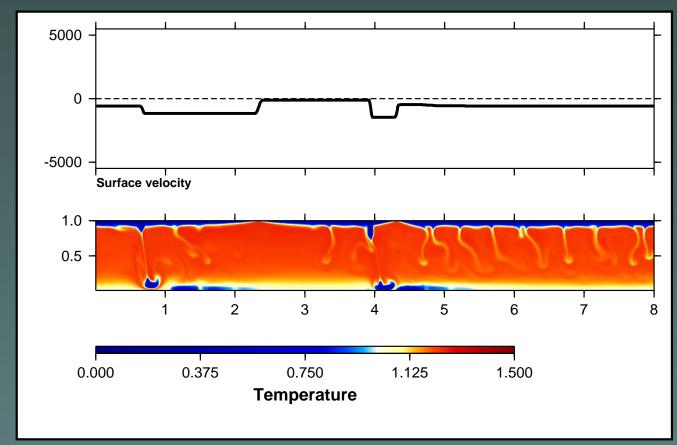
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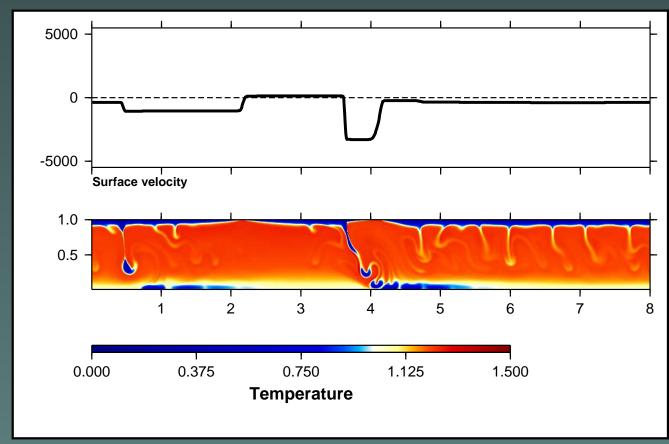
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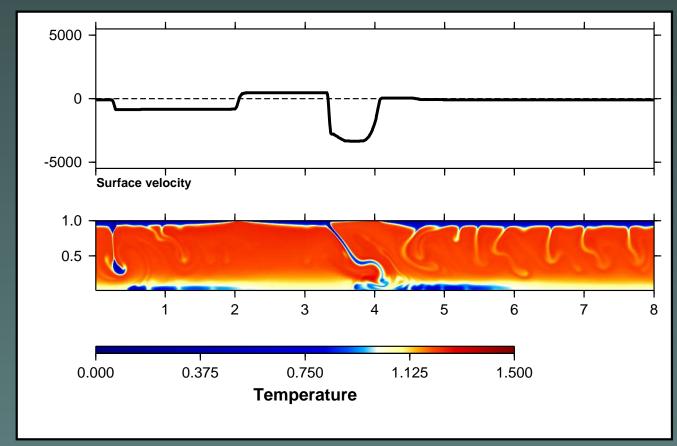
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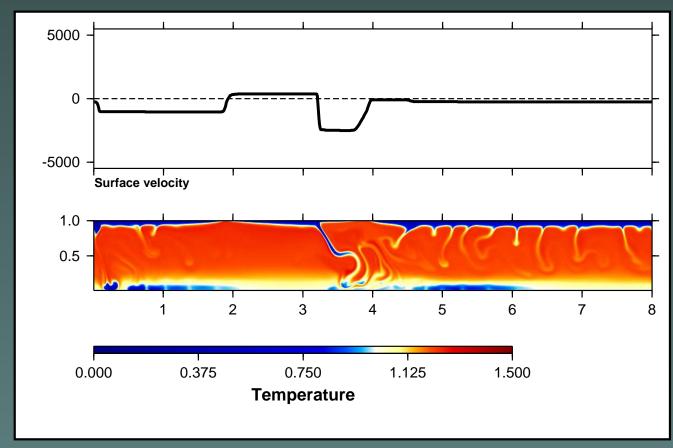
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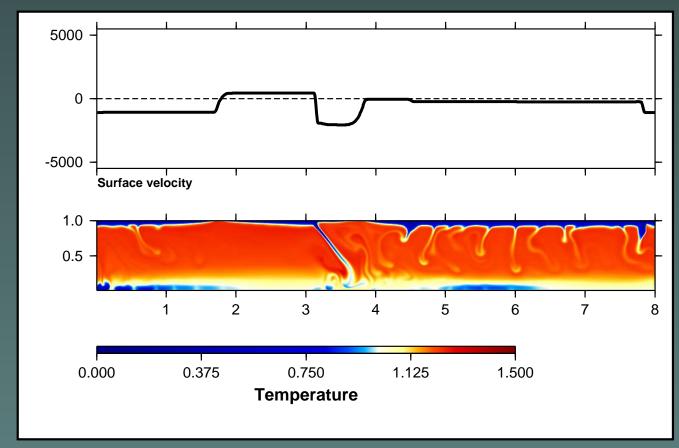
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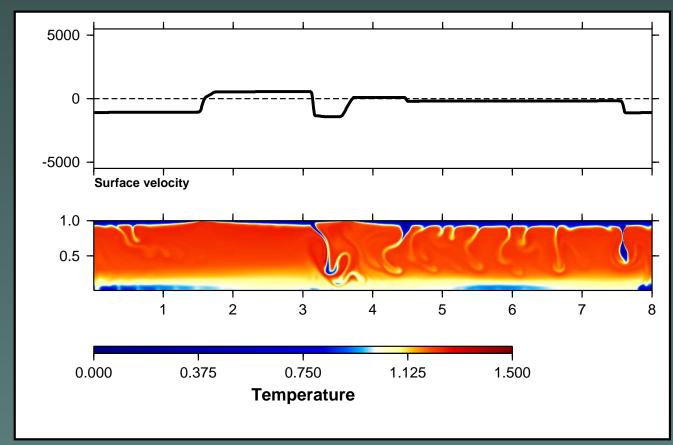
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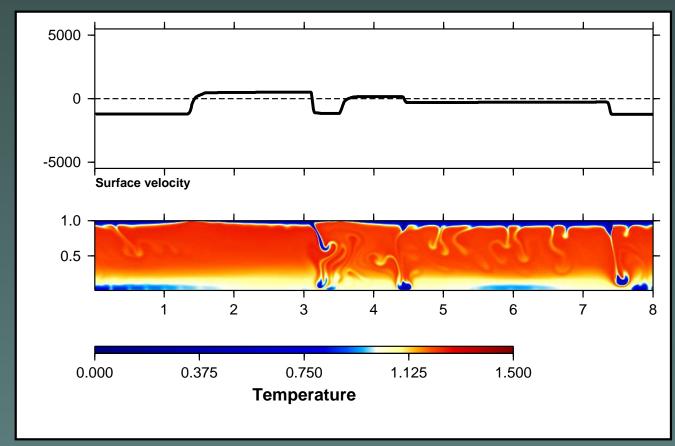
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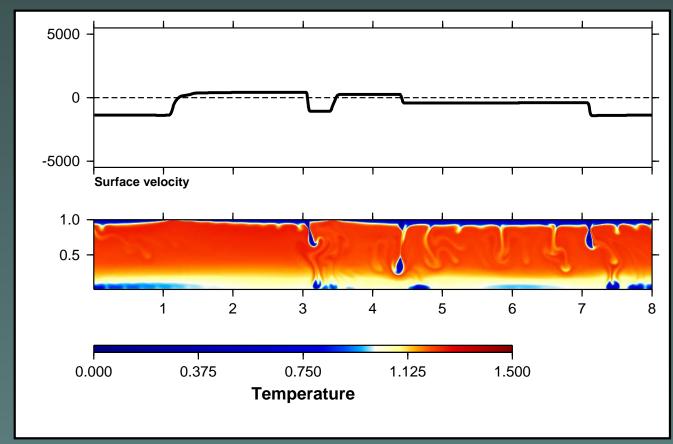
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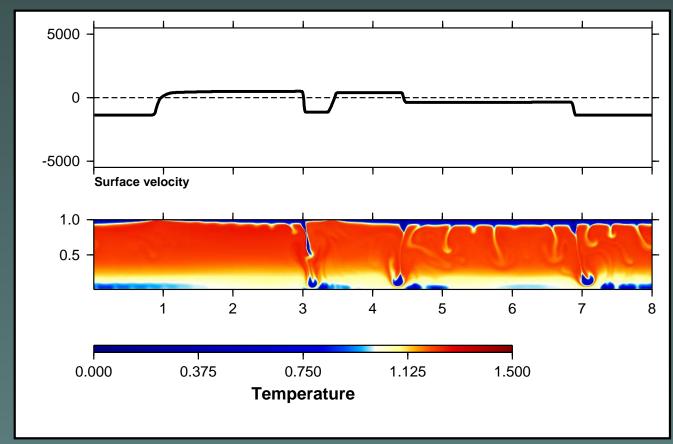
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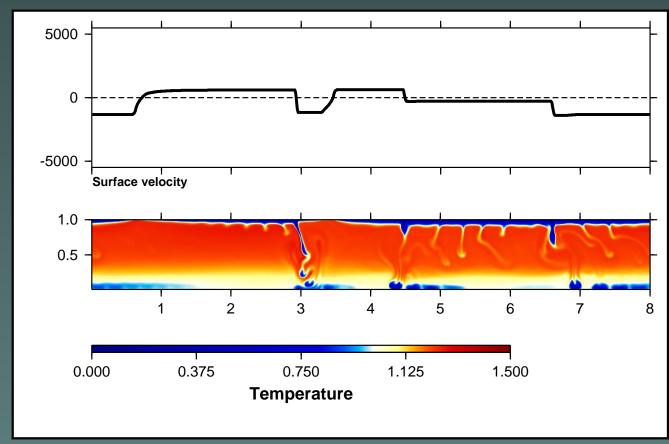
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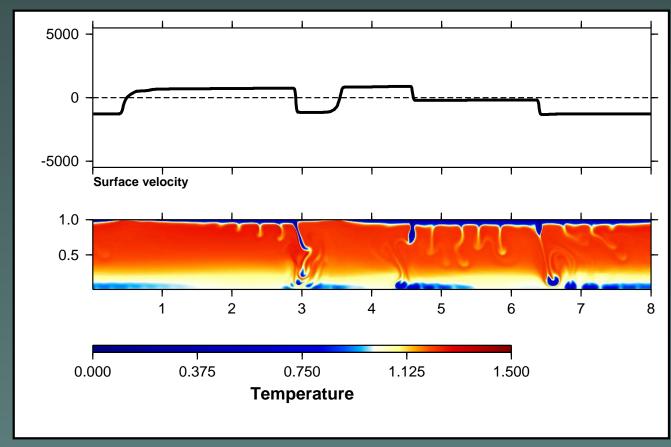
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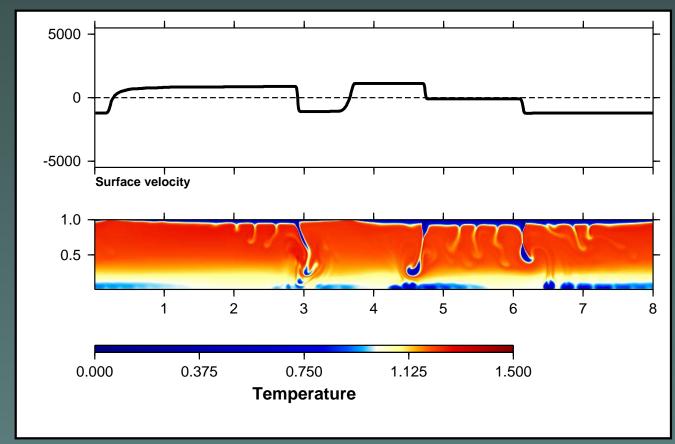
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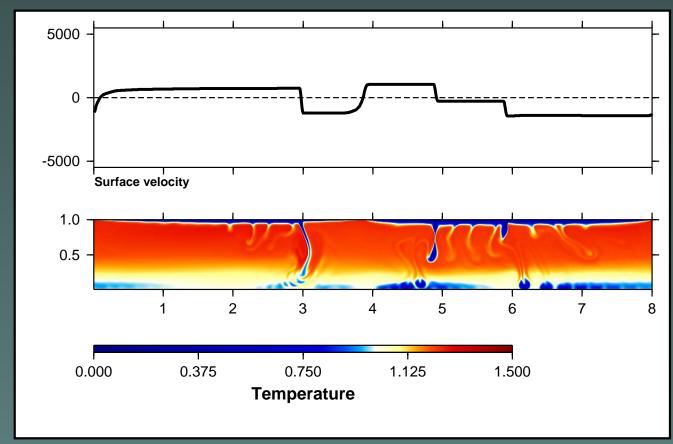
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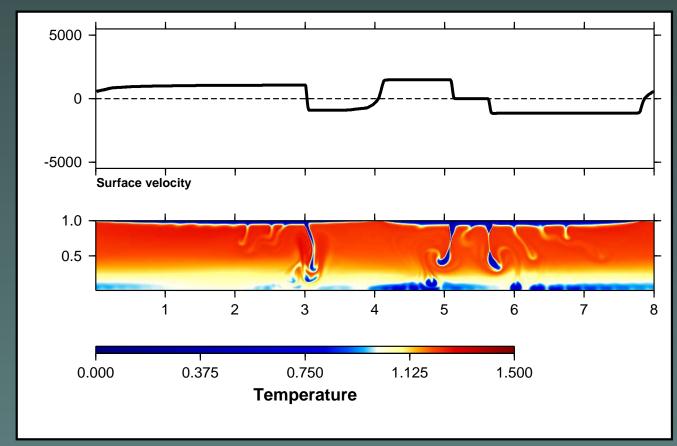
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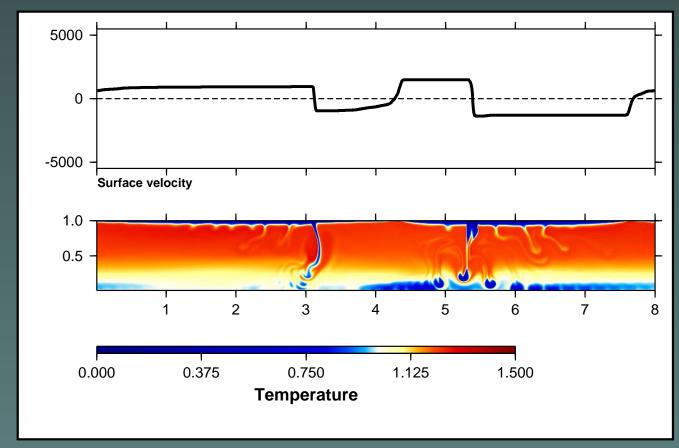
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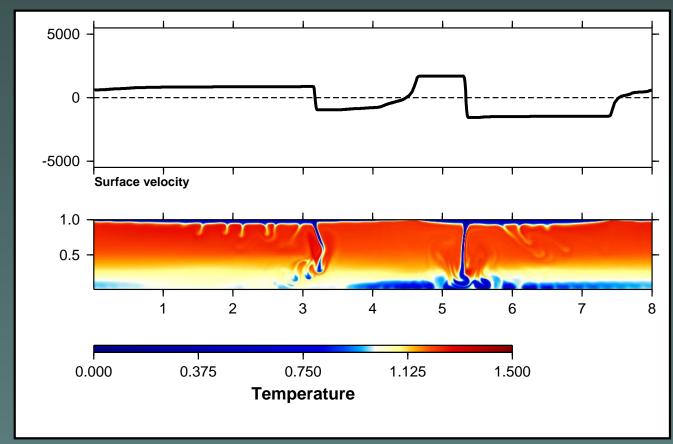
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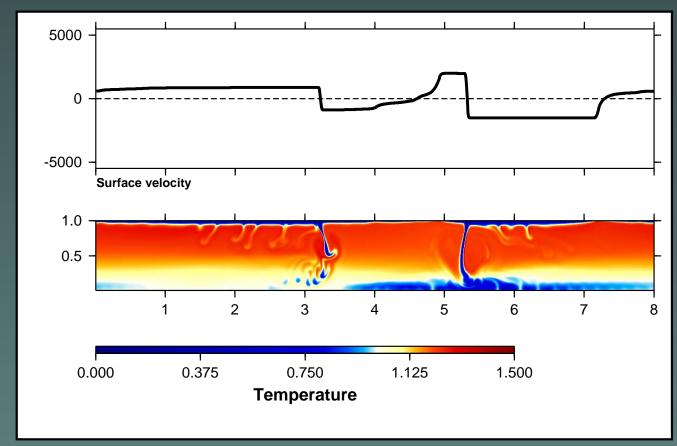
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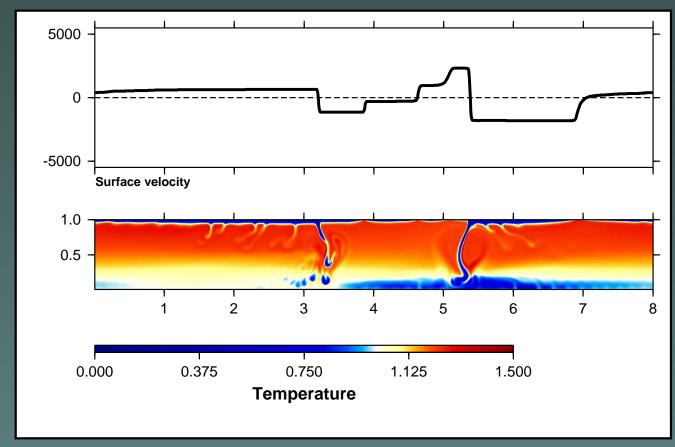
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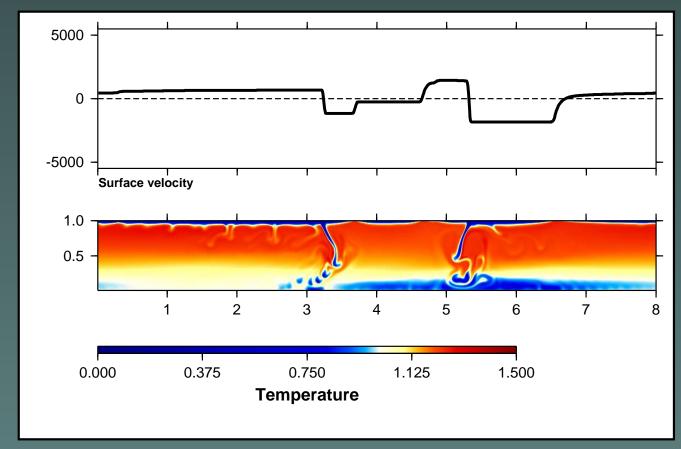
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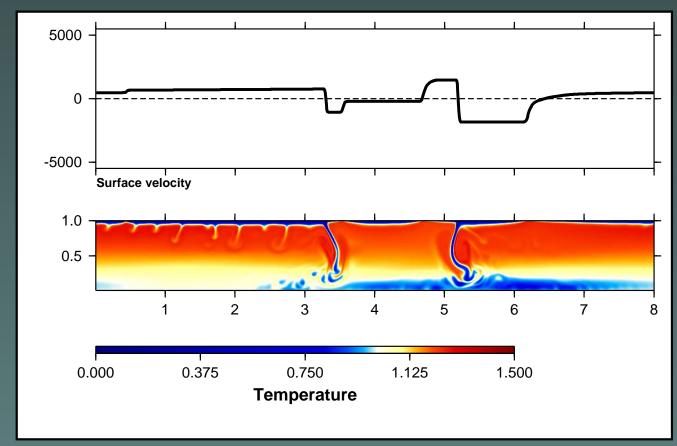
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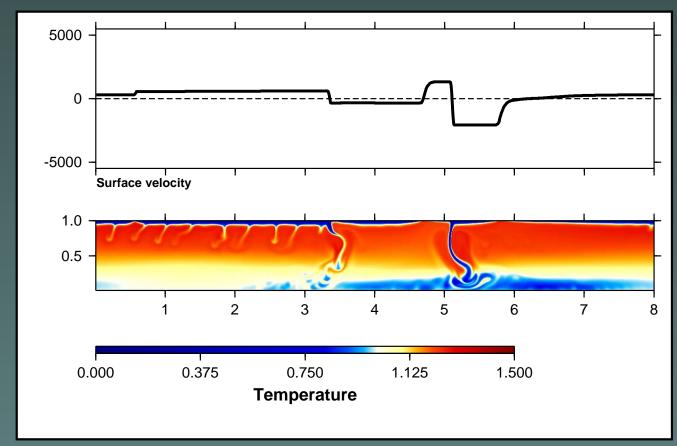
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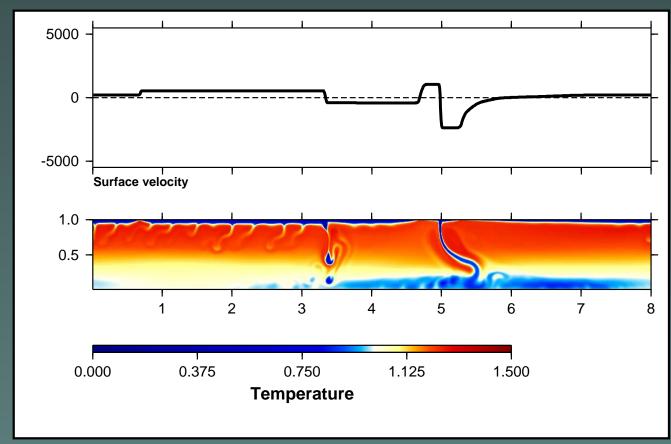
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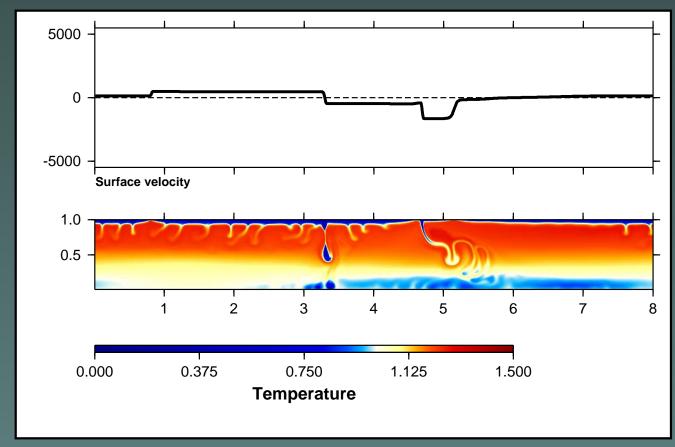
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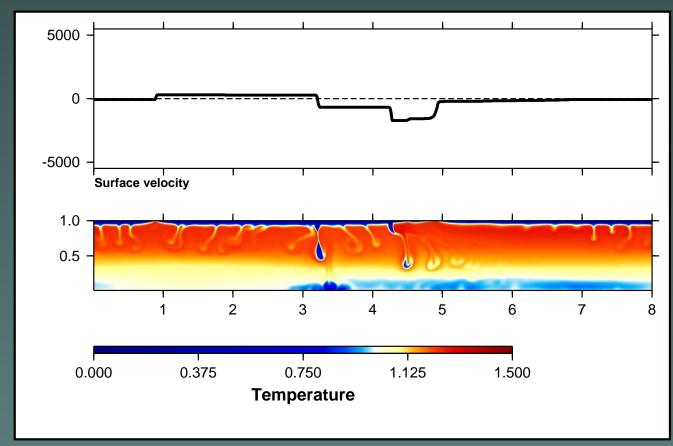
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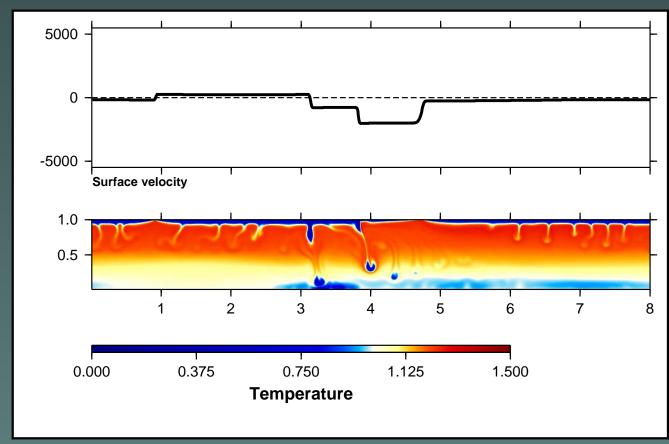
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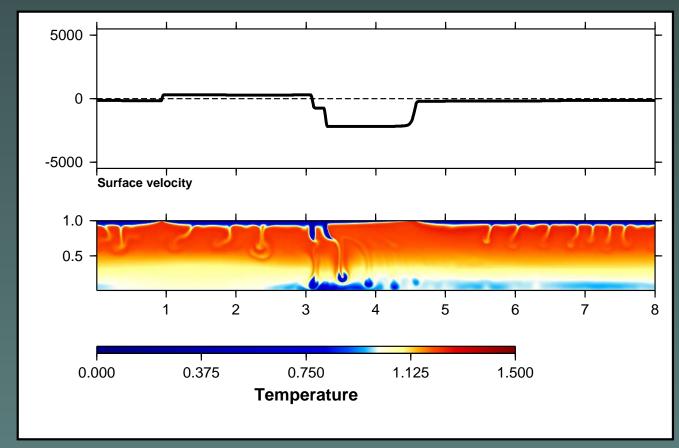
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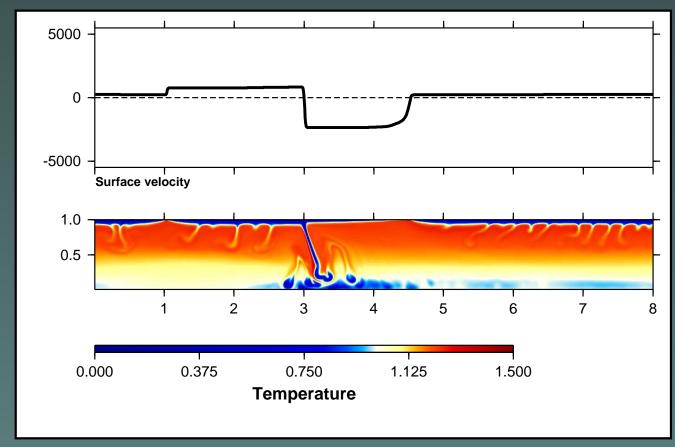
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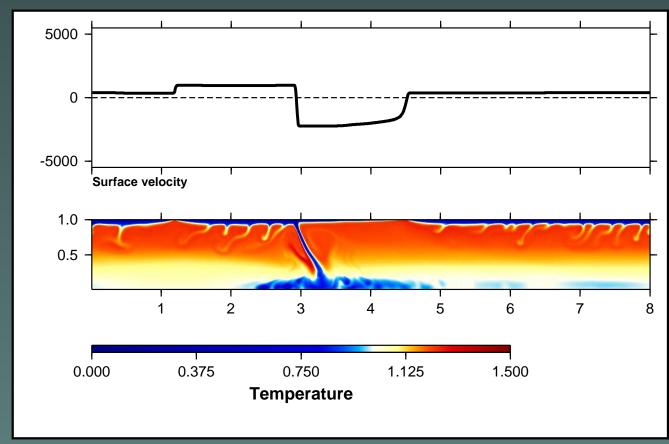
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m Ra} = 7.10^6 \quad {
m H} = 23 \; ({
m present}) \qquad \sigma_{
m y} = 2.10^5 \; (175 \; {
m MPa})$$



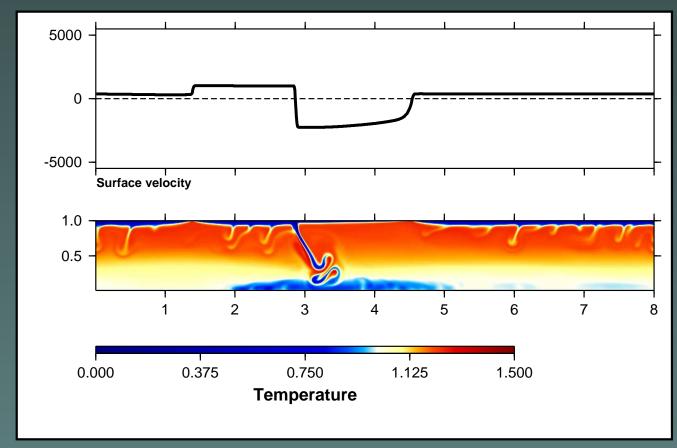
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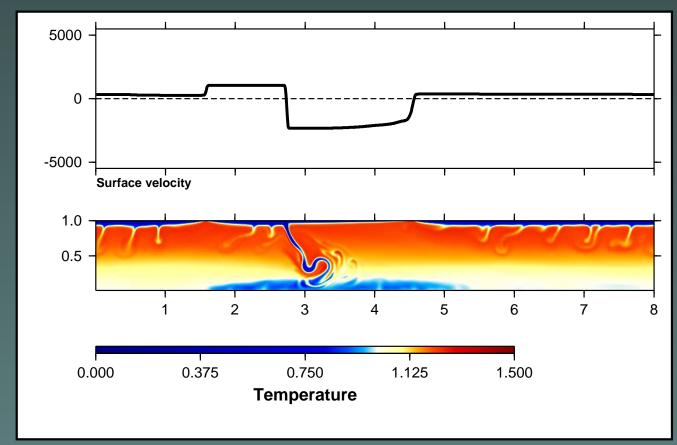
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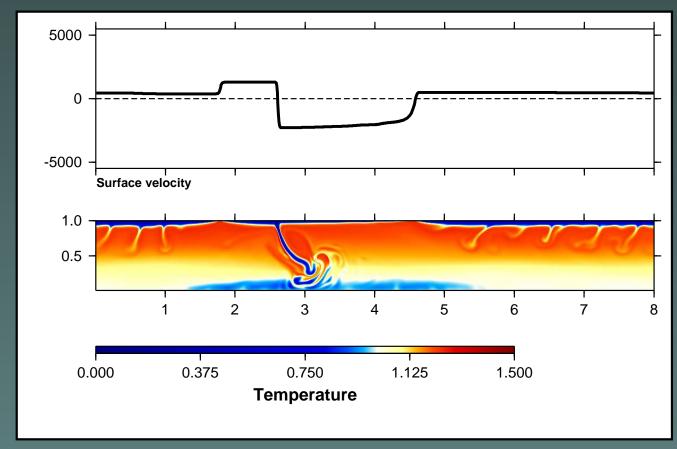
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m present}) \qquad \sigma_{
m y} = 2.10^5 \; (175 \; {
m MPa})$$



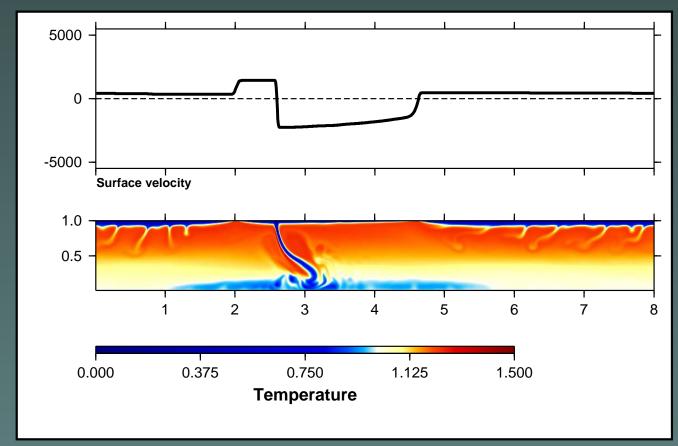
$${\sf Ra} = 7.10^6 \quad {\sf H} = 23 \; ({\sf present}) \qquad \sigma_{\sf y} = 2.10^5 \; (175 \; {\sf MPa})$$



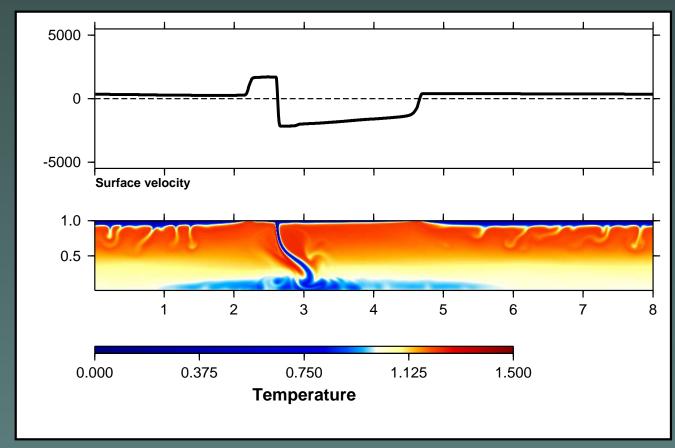
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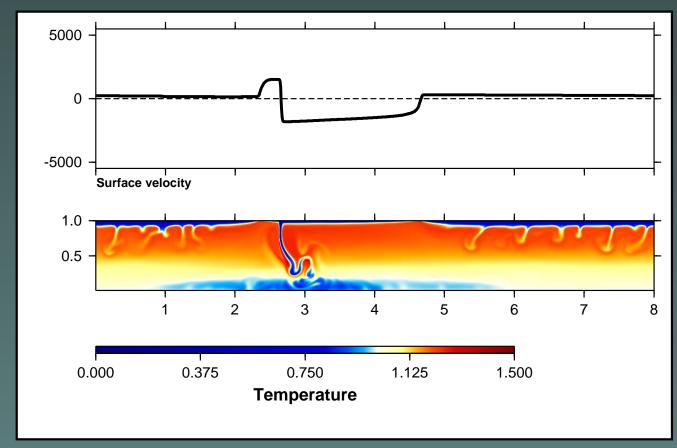
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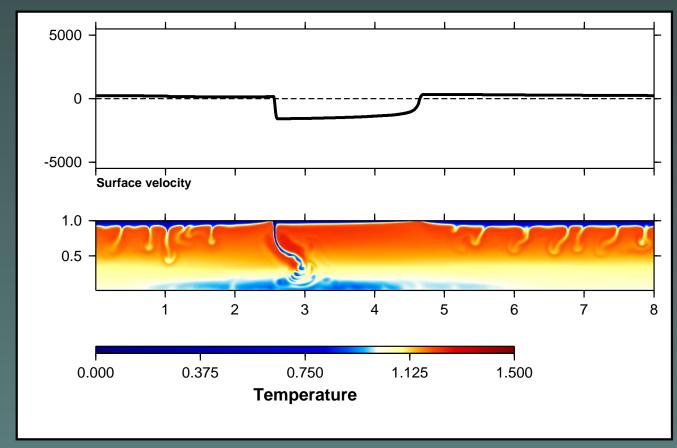
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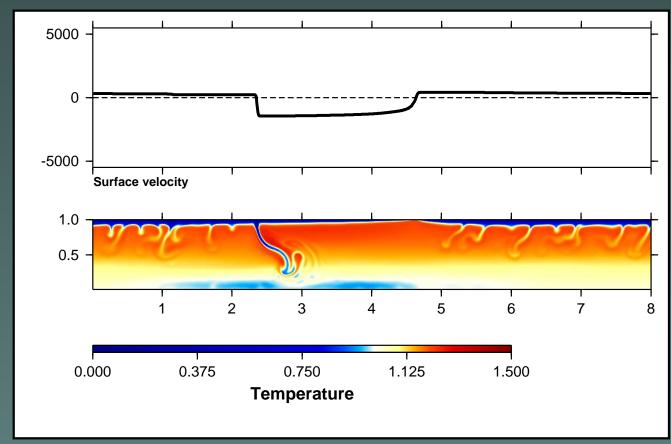
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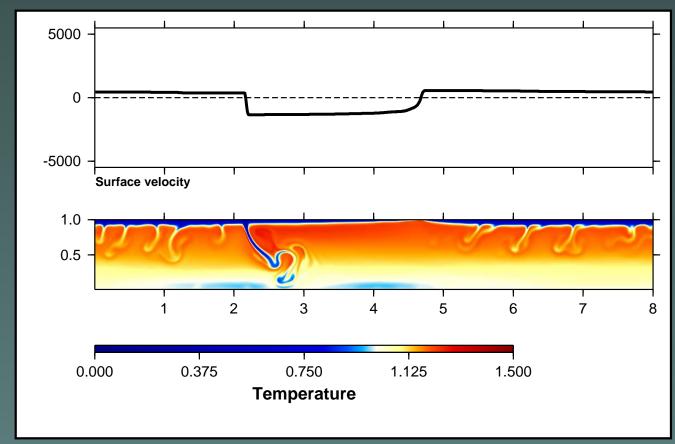
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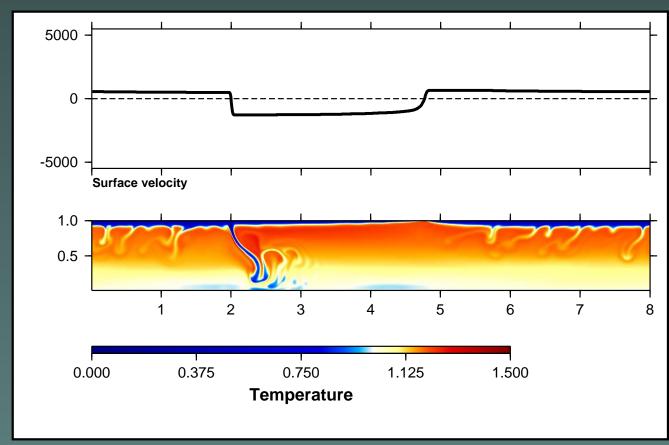
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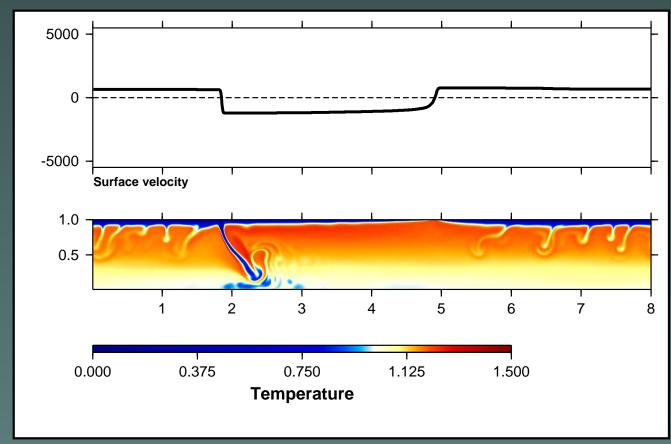
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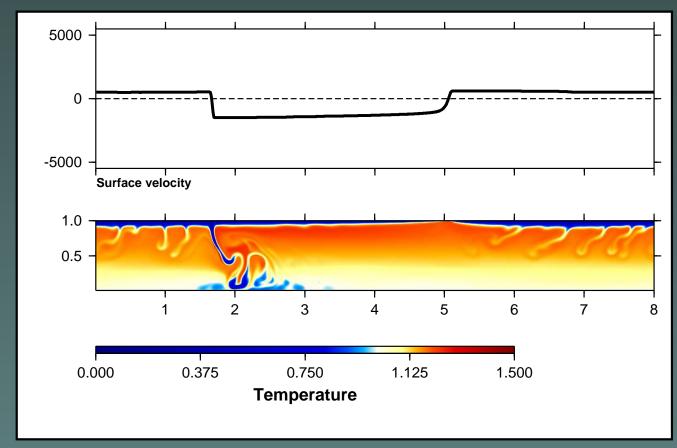
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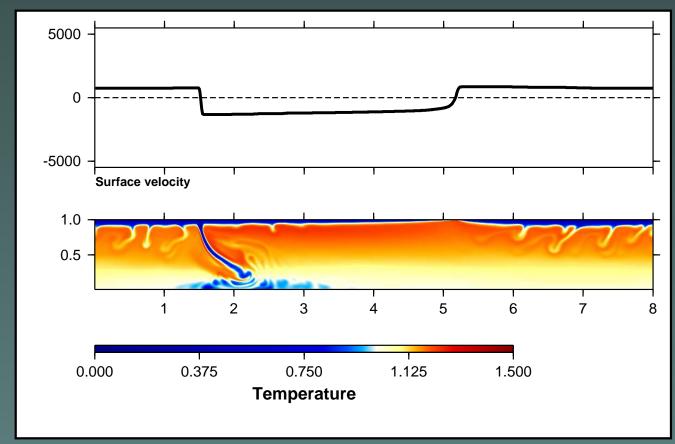
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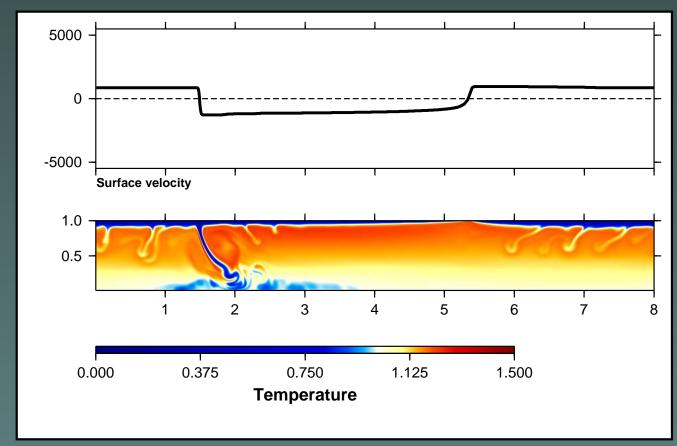
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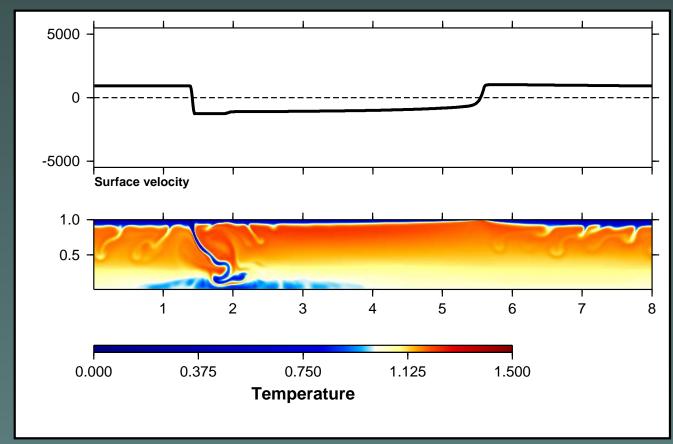
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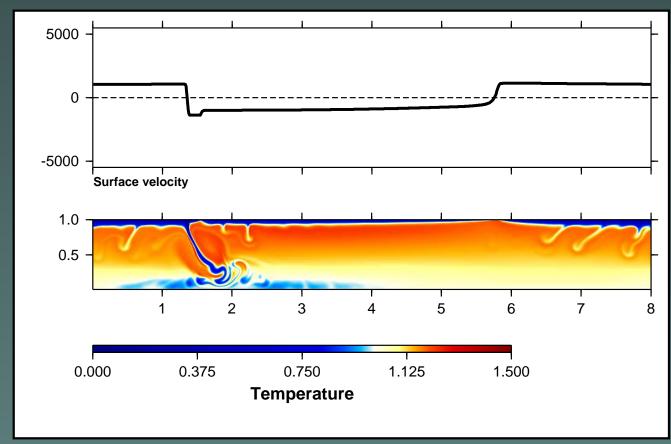
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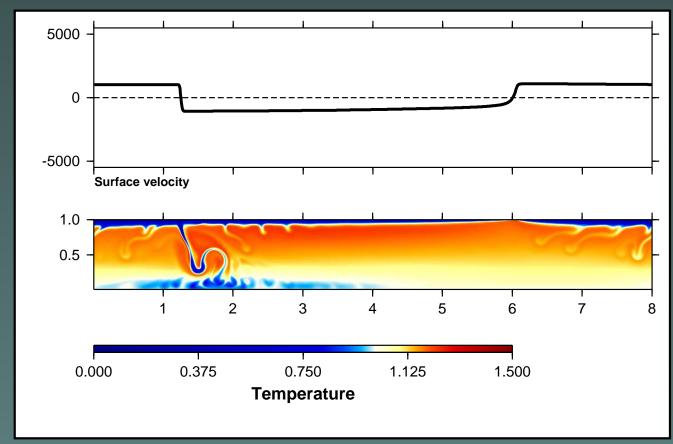
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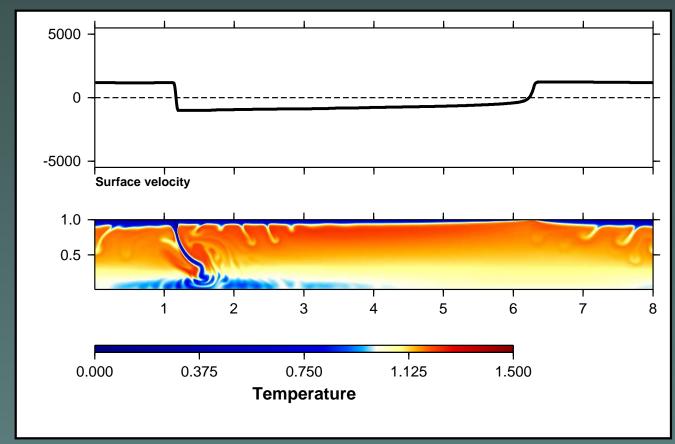
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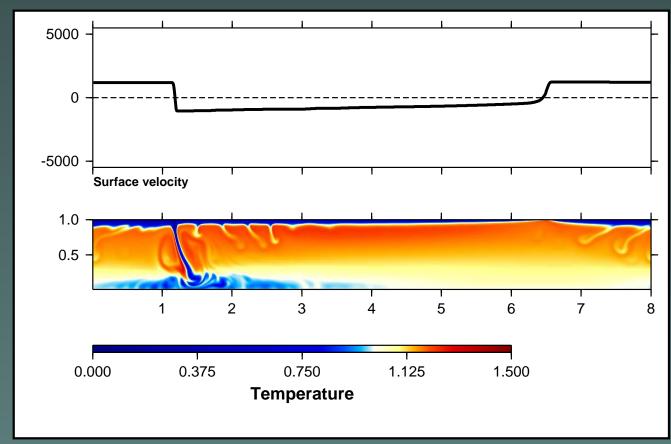
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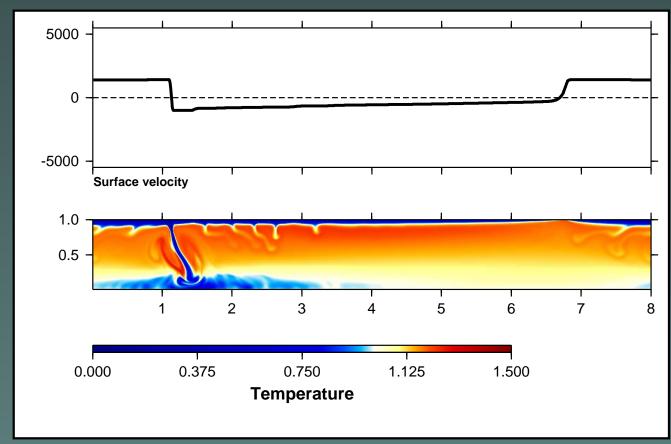
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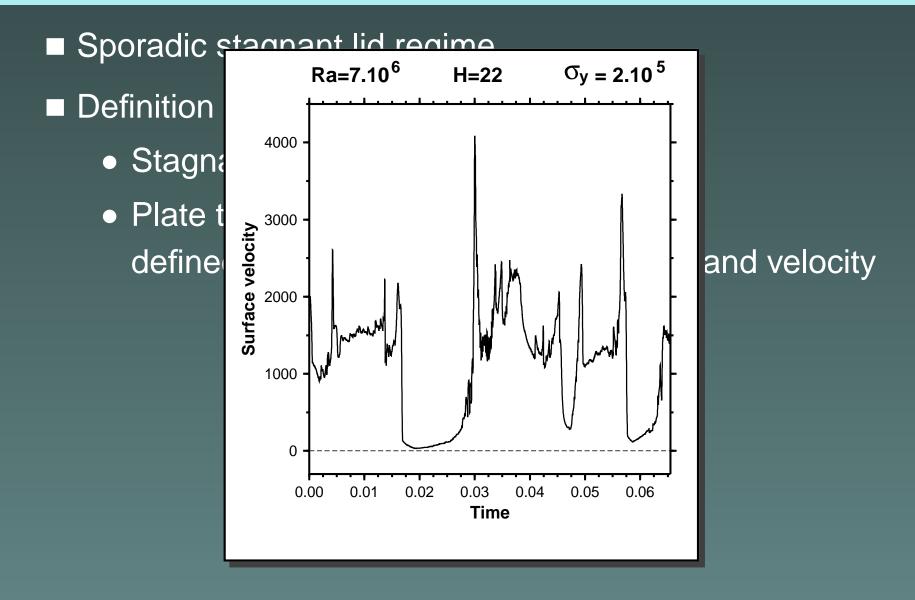
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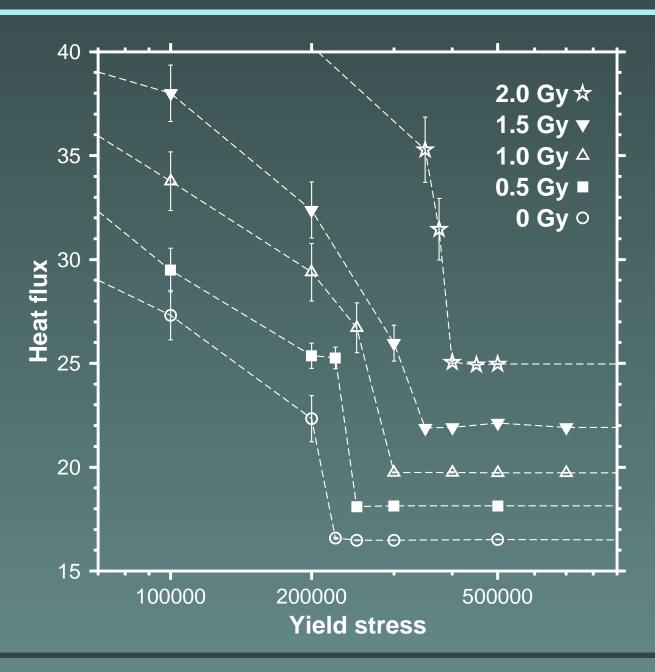
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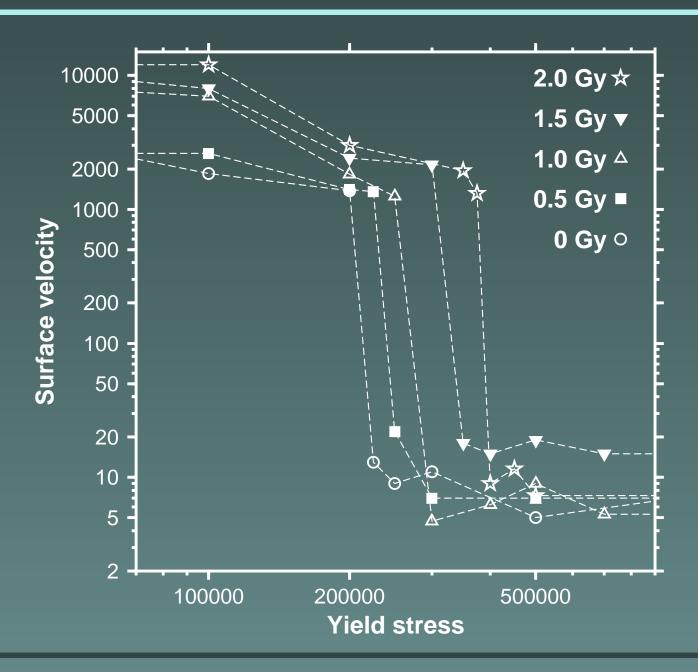


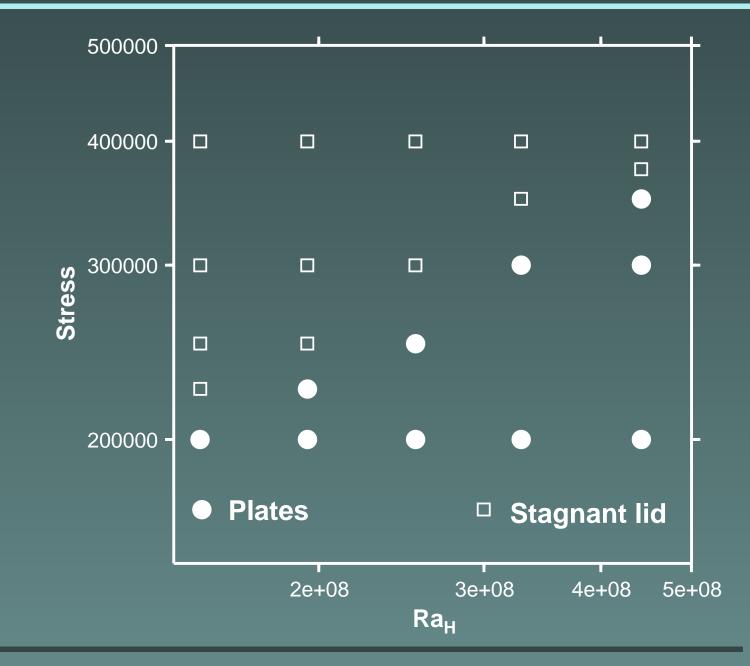
- Sporadic stagnant lid regime.
- Definition of two regimes:
 - Stagnant lid
 - Plate tectonics
 defined on the time-averaged heat flux and velocity



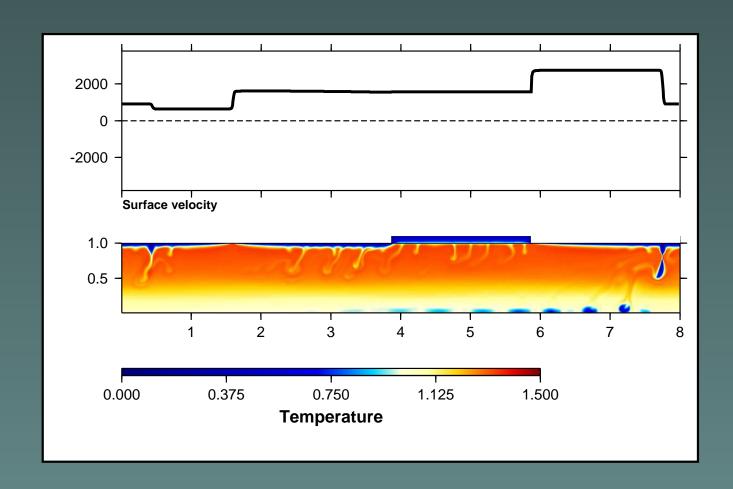
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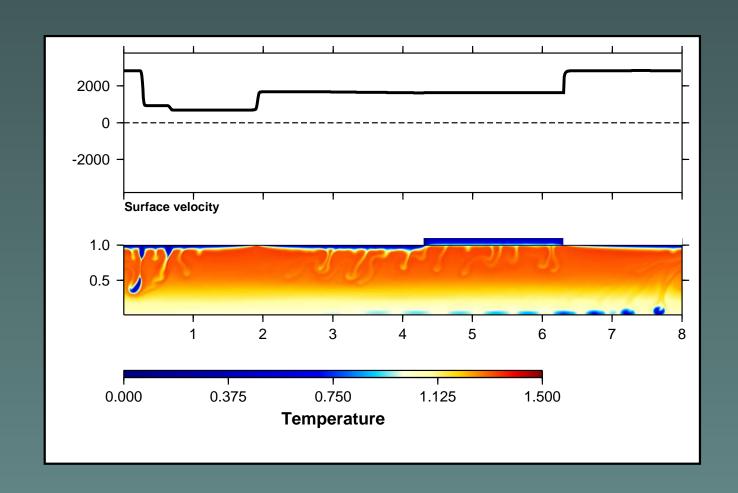




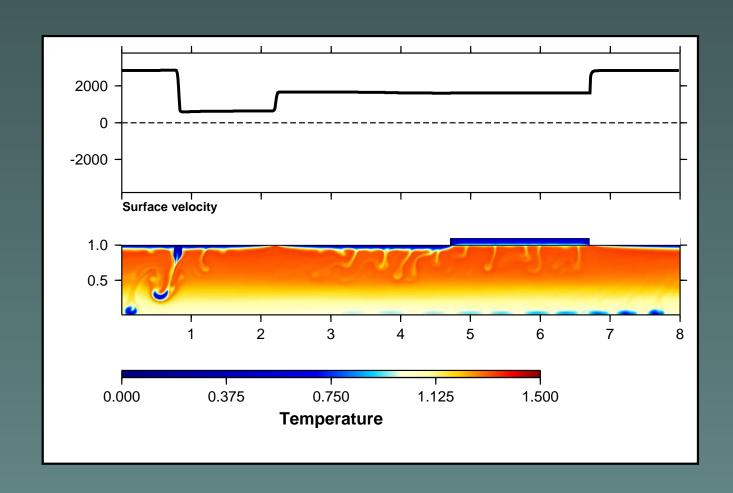
$$Ra = 7.10^6$$
 $H = 23$ (present) $\sigma_y = 3.10^5$ (263 MPa)



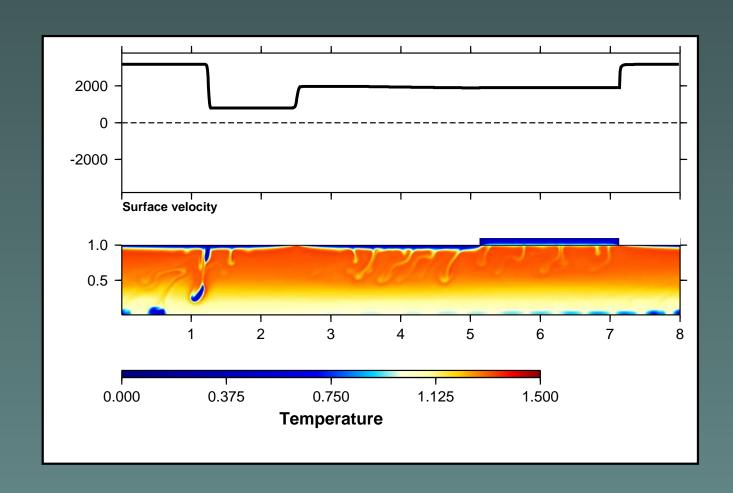
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 $H = 23$ (present) $\sigma_y = 3.10^5$ (263 MPa)



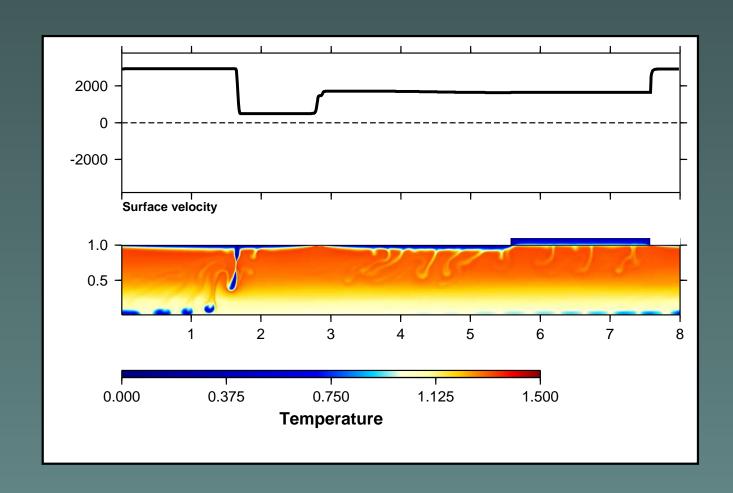
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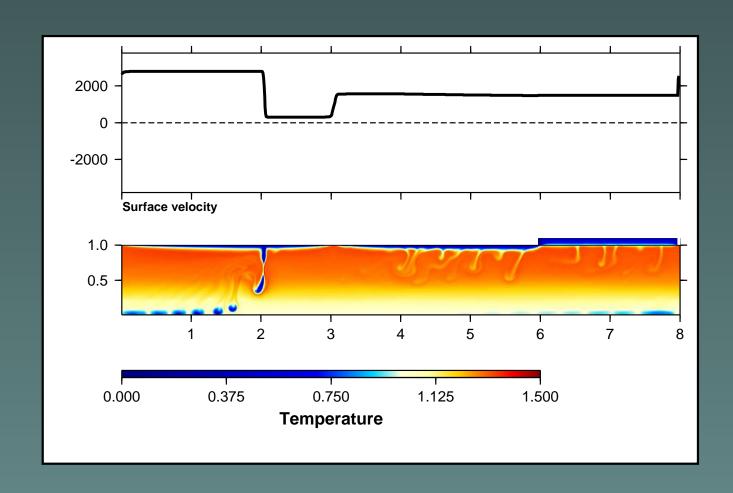
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 $H = 23$ (present) $\sigma_y = 3.10^5$ (263 MPa)



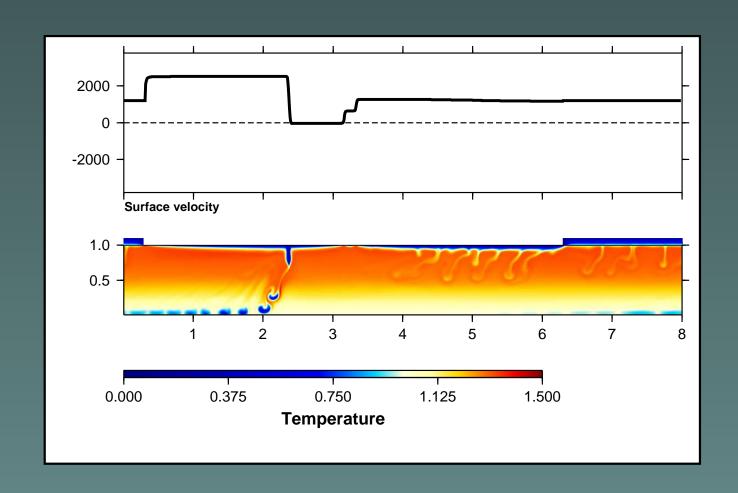
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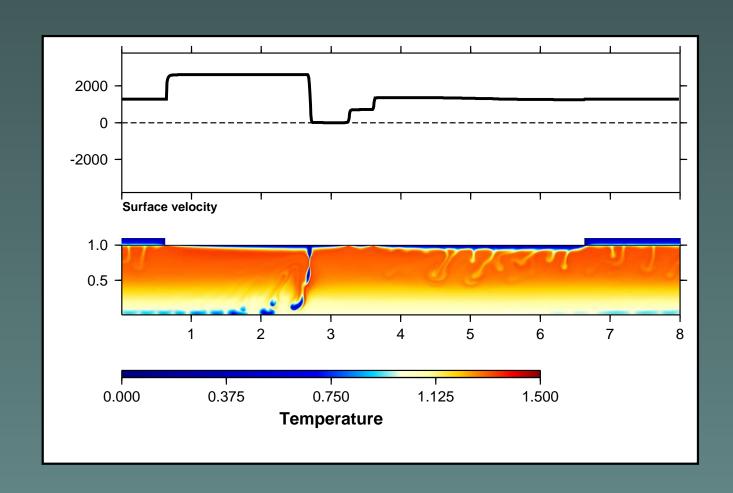
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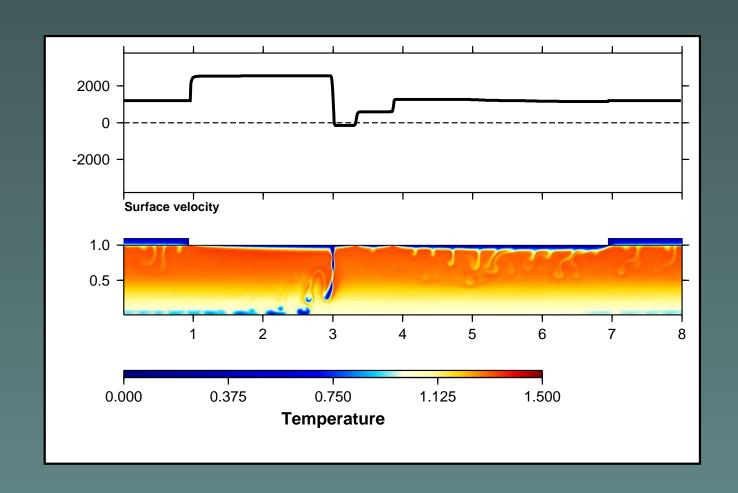
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 $H = 23$ (present) $\sigma_y = 3.10^5$ (263 MPa)



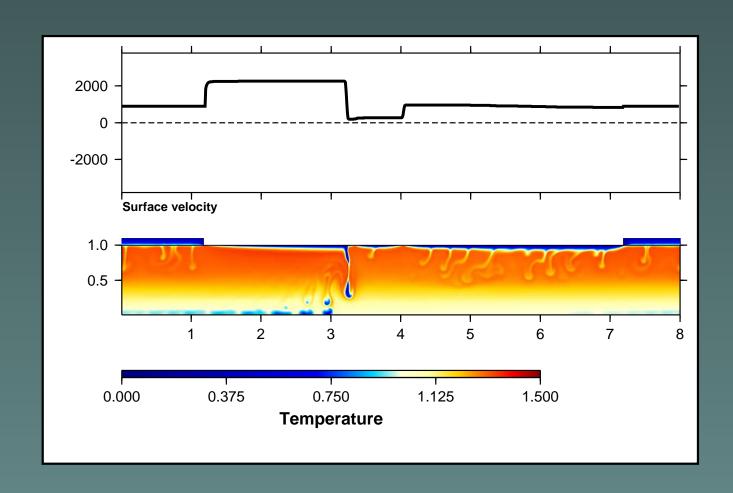
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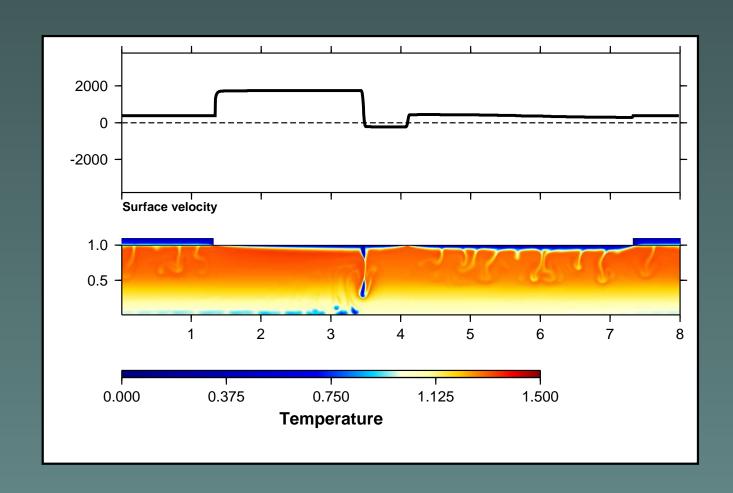
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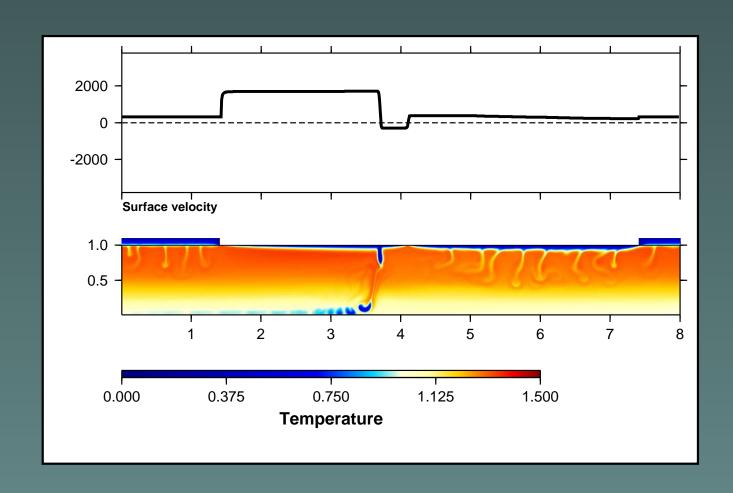
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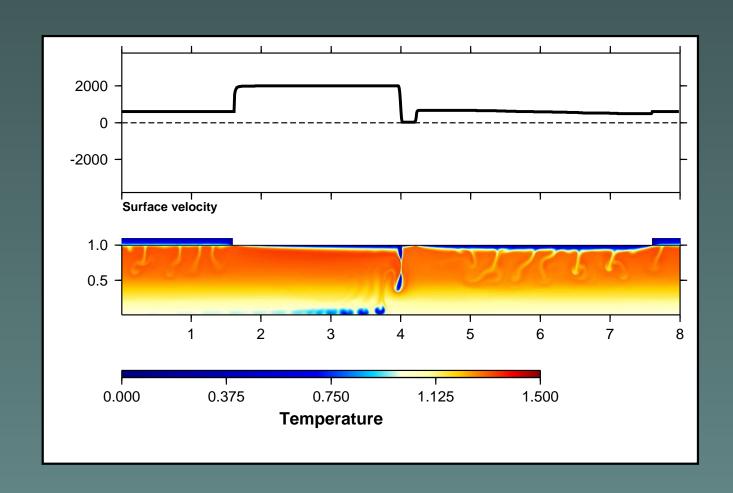
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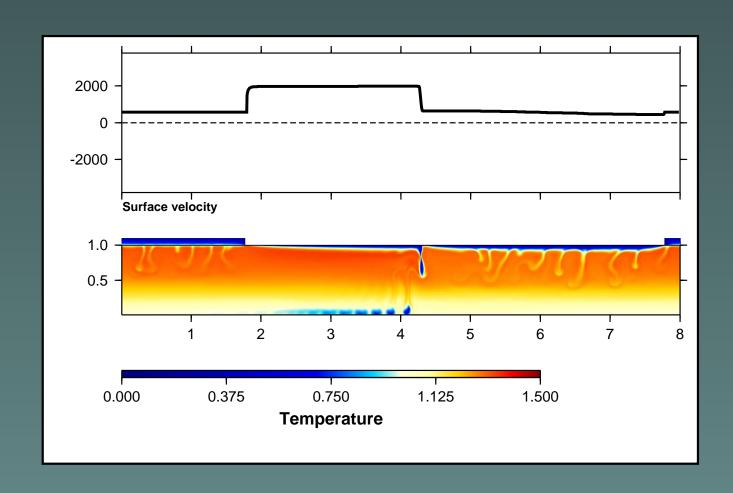
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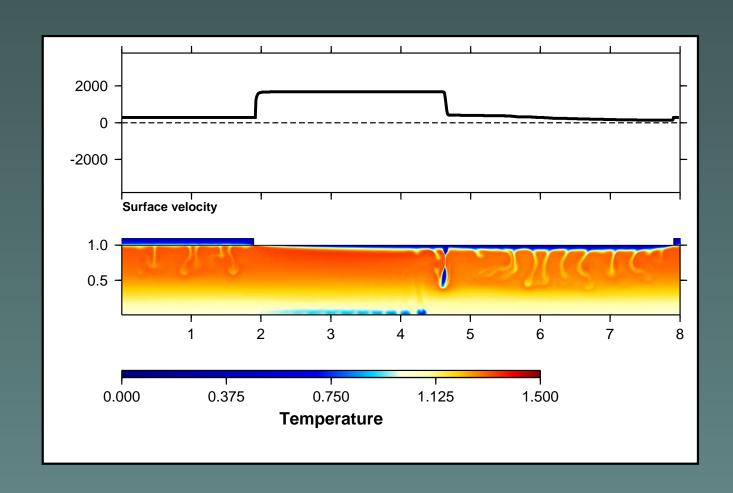
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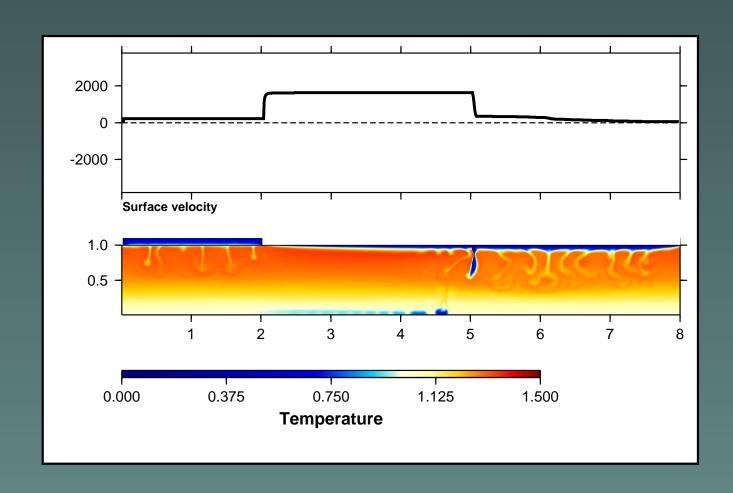
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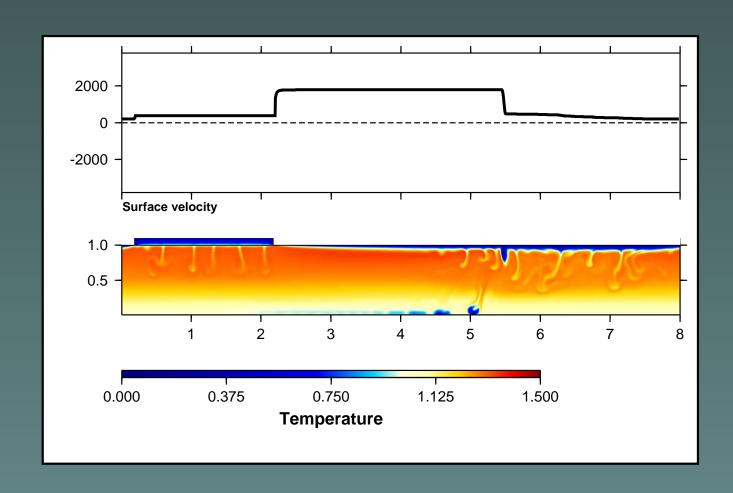
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 $H = 23$ (present) $\sigma_y = 3.10^5$ (263 MPa)



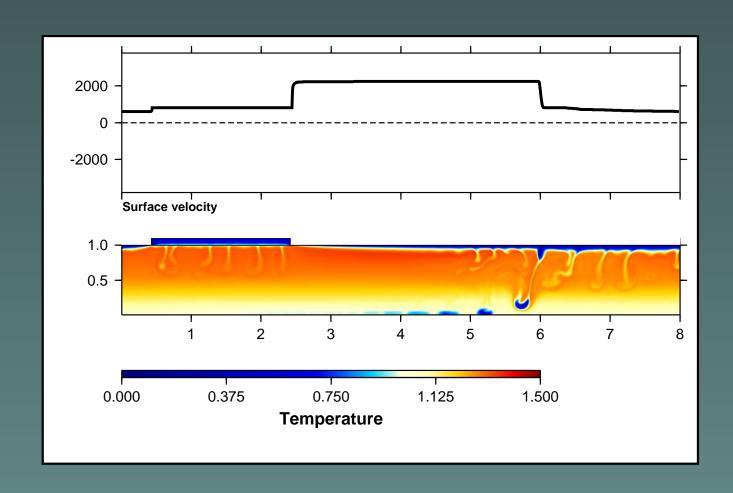
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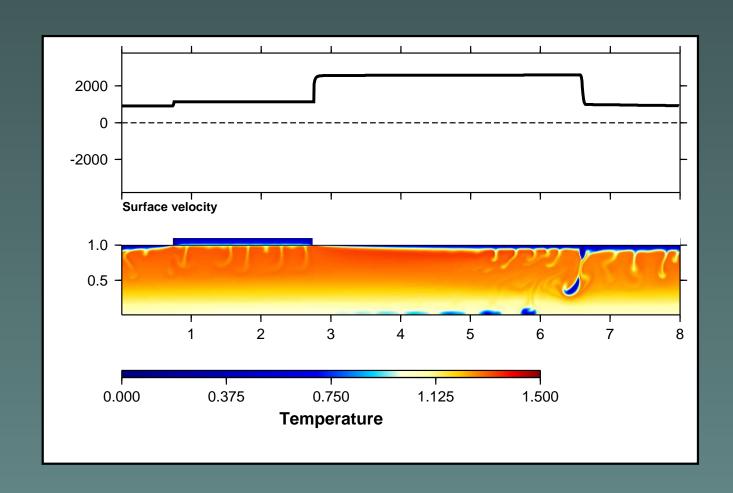
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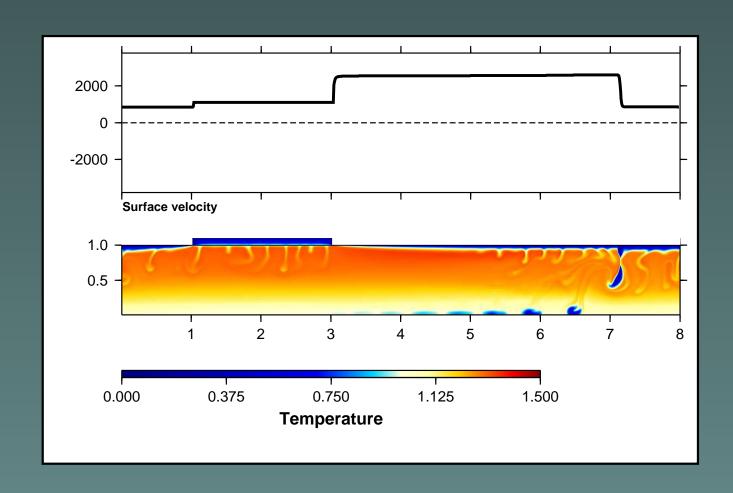
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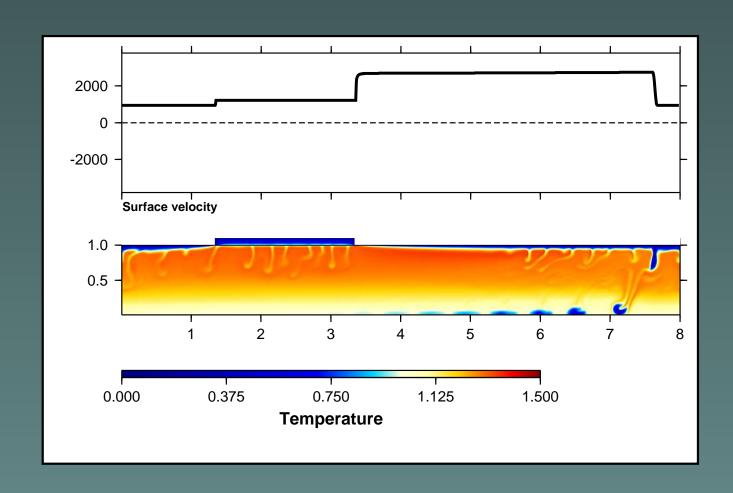
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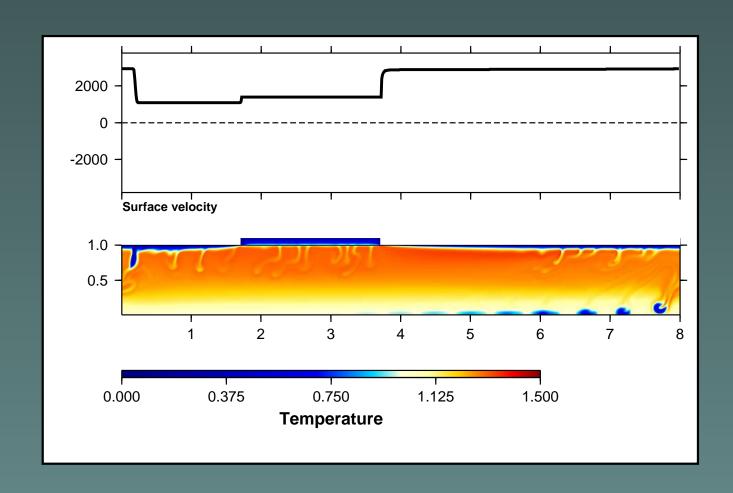
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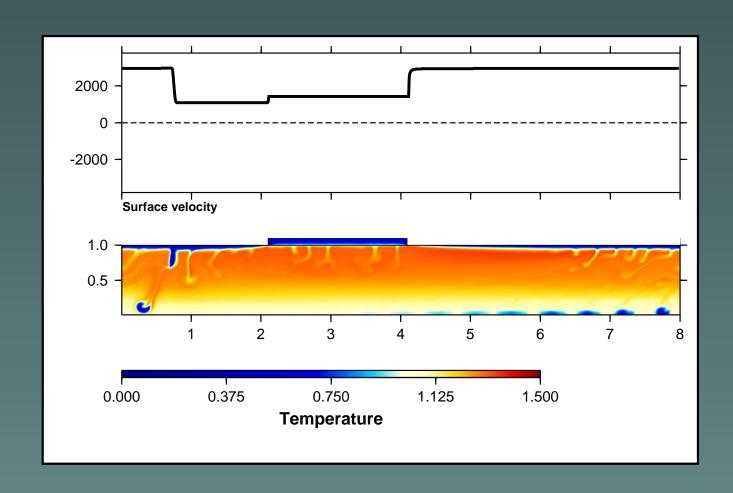
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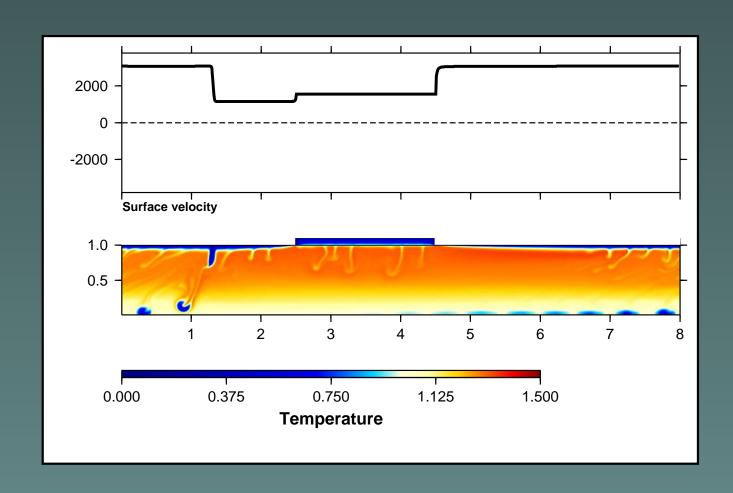
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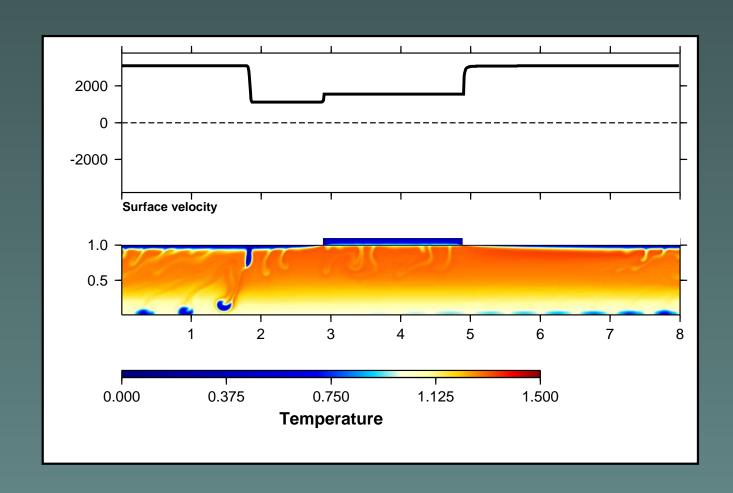
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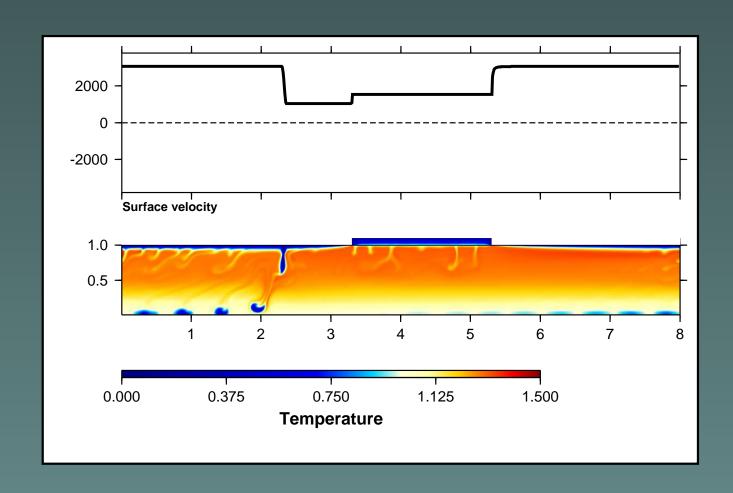
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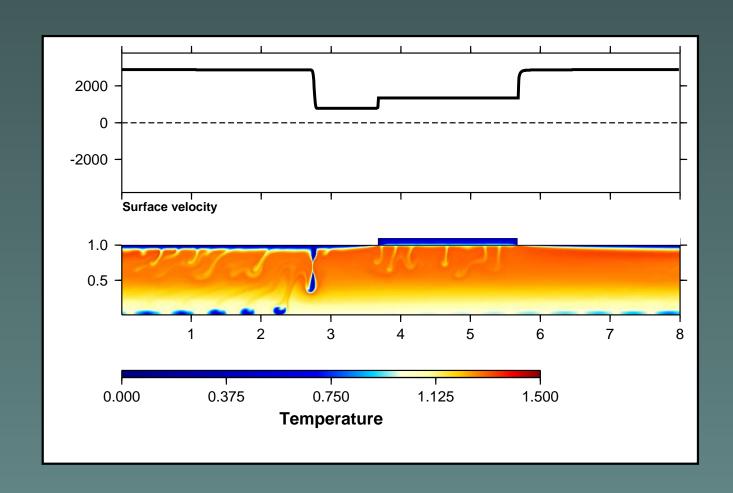
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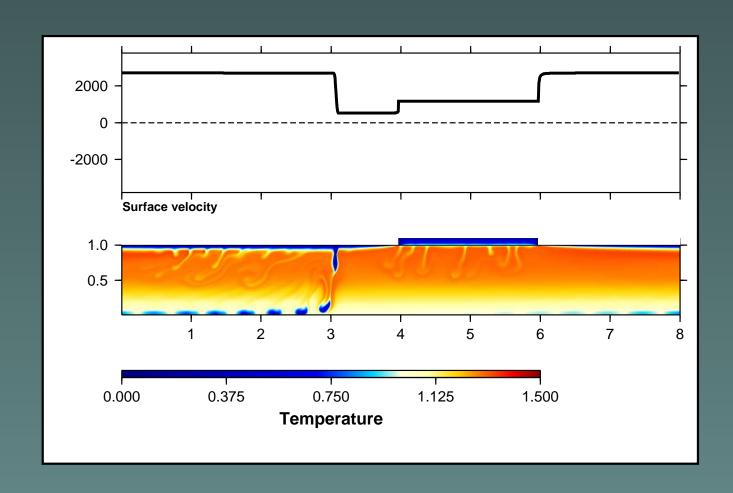
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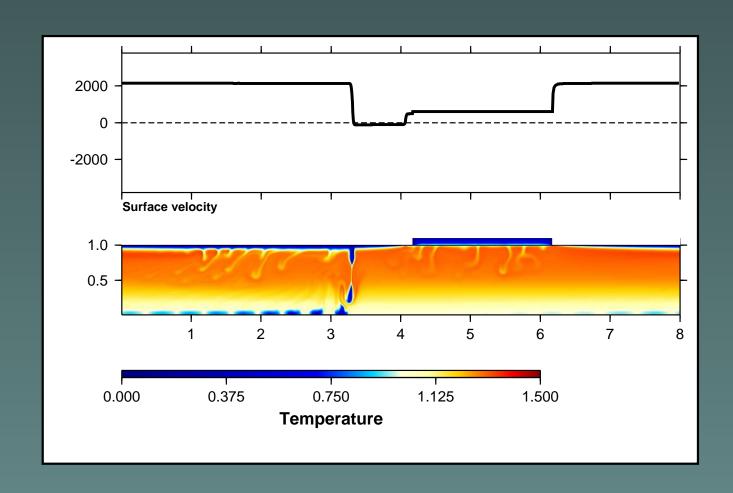
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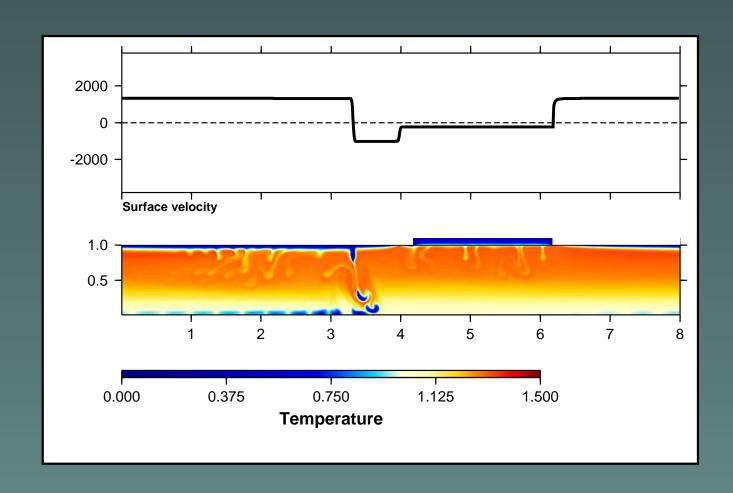
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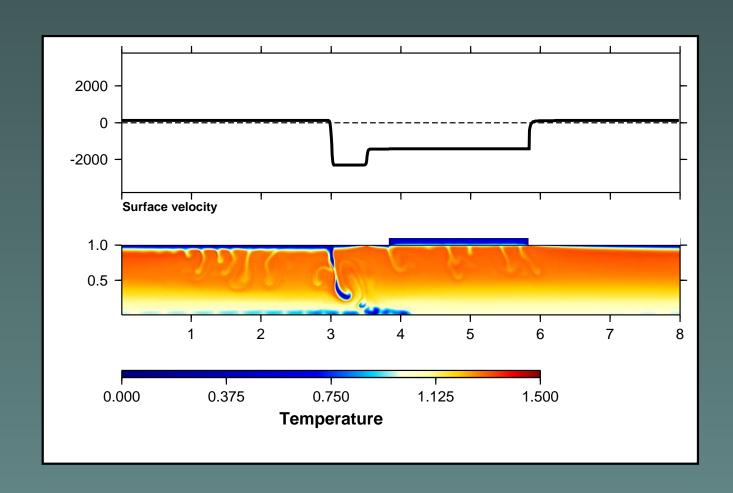
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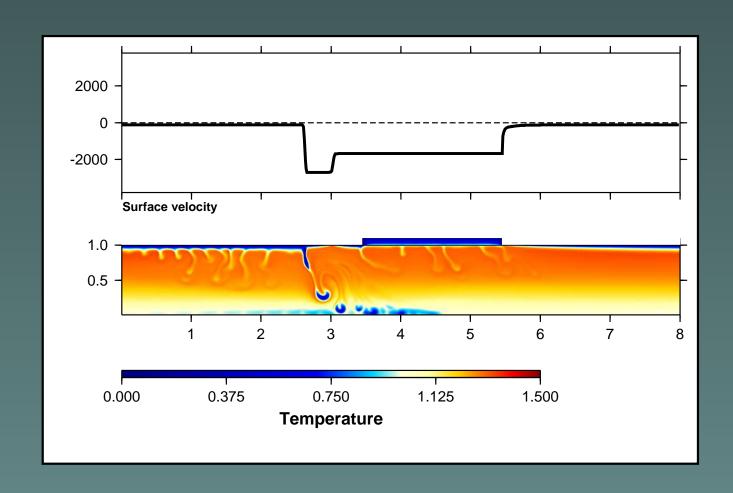
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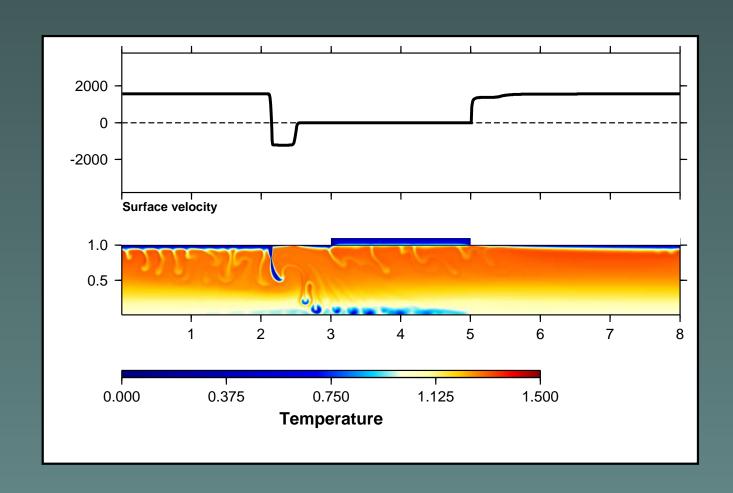
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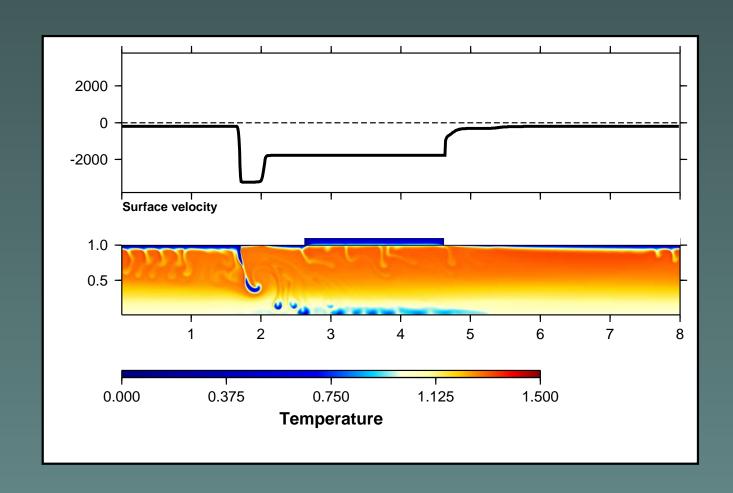
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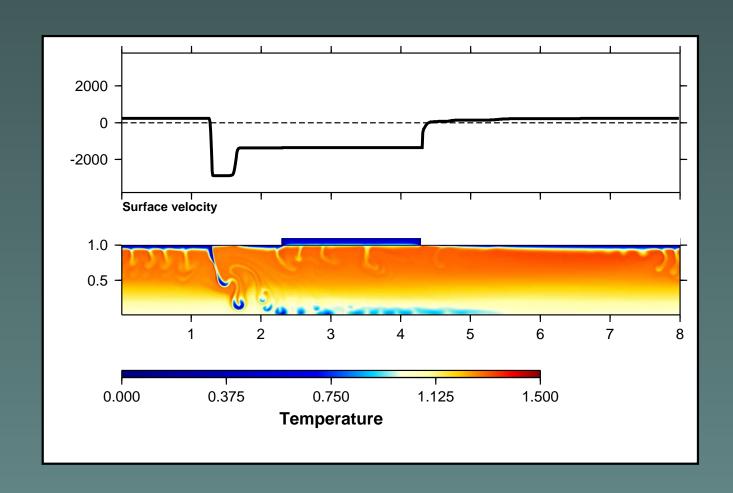
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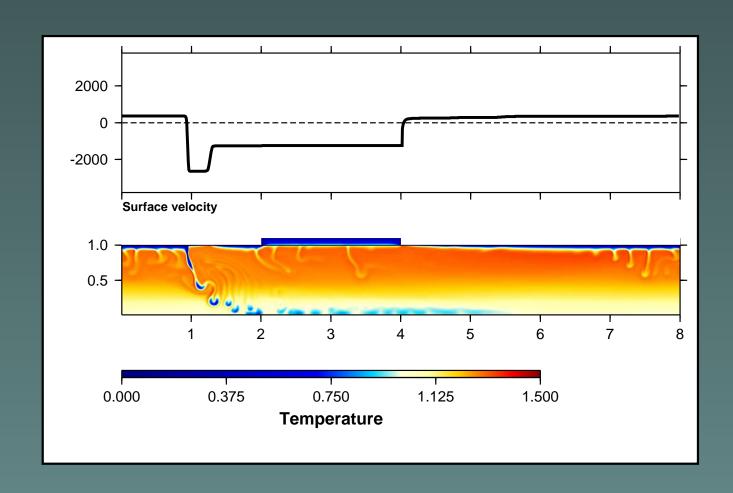
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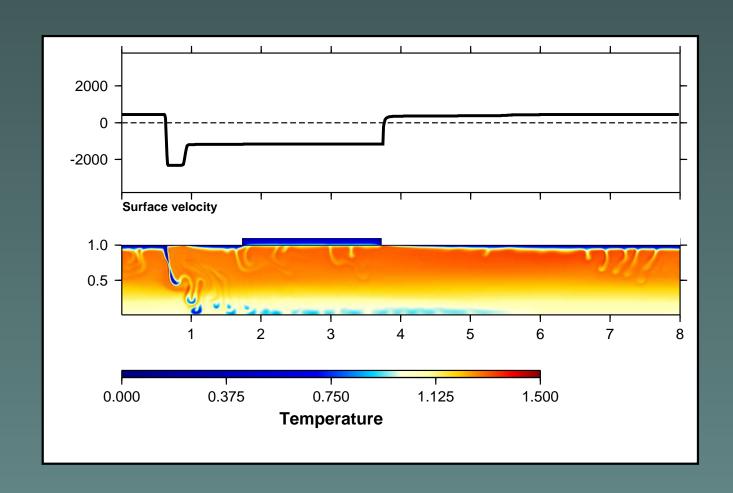
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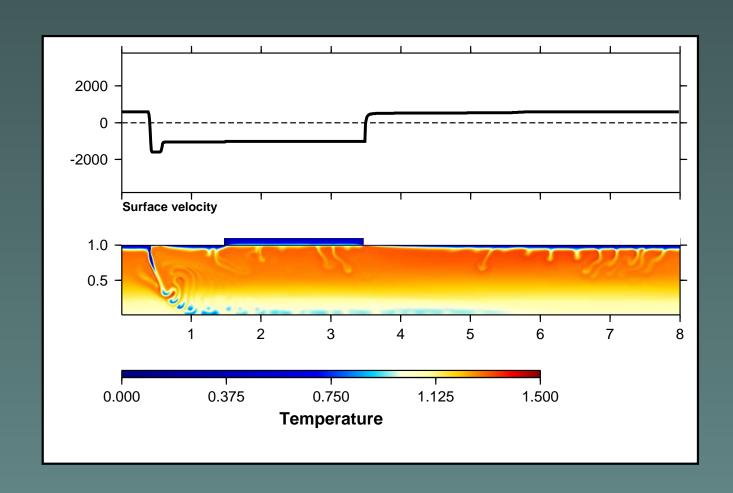
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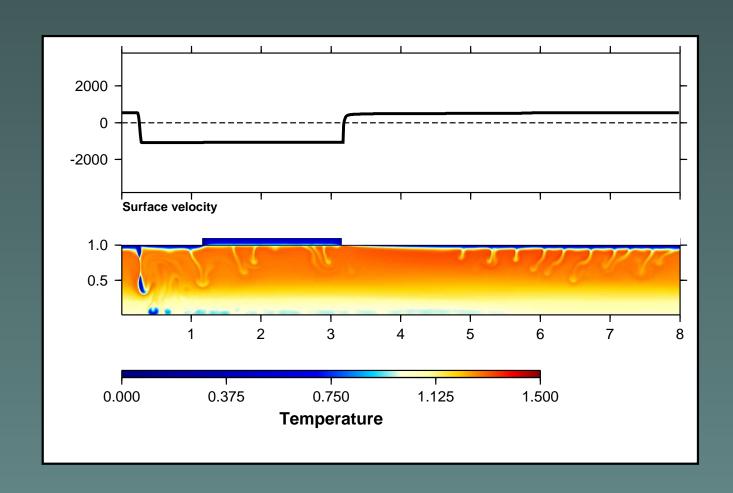
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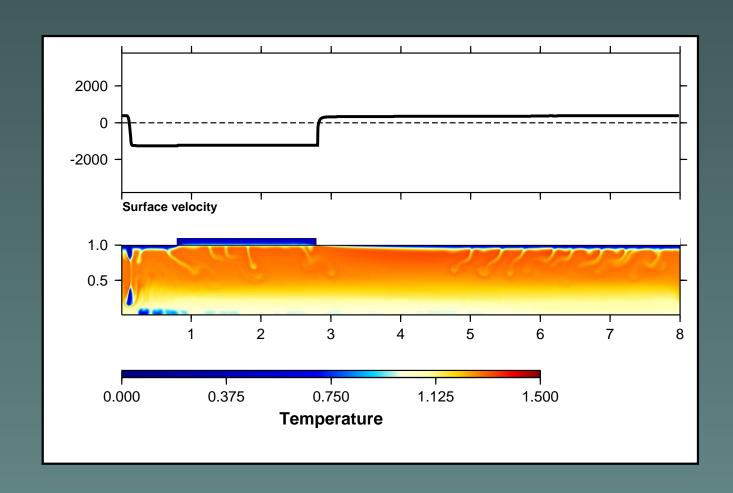
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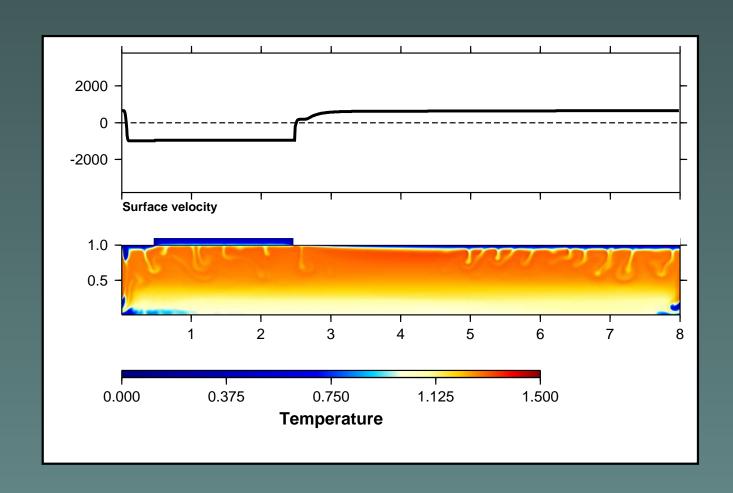
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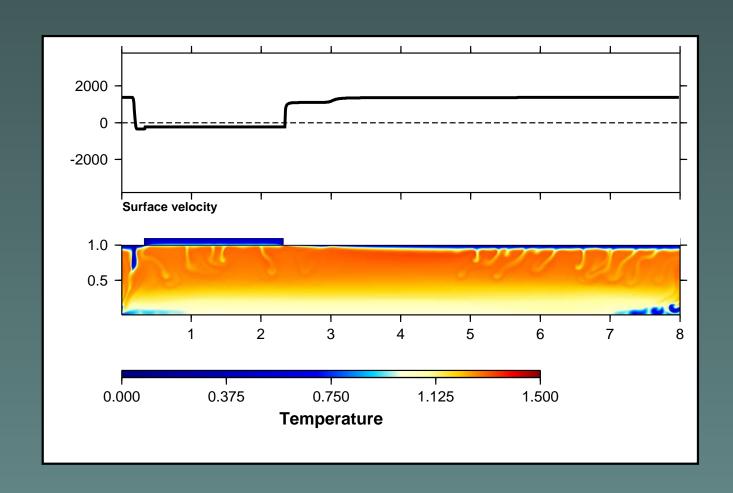
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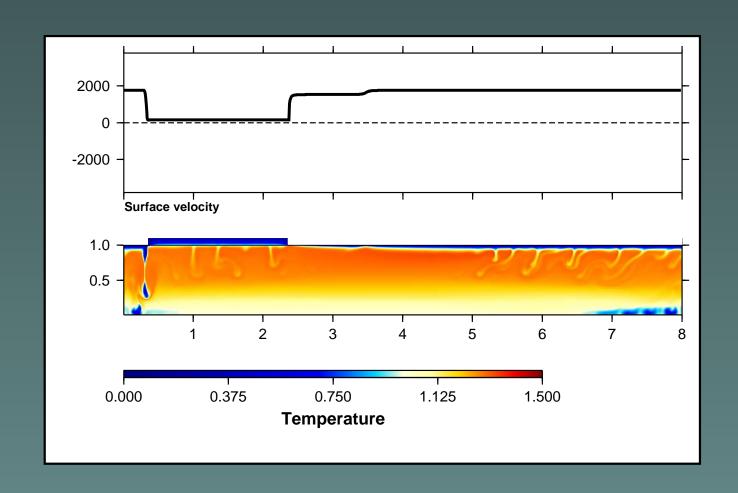
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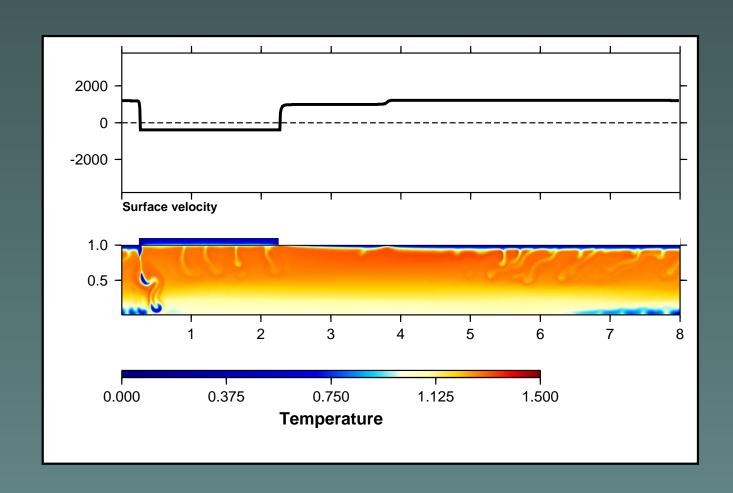
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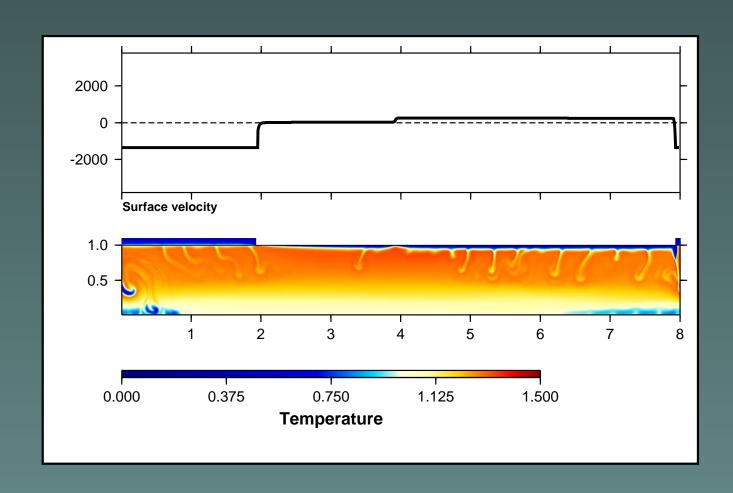
$$Ra = 7.10^6$$
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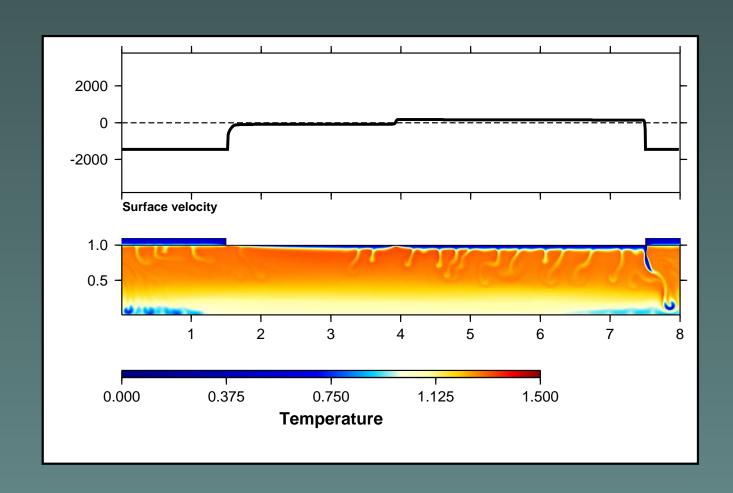
$$Ra = 7.10^6$$
 $H = 23$ (present) $\sigma_y = 3.10^5$ (263 MPa)



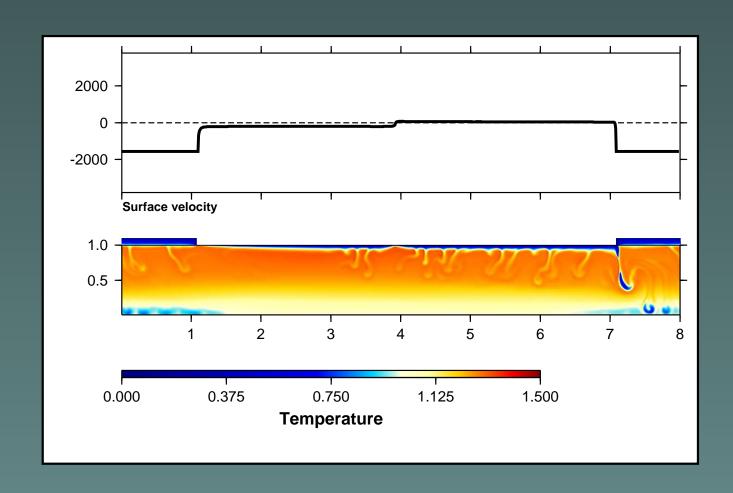
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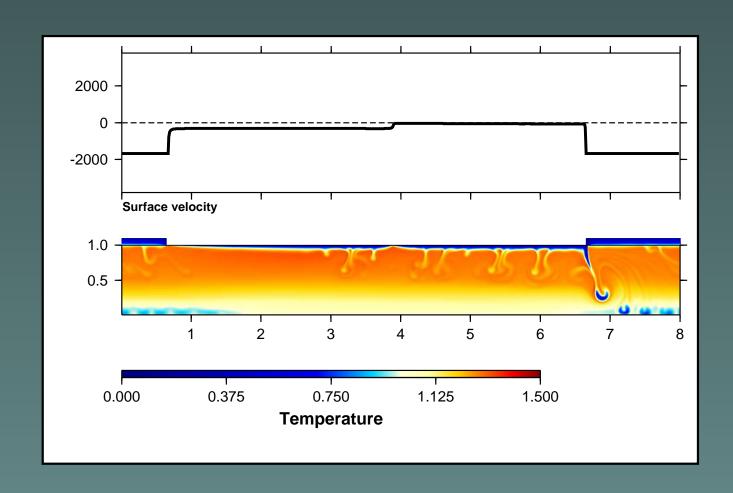
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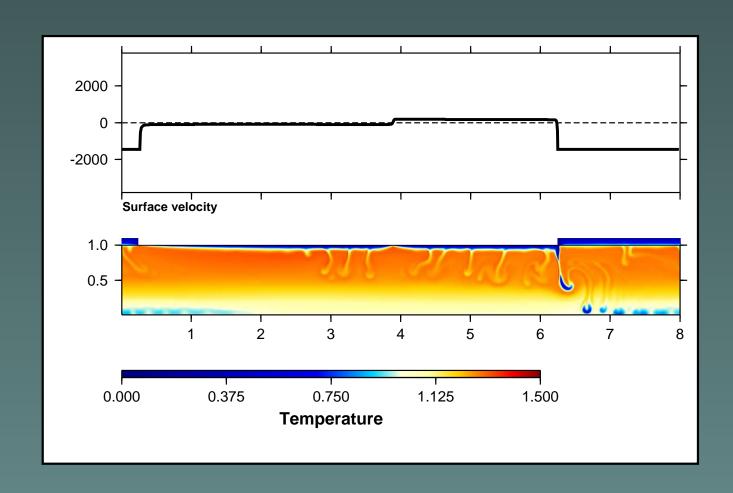
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 $H = 23$ (present) $\sigma_y = 3.10^5$ (263 MPa)



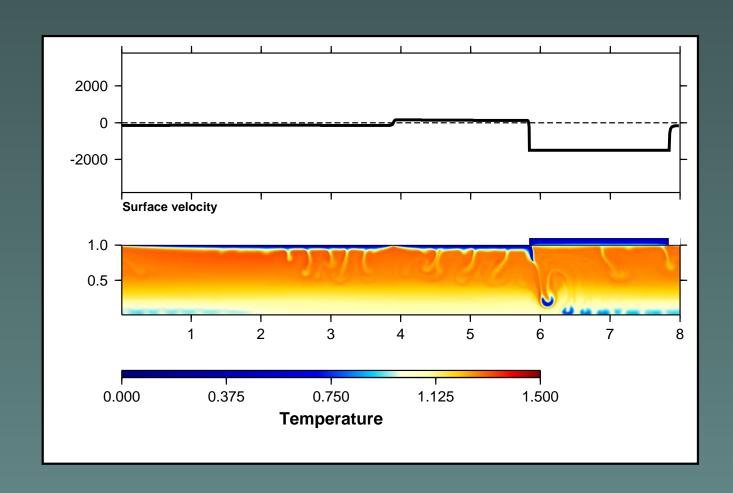
$$Ra = 7.10^6$$
 $H = 23$ (present) $\sigma_y = 3.10^5$ (263 MPa)



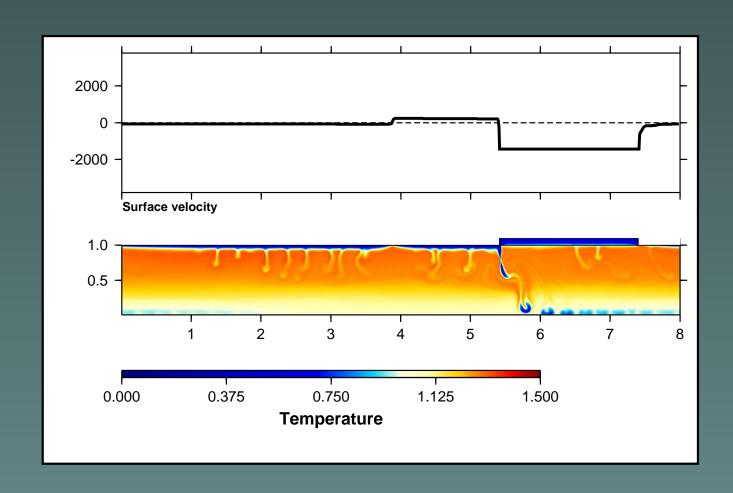
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 $H = 23$ (present) $\sigma_y = 3.10^5$ (263 MPa)



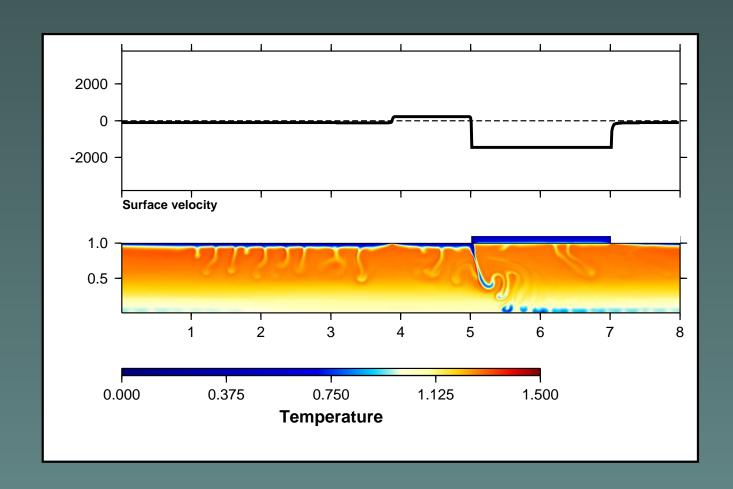
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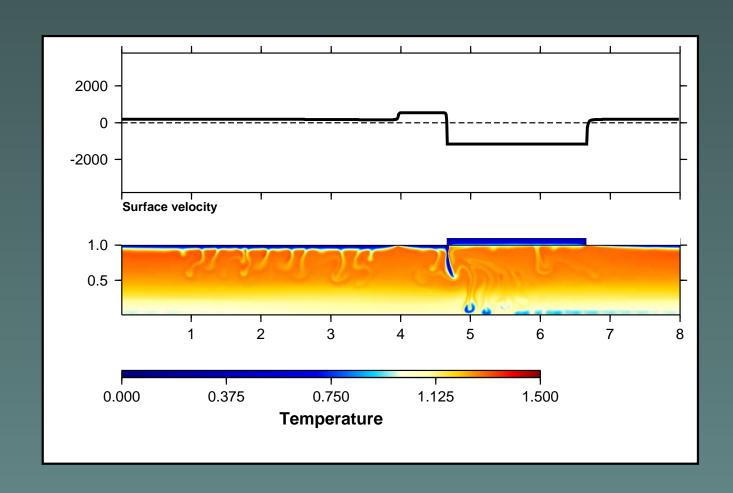
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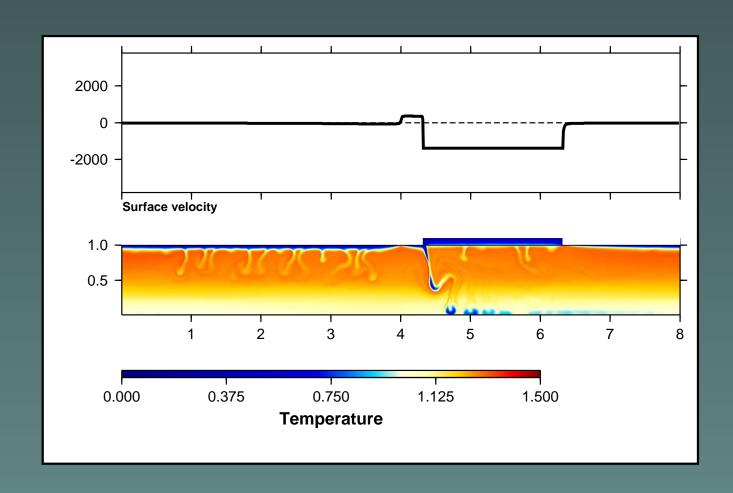
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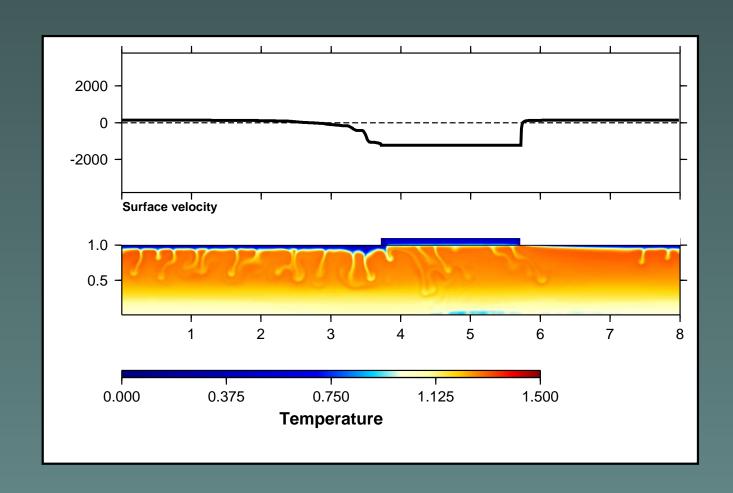
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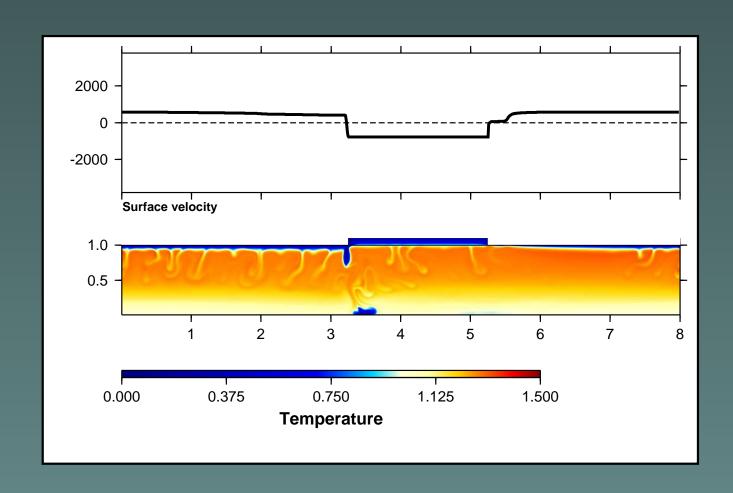
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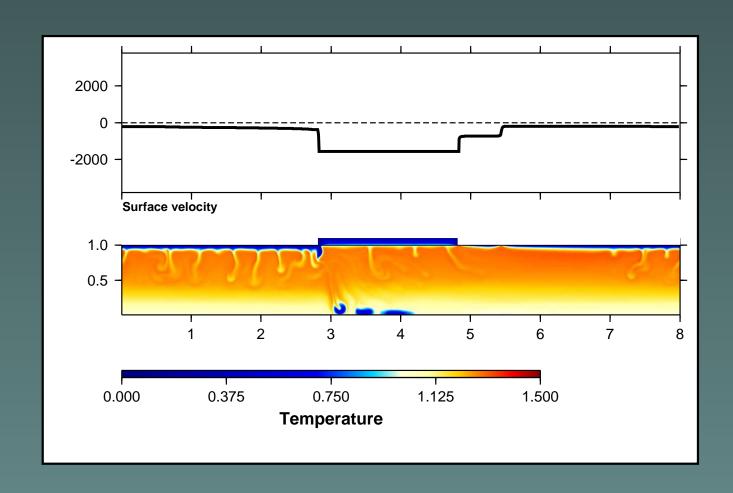
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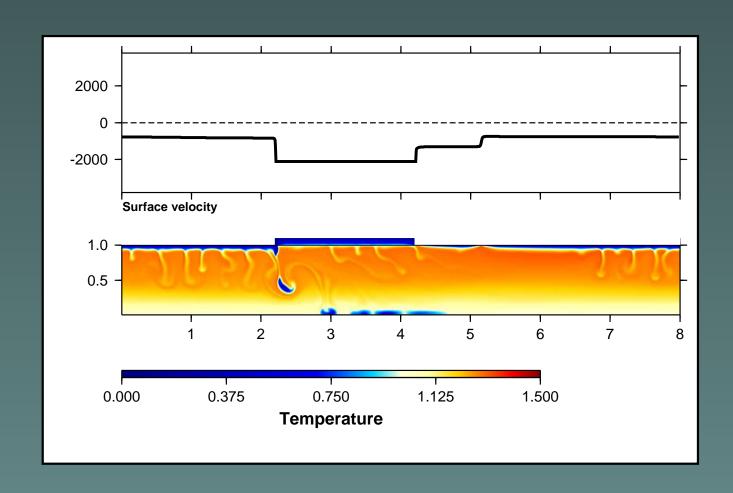
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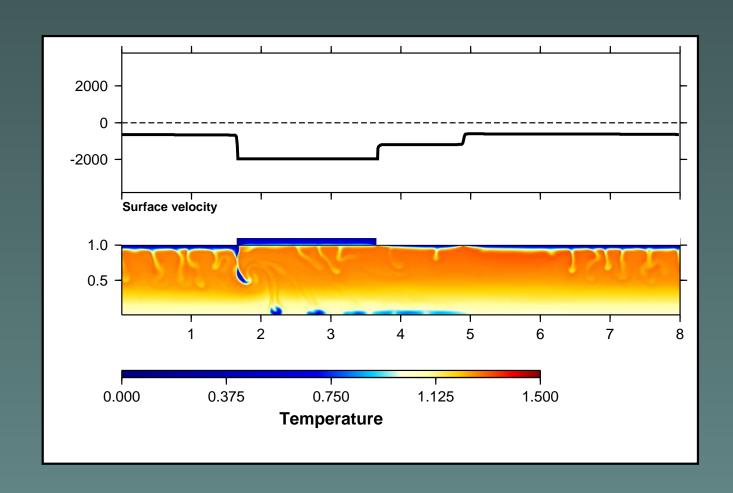
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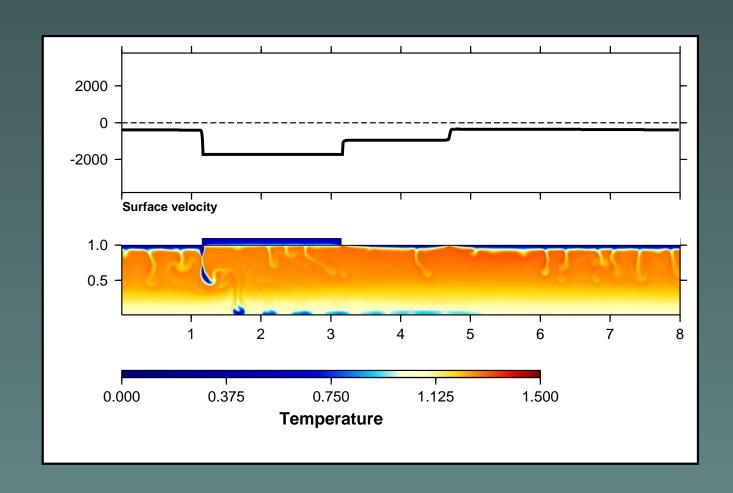
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 $H = 23$ (present) $\sigma_y = 3.10^5$ (263 MPa)



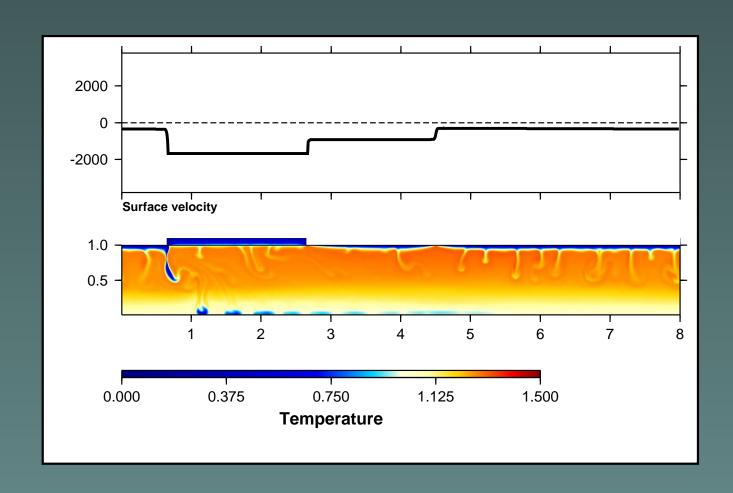
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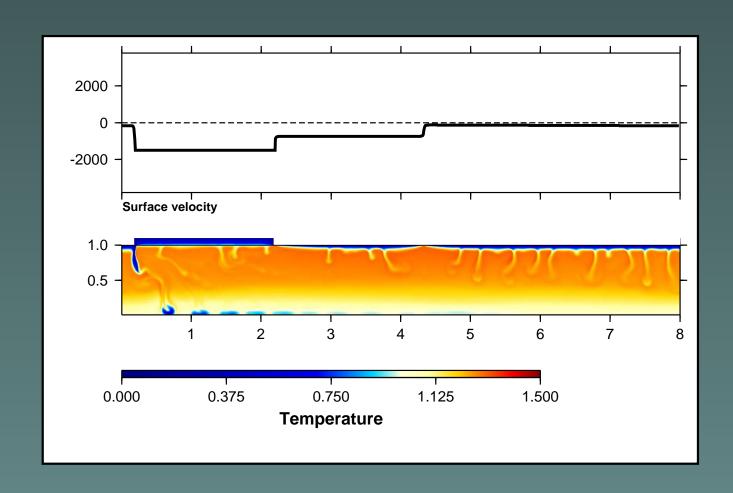
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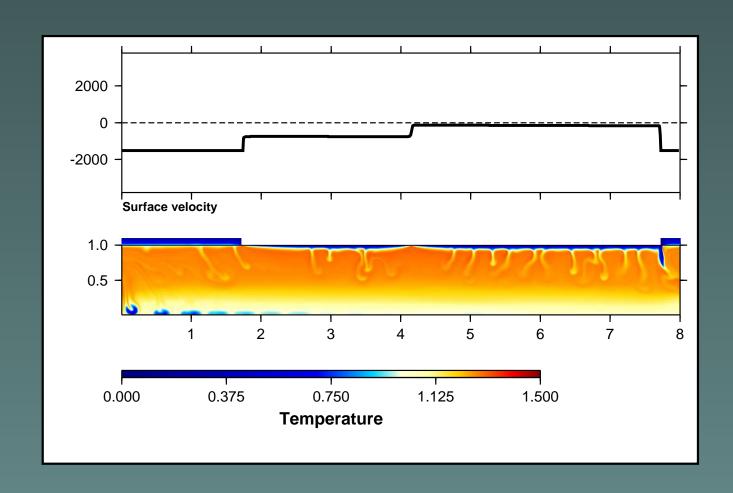
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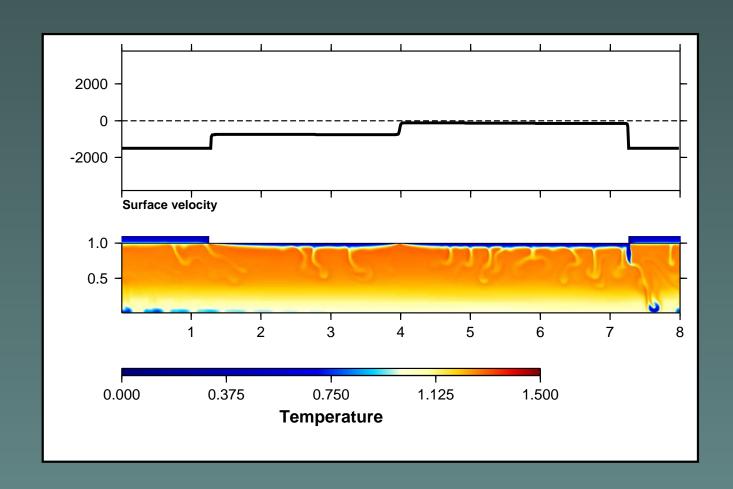
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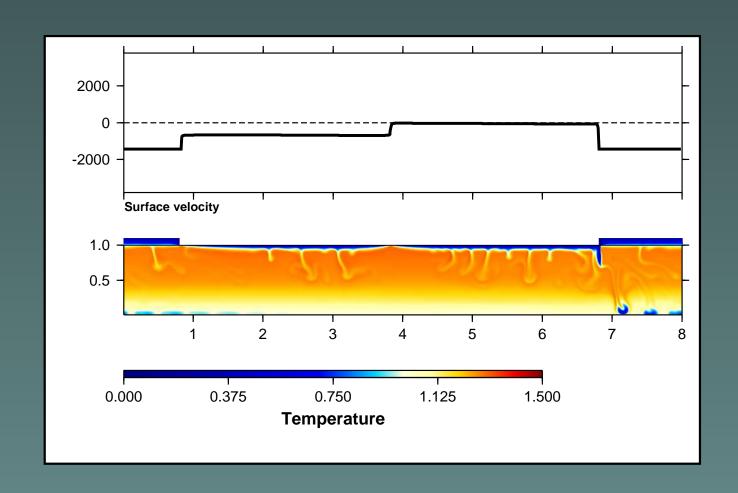
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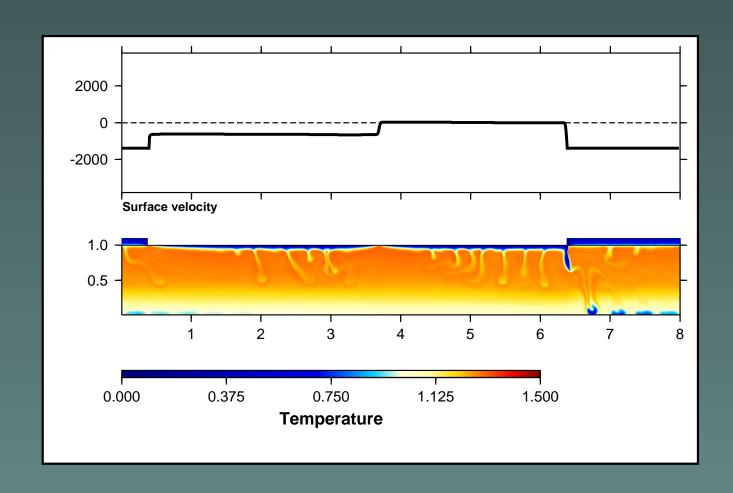
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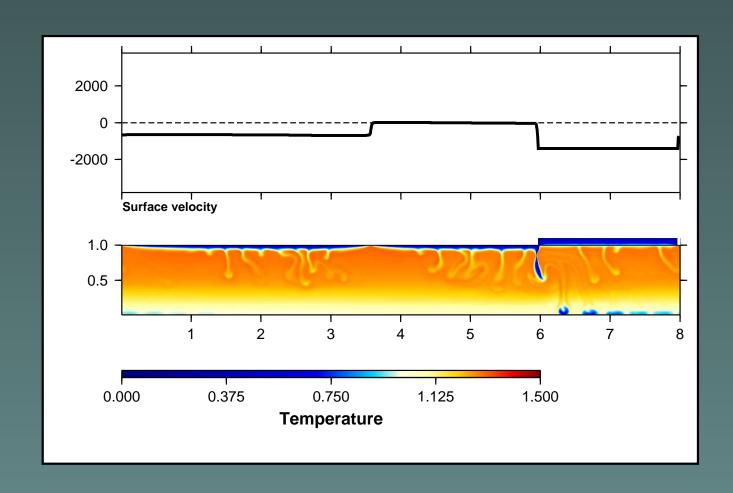
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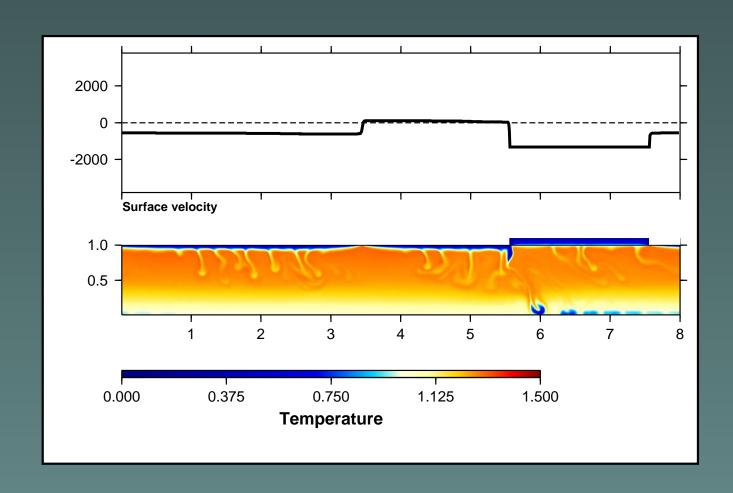
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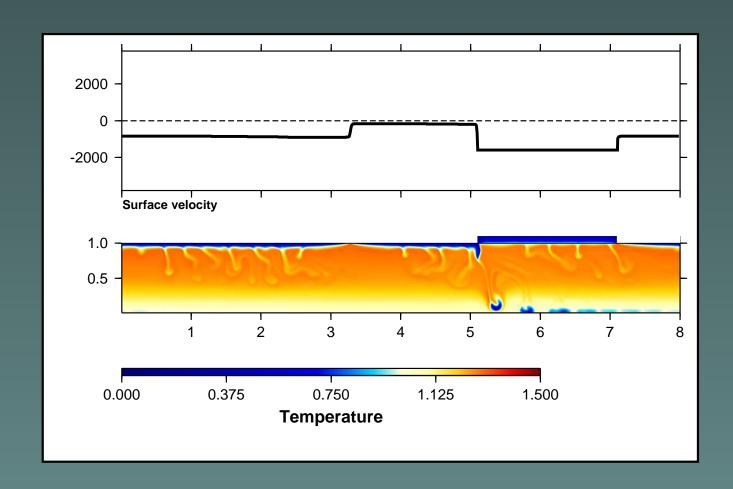
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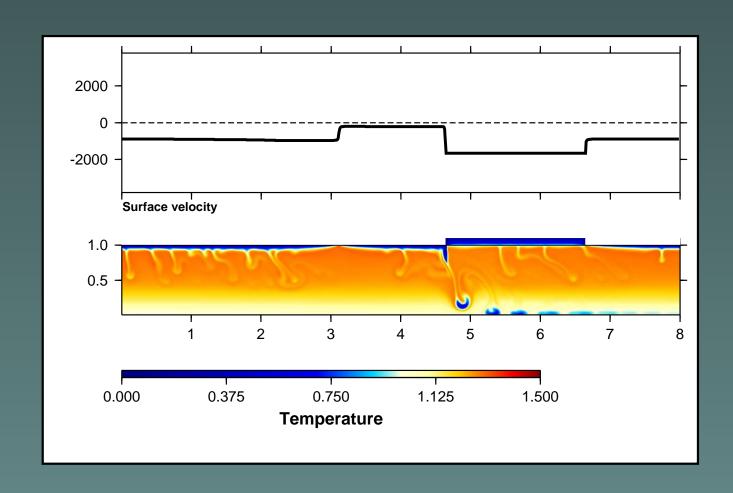
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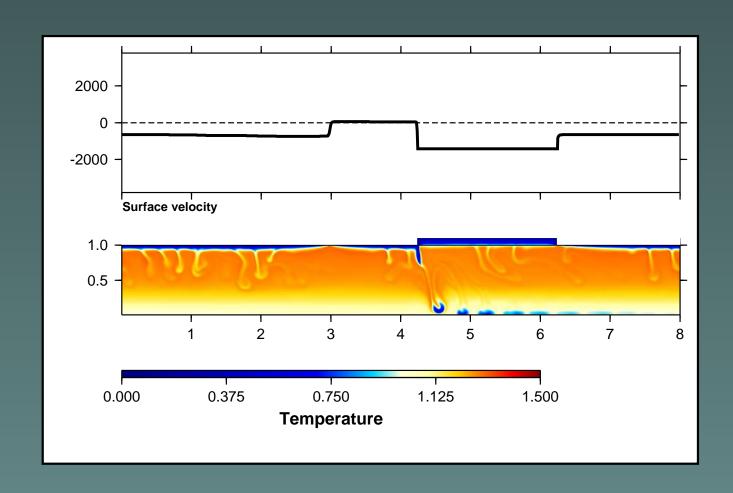
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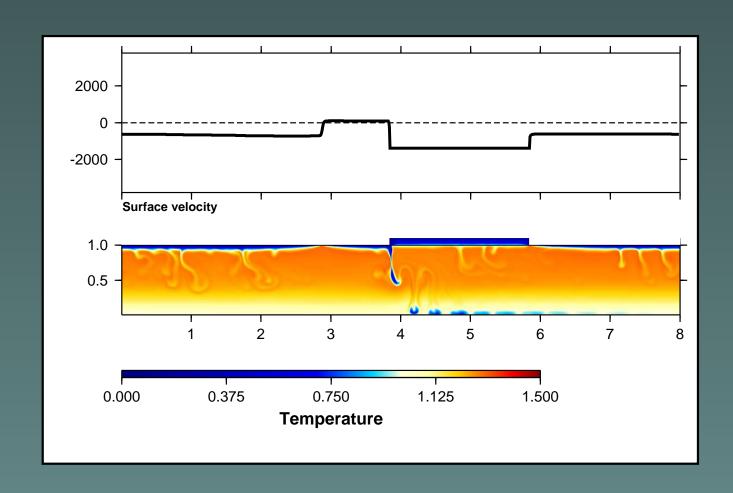
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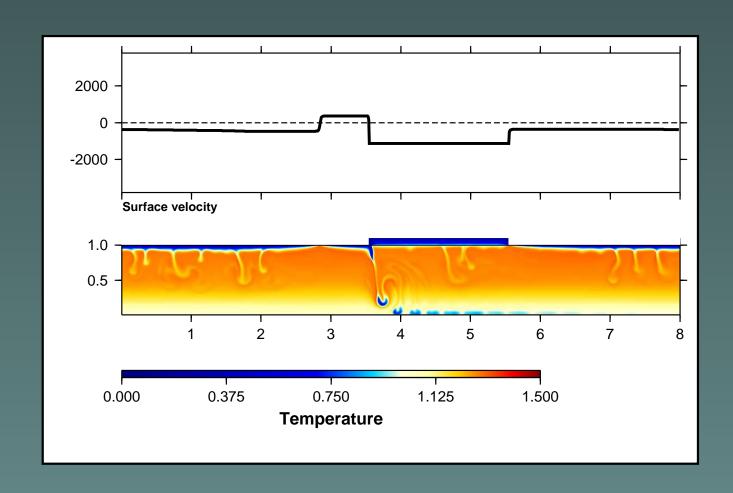
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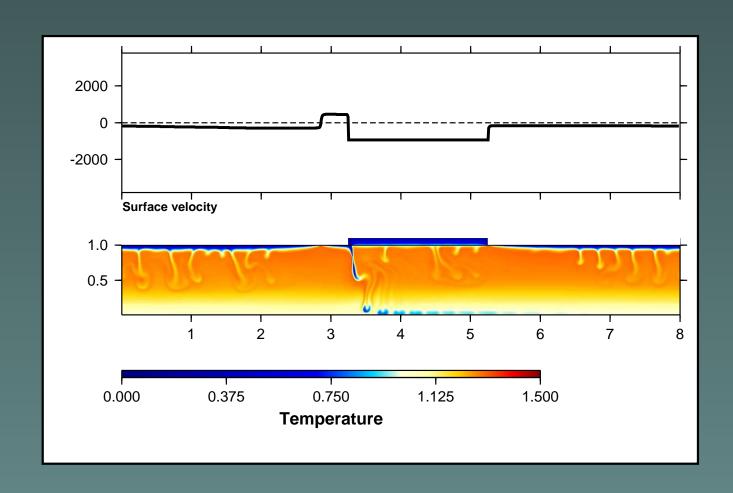
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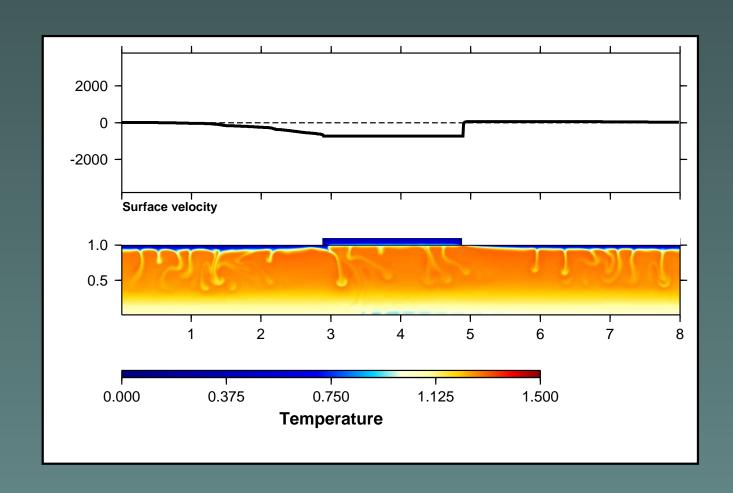
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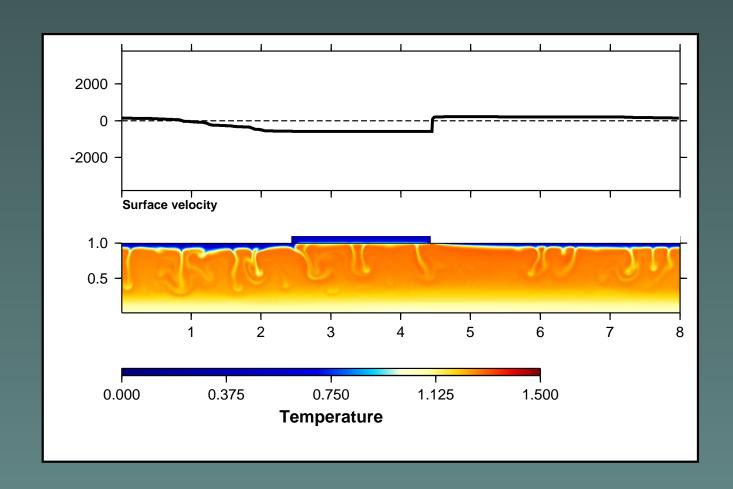
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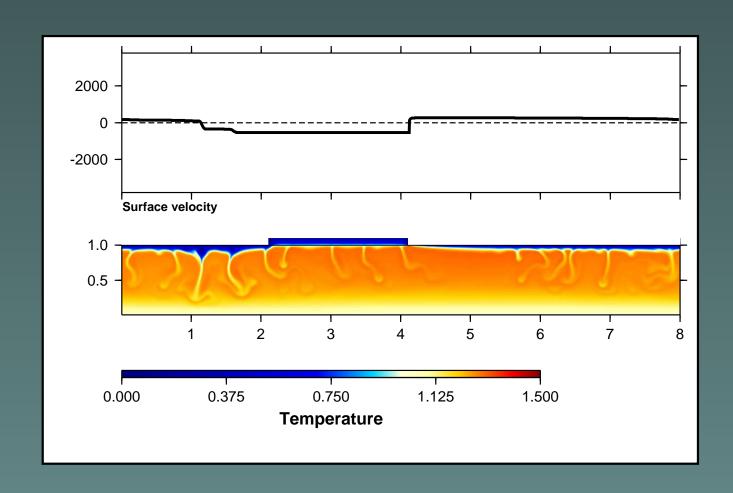
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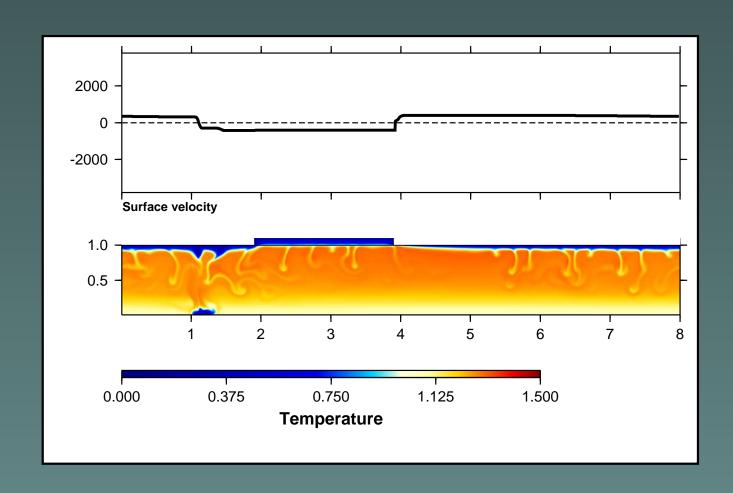
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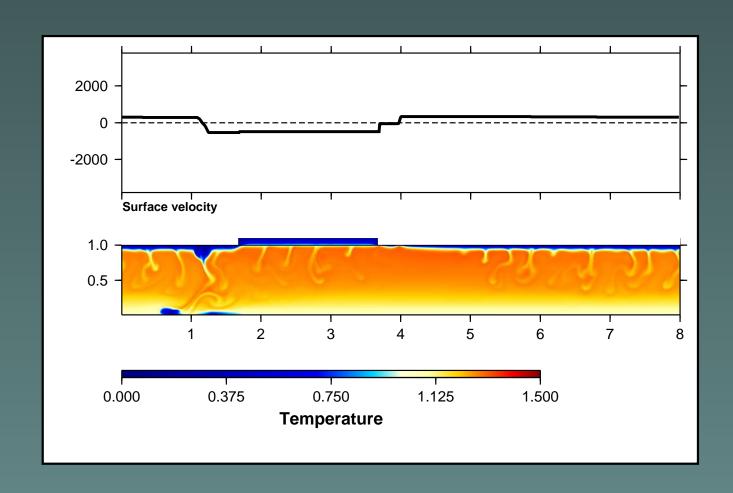
$$Ra = 7.10^6$$
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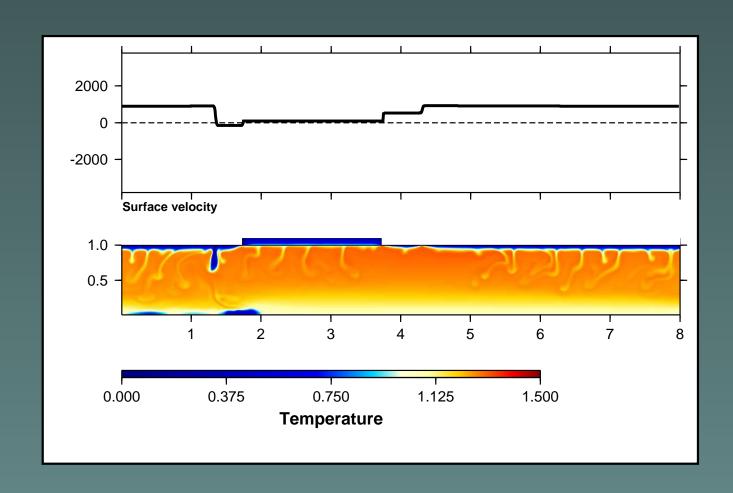
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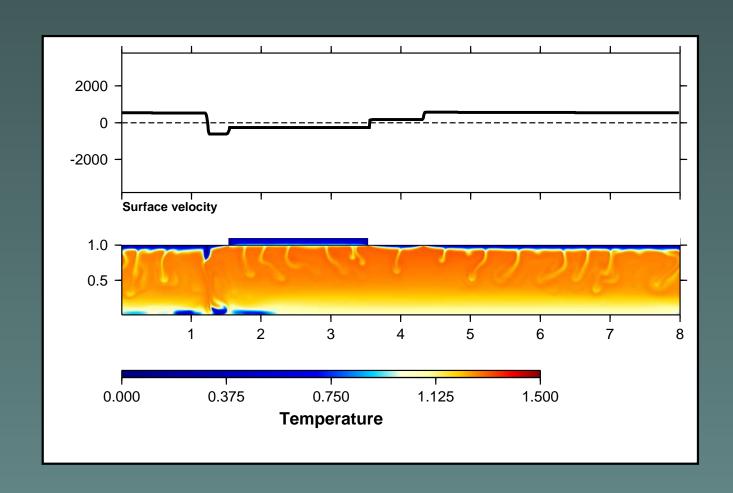
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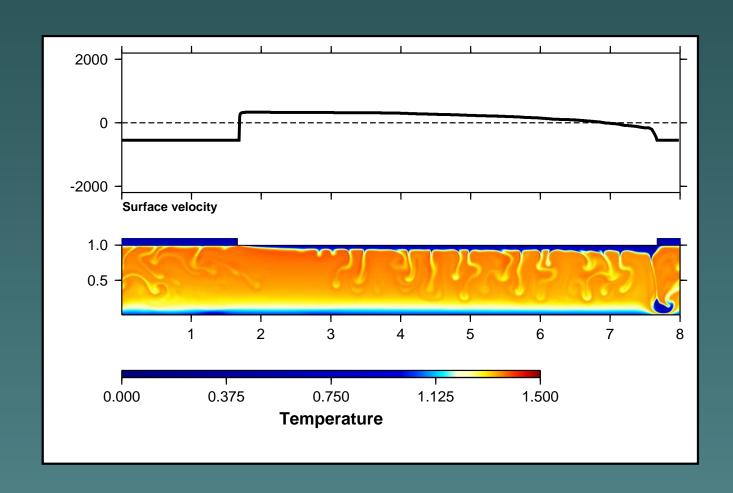
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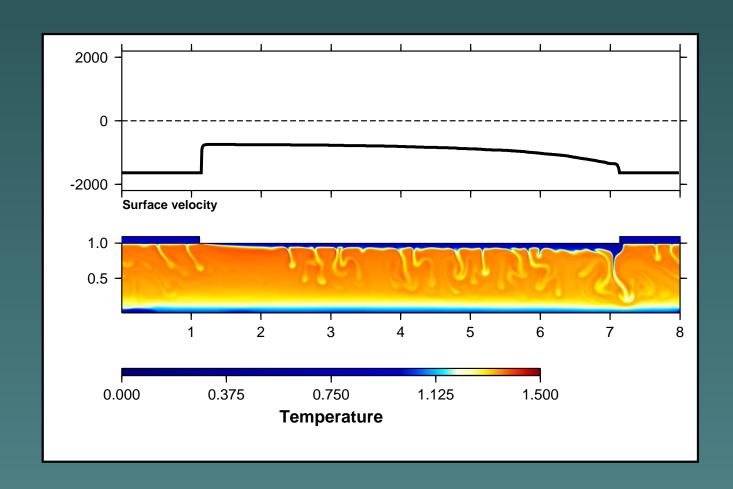
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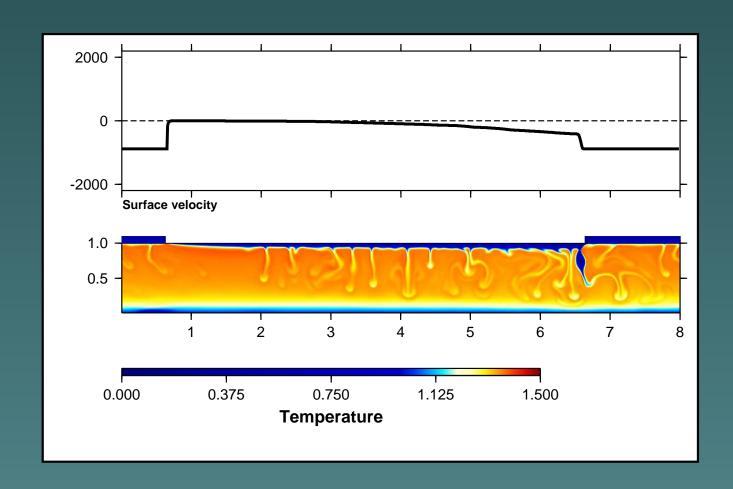
$$Ra = 7.10^6$$
 $H = 23$ (present) $\sigma_y = 5.10^5$ (438 MPa)



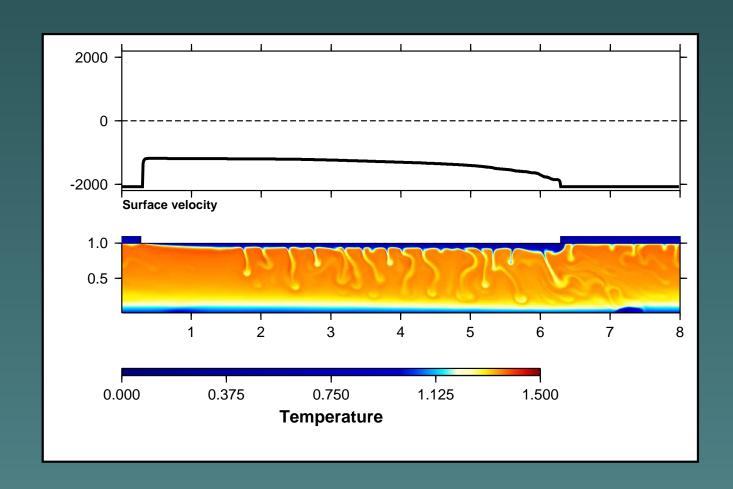
$$Ra = 7.10^6$$
 $H = 23$ (present) $\sigma_y = 5.10^5$ (438 MPa)



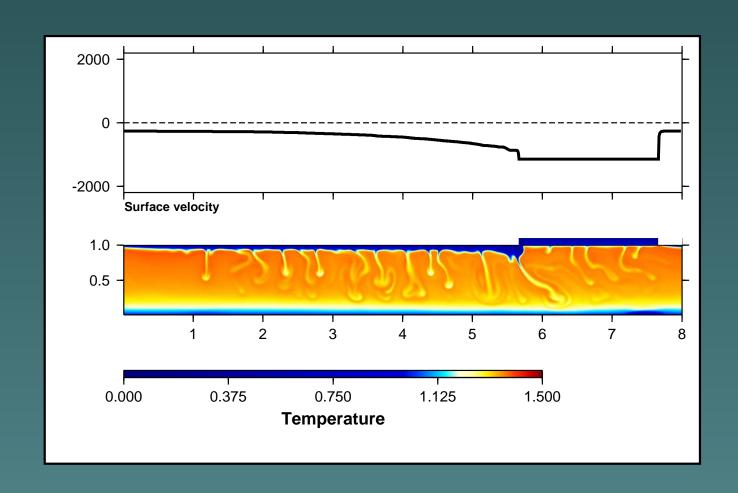
$$Ra = 7.10^6$$
 $H = 23$ (present) $\sigma_y = 5.10^5$ (438 MPa)



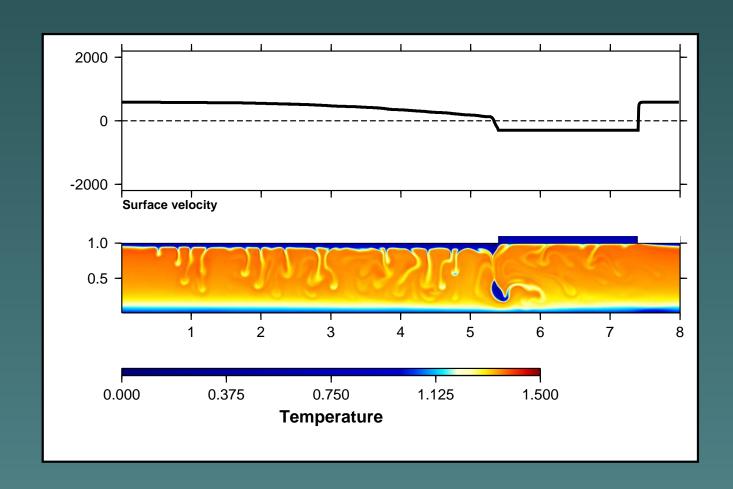
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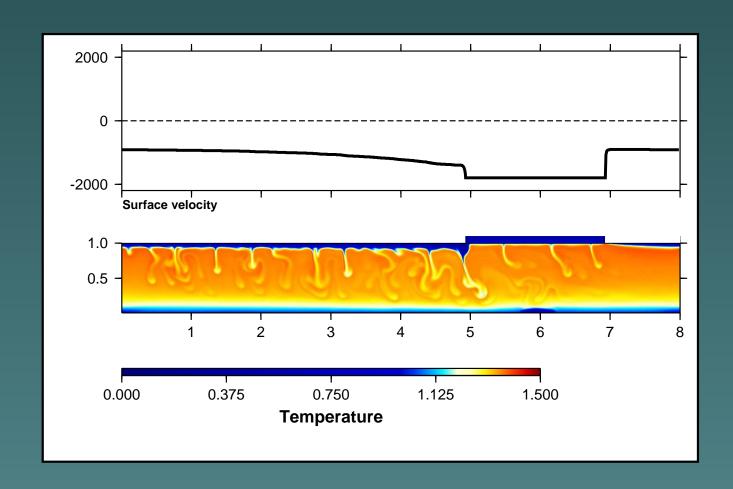
$$Ra = 7.10^6$$
 $H = 23$ (present) $\sigma_y = 5.10^5$ (438 MPa)



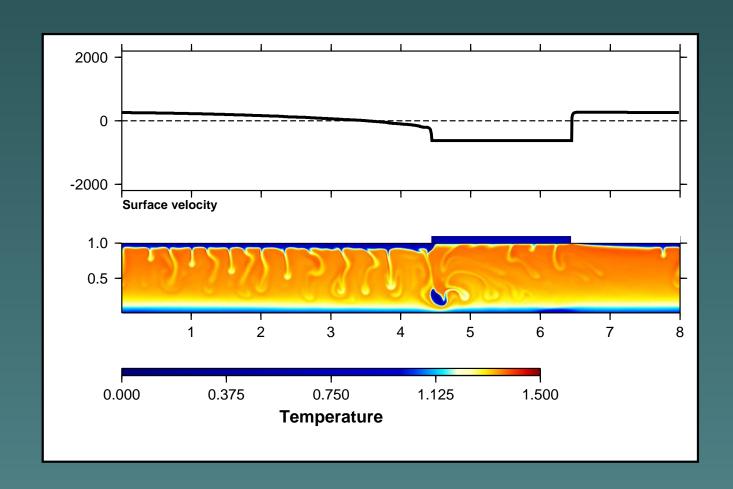
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 $H = 23$ (present) $\sigma_y = 5.10^5$ (438 MPa)



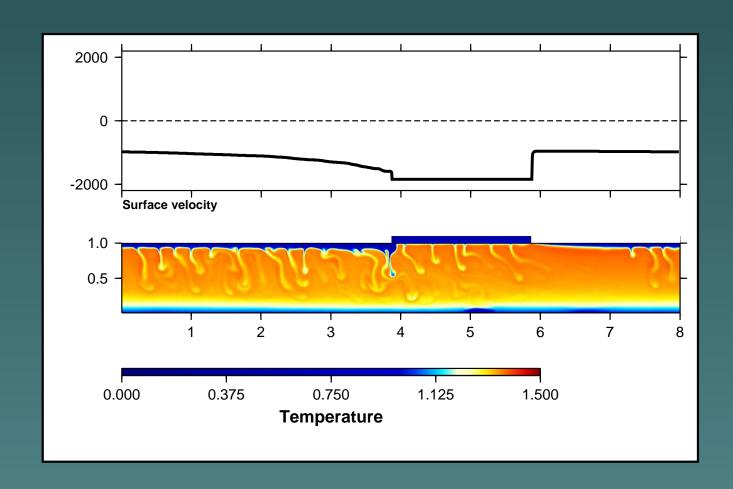
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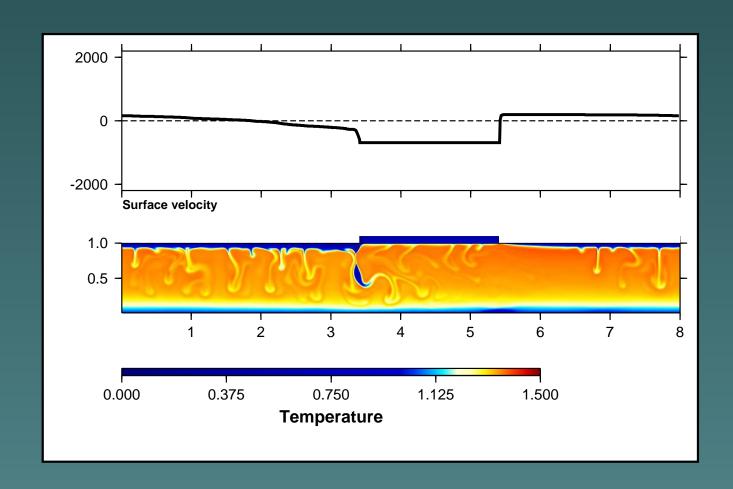
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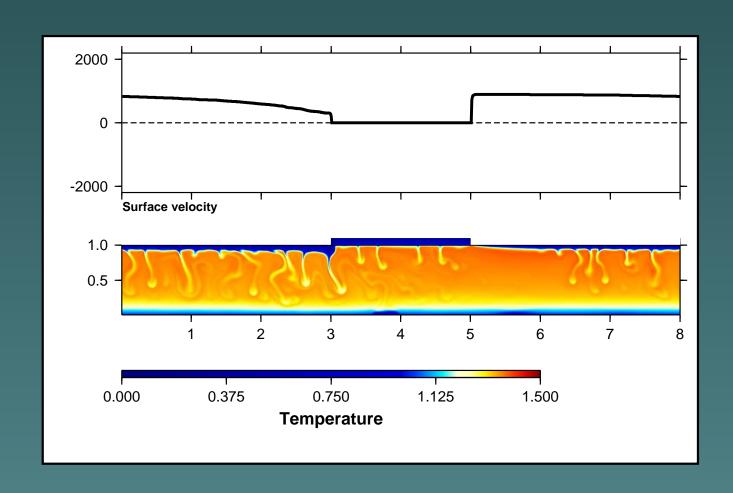
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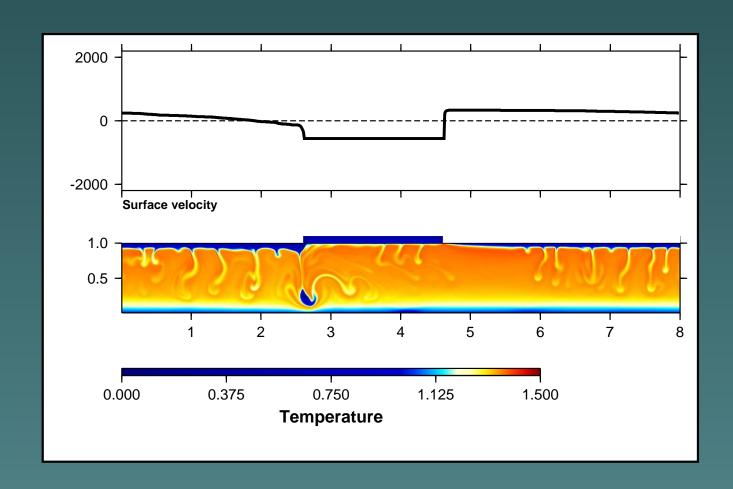
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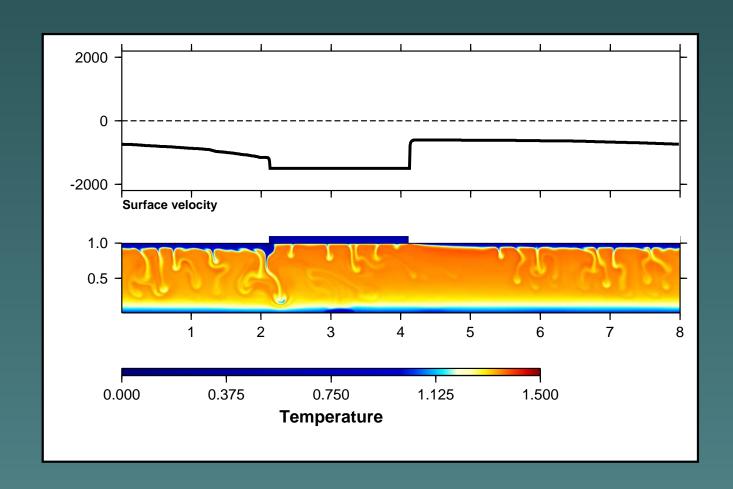
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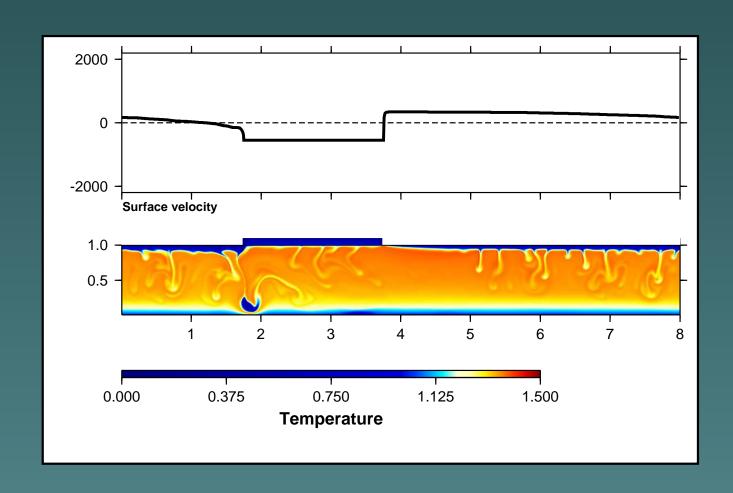
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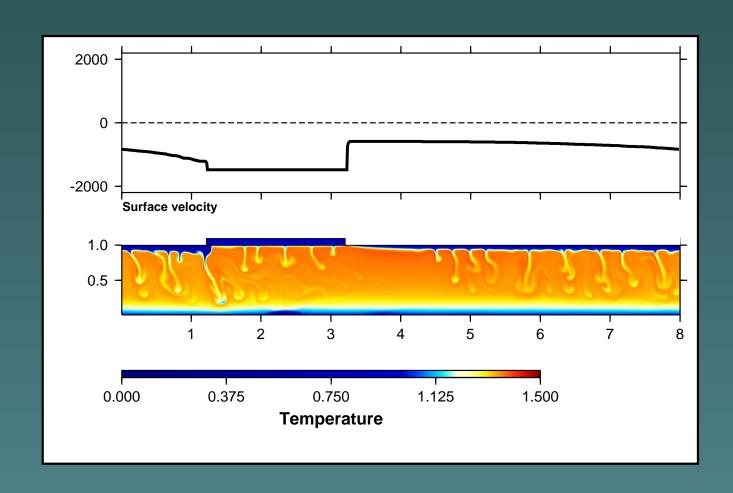
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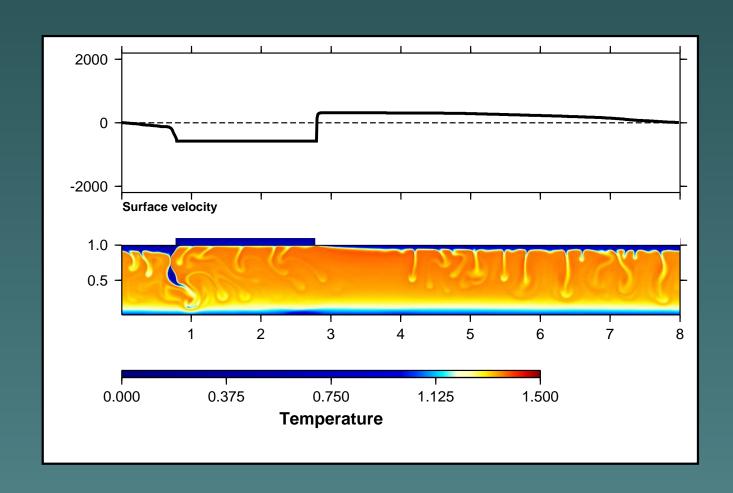
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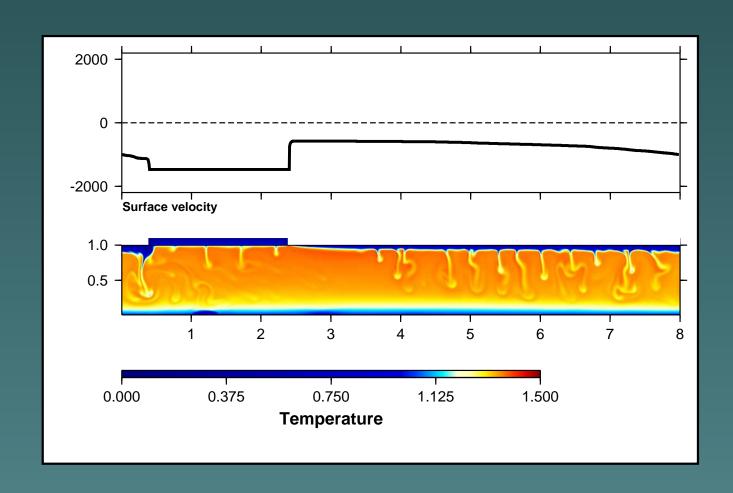
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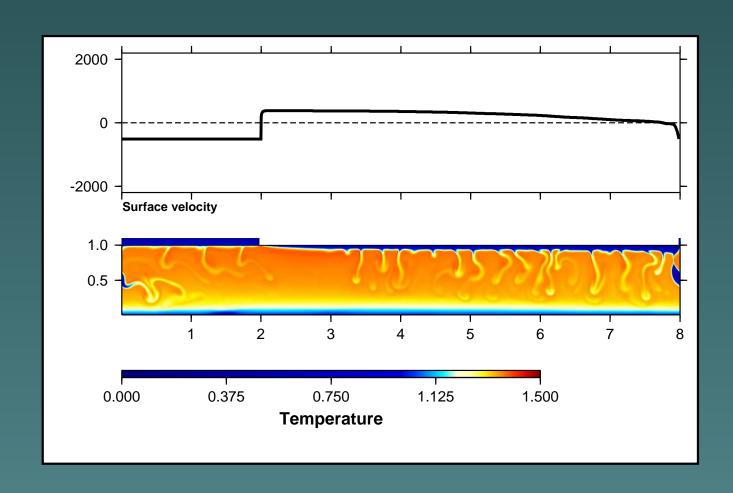
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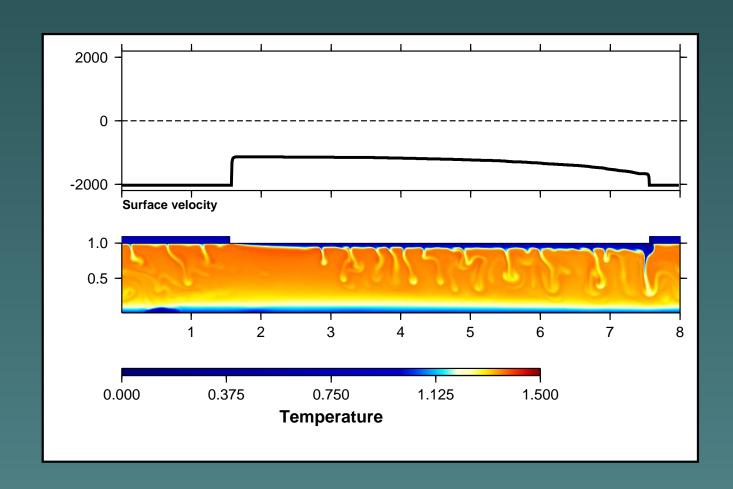
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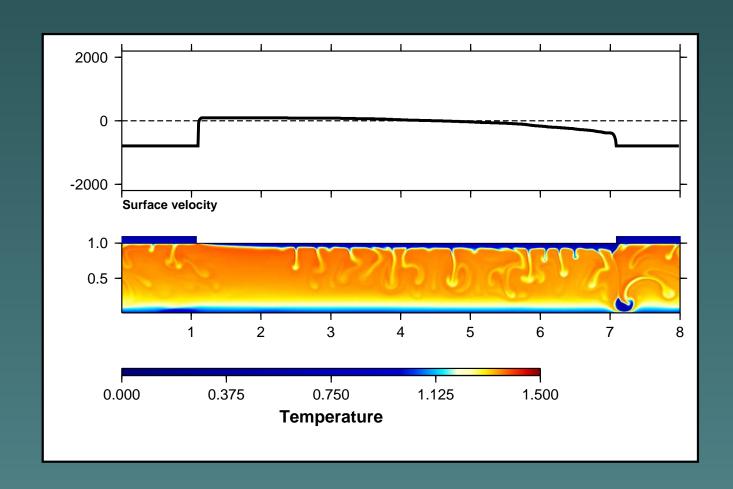
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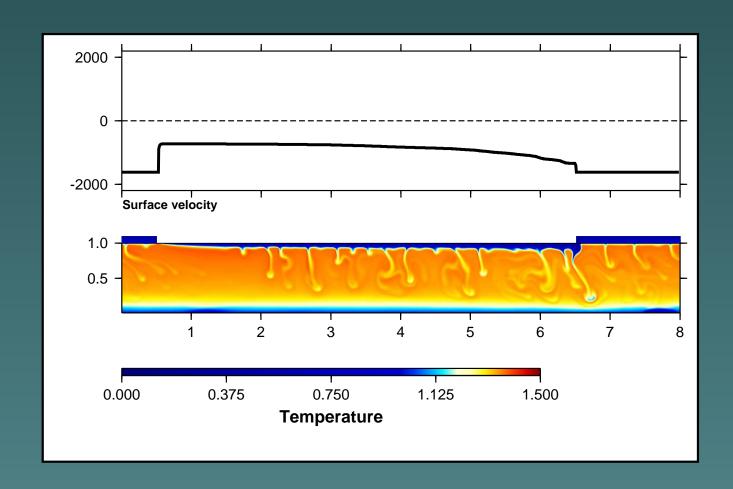
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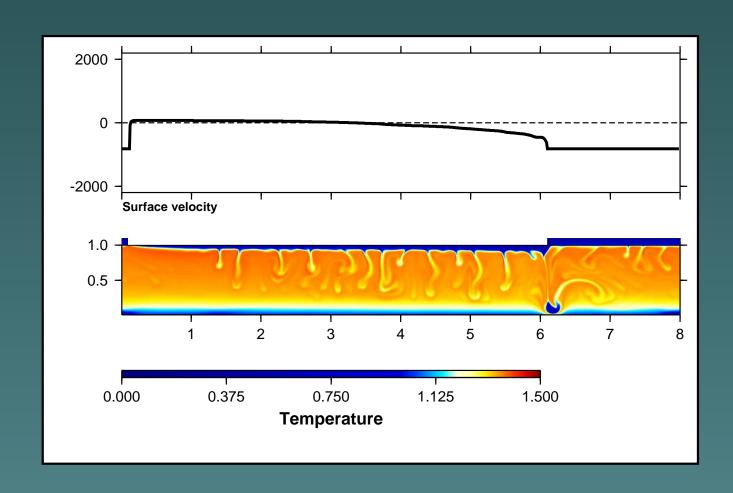
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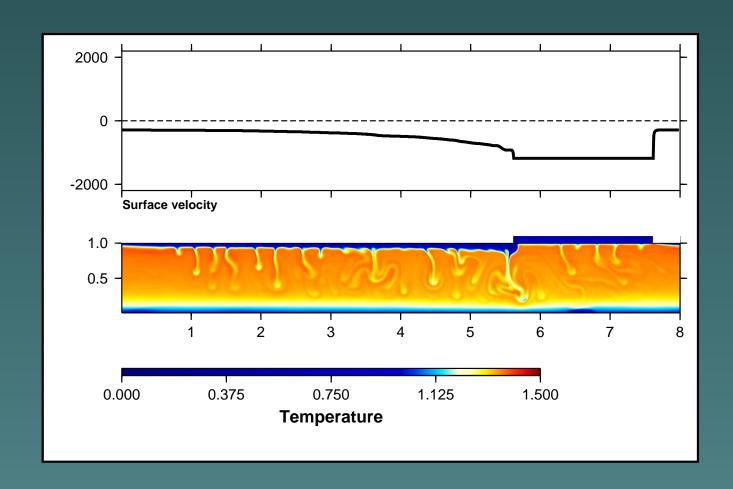
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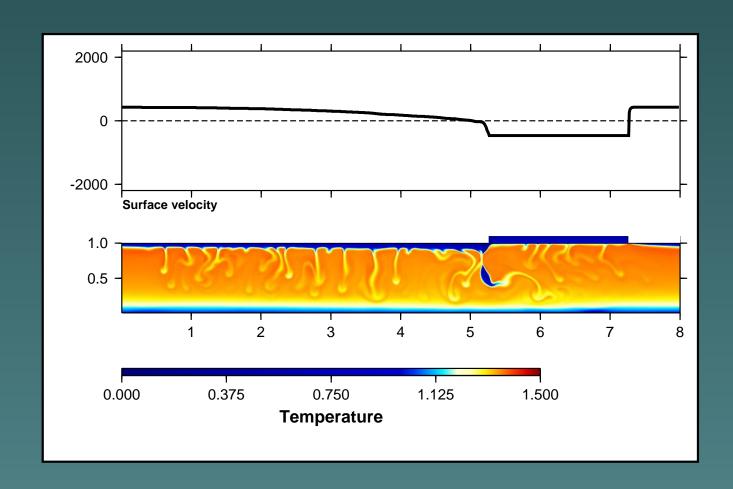
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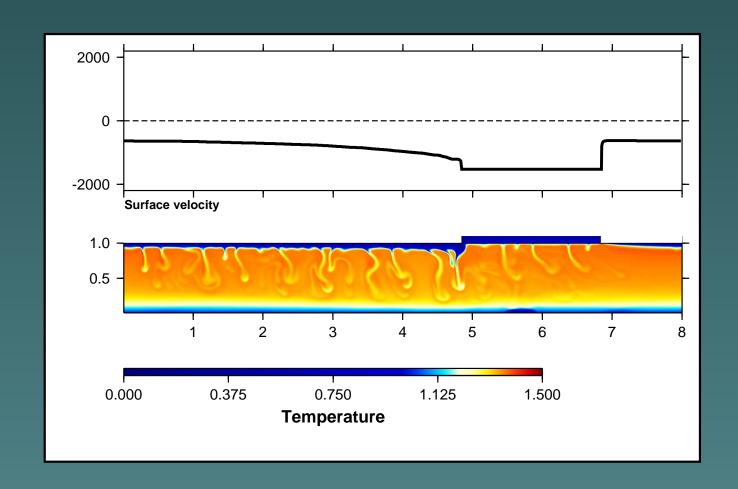
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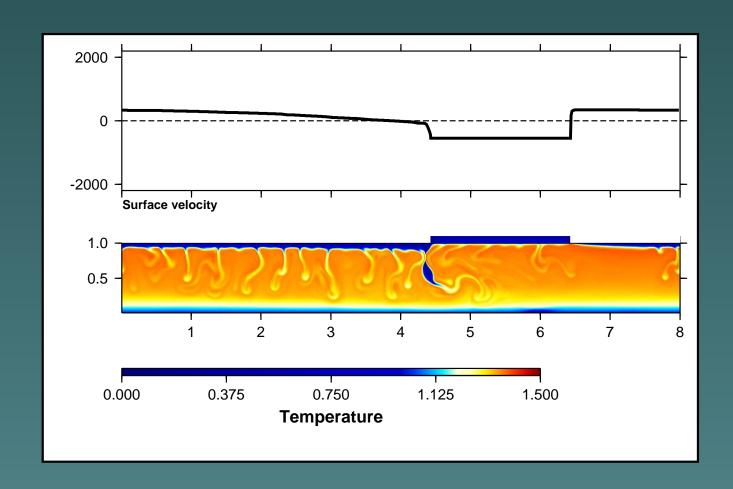
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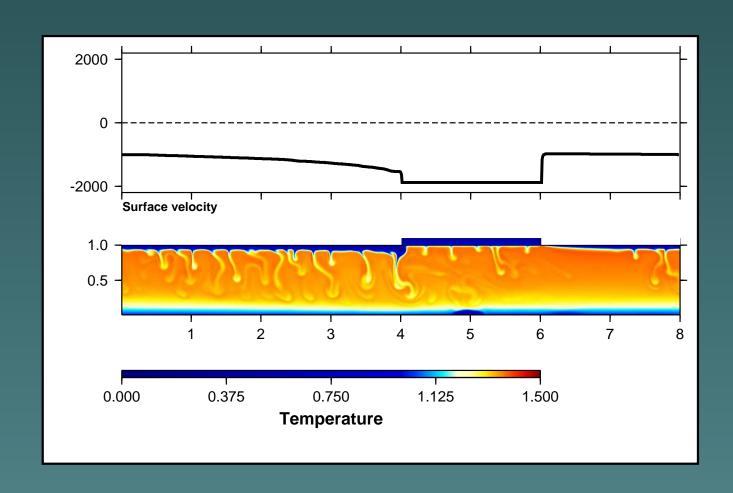
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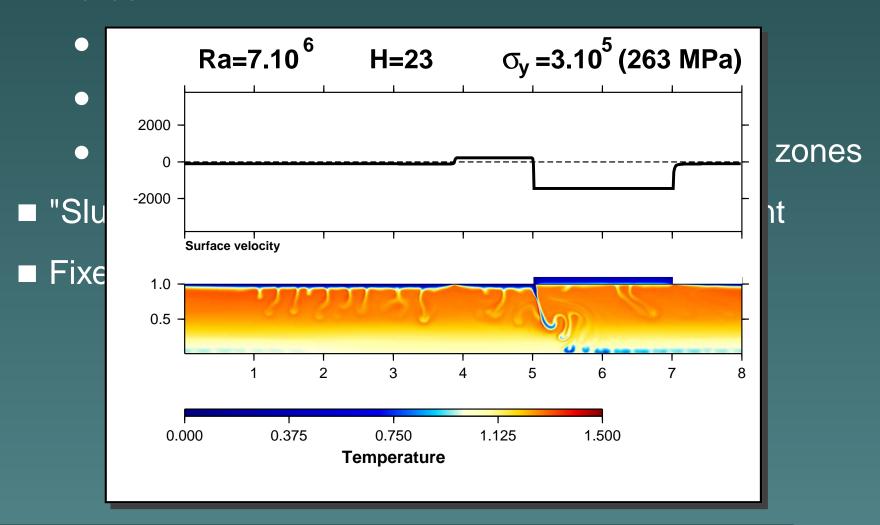


Different regimes:

- Plates:
 - Stable plate tectonics
 - "Real" subduction zones
 - Reorganization of divergence and subduction zones
- "Sluggish" motion of the stagnant lid and continent
- Fixed viscous lid and continent

Different regimes:

■ Plates:

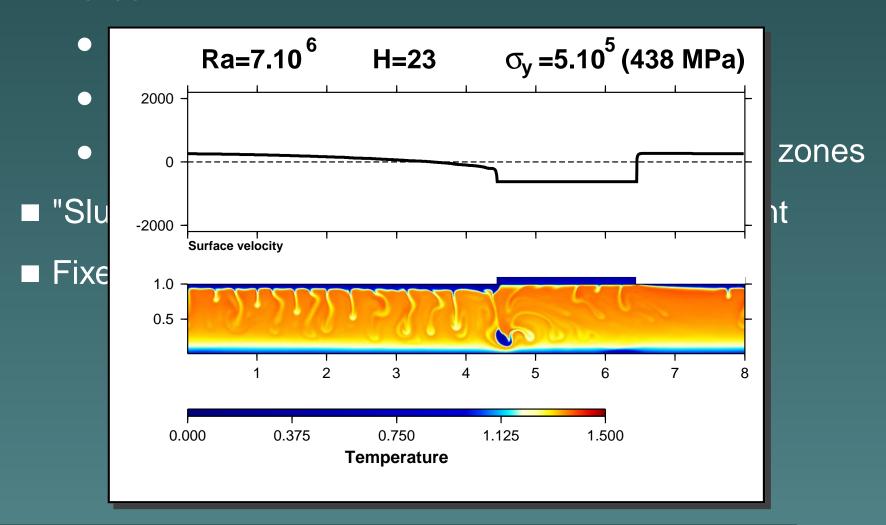


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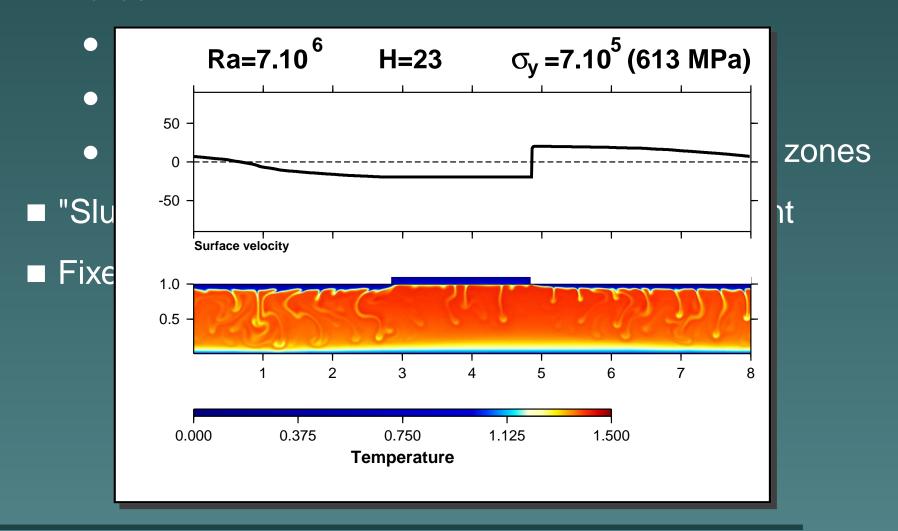


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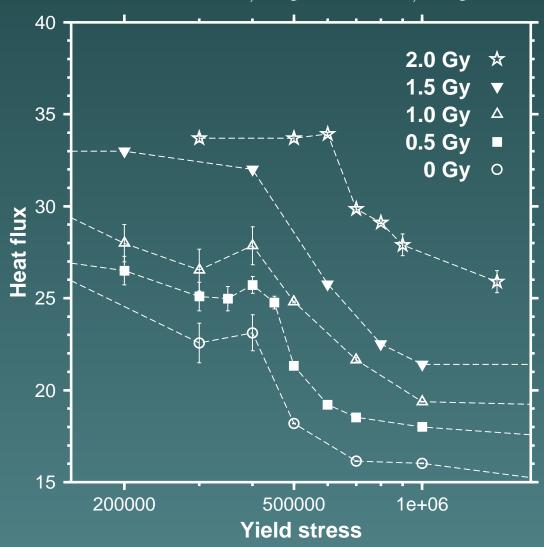
■ Plates:



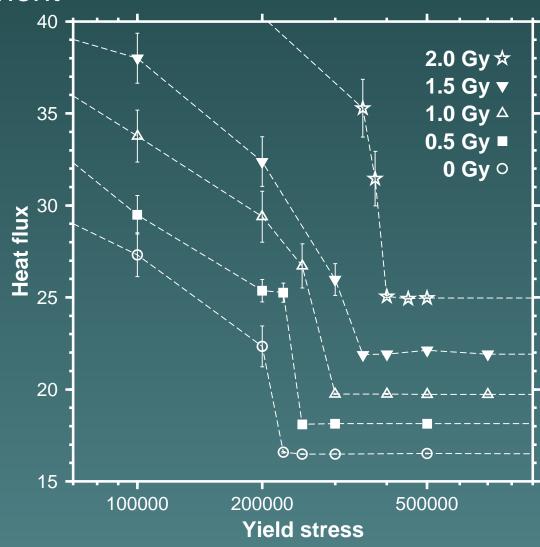
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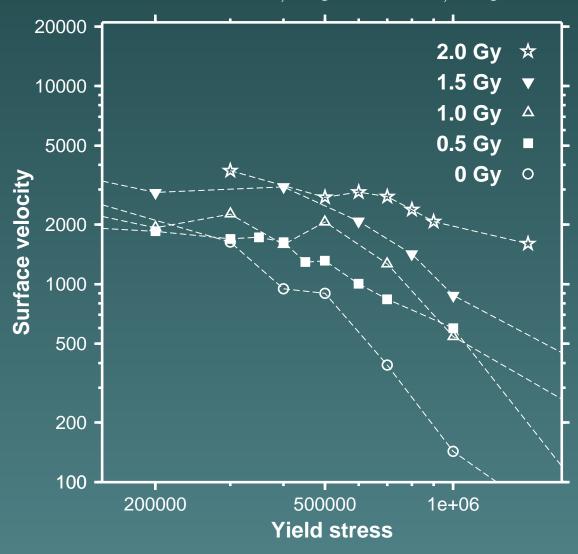
With a continent of width $a=2,\ d_c=0.1\ d,\ H_c=H$



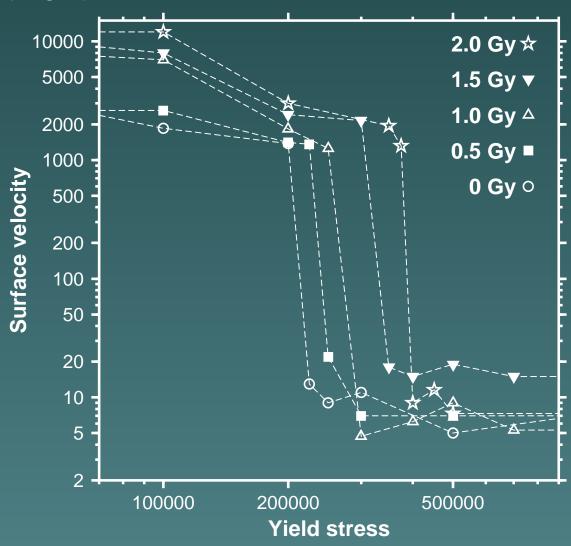
Without continent



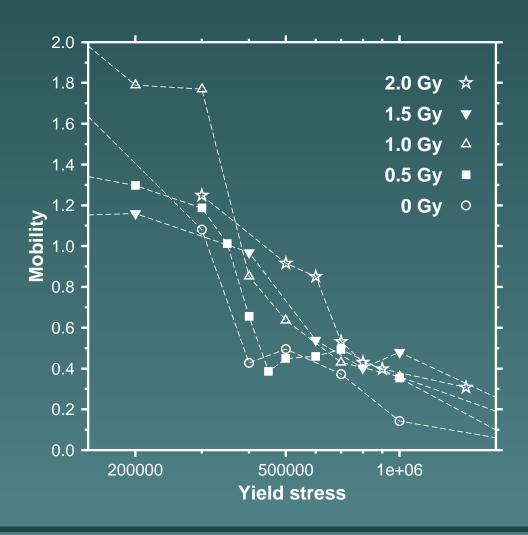
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Without continent

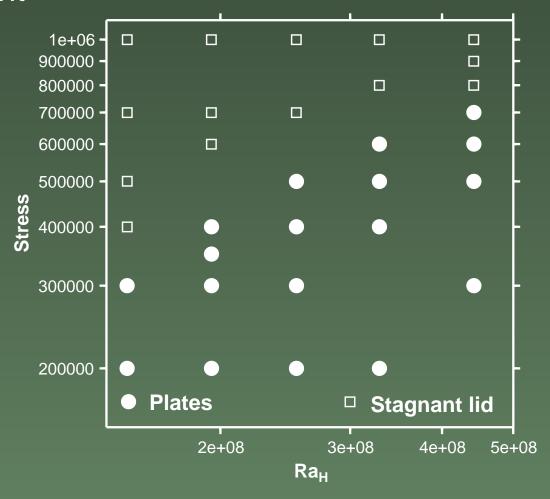


lacksquare Criteria on the mobility: mobility $= rac{V_{
m rms}^{
m surf}}{V_{
m rms}^{
m tot}}$

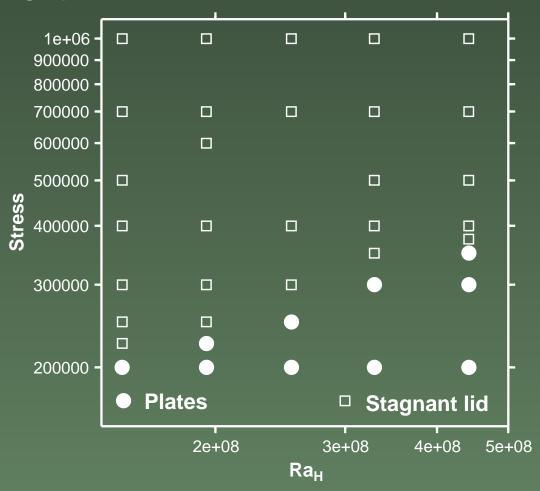


- Criteria on the mobility: mobility = $\frac{V_{rms}^{surf}}{V_{rms}^{tot}}$
- Plate if mobility > 0.5
- Observation: mobility $> 0.5 \iff Q_{bot} > 0$

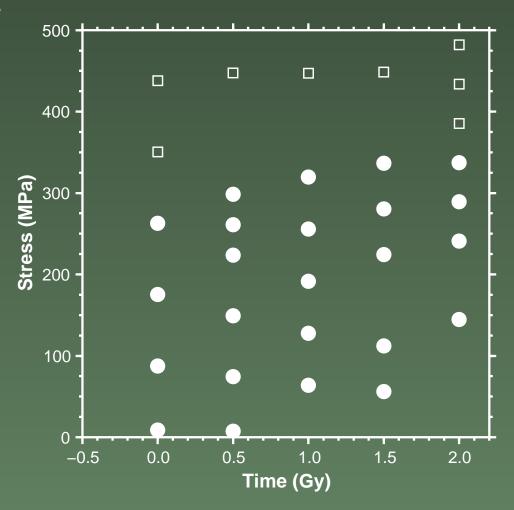
With continent



Without continent

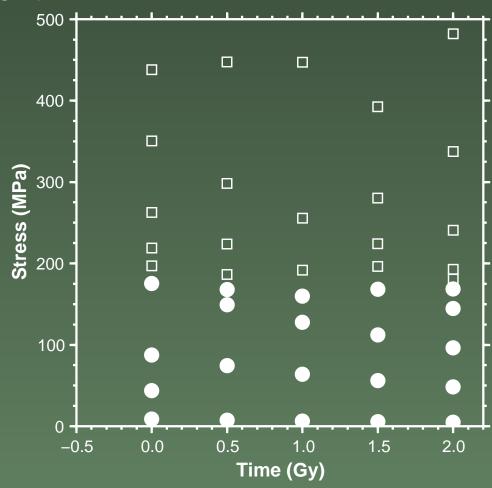


With continent



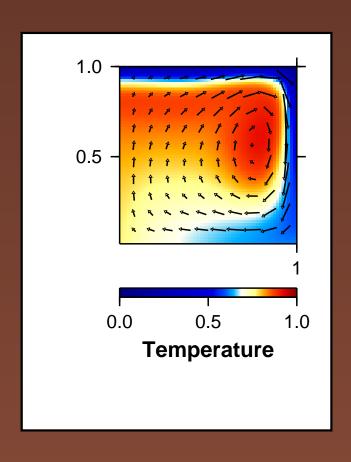
Regimes with continent

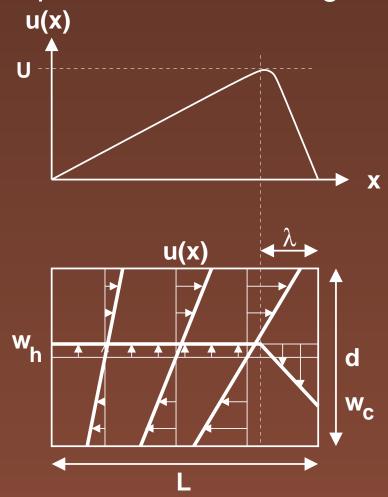
Without continent



Scaling laws

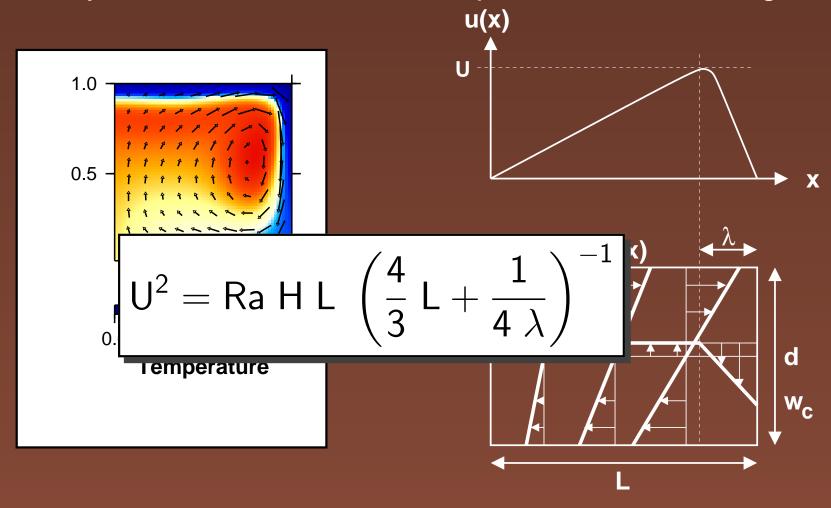
Velocity for a convective cell with pure internal heating:

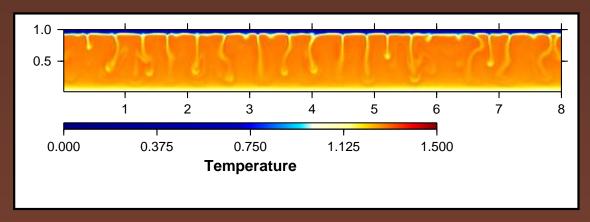




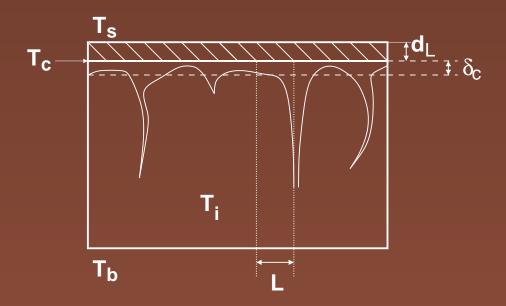
Scaling laws

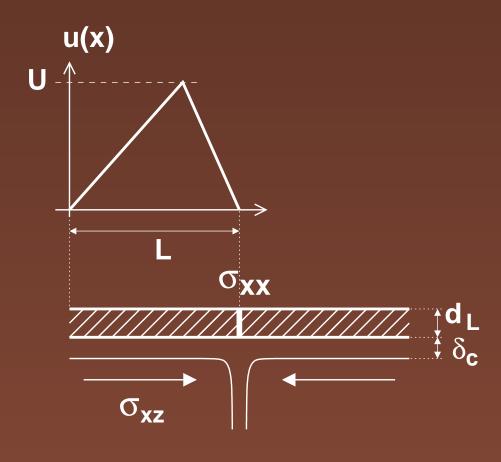
Velocity for a convective cell with pure internal heating:



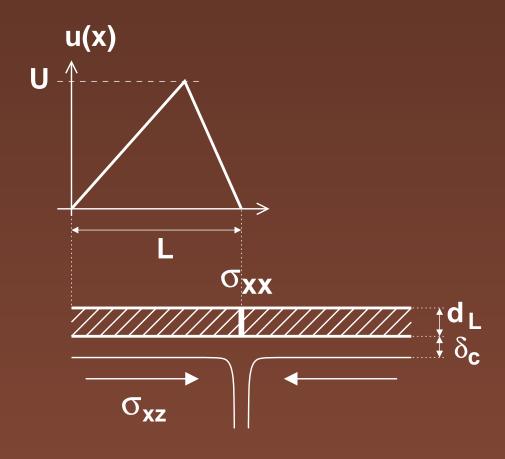


Ra= 7.10^6 , H=22 (present), $\sigma_y = 3.10^5$ (260 MPa).

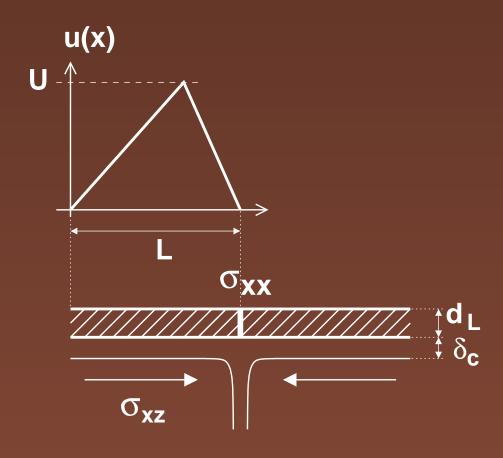




▶ Yielding if vertically averaged normal stress $\overline{\sigma_{xx}} > \sigma_{y}$.

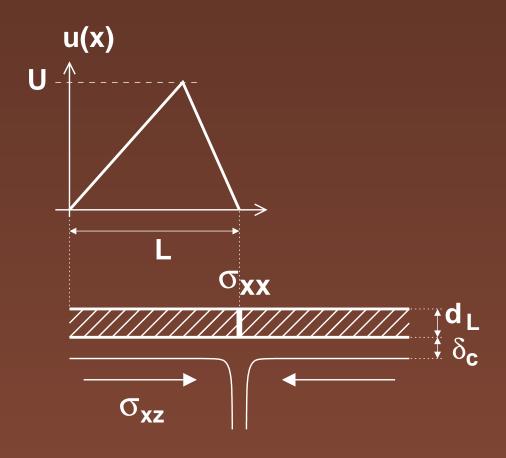


▶ Force acting on the stagnant lid: $F = \overline{\sigma_{xx}} d_L$.

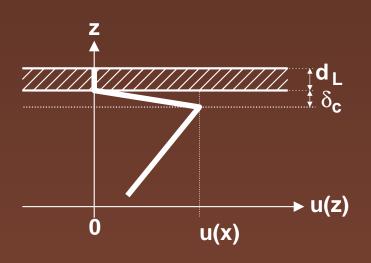


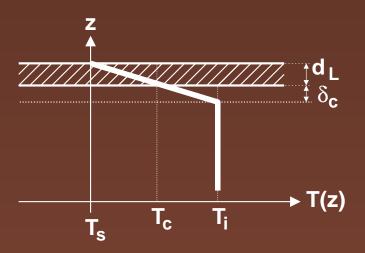
▶ This force equals the viscous drag at the base of the lid:

$$F = \int_0^L \sigma_{xz}(x) dx$$
.

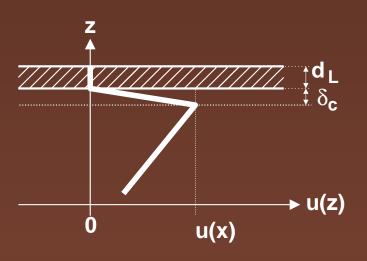


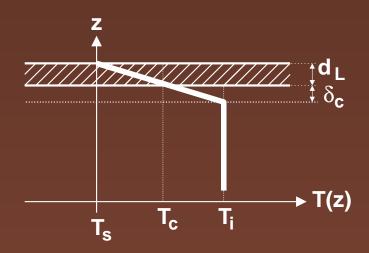
▶ Condition for breaking the lid:
$$\int_0^L \sigma_{xz}(x) dx > \sigma_y d_L$$



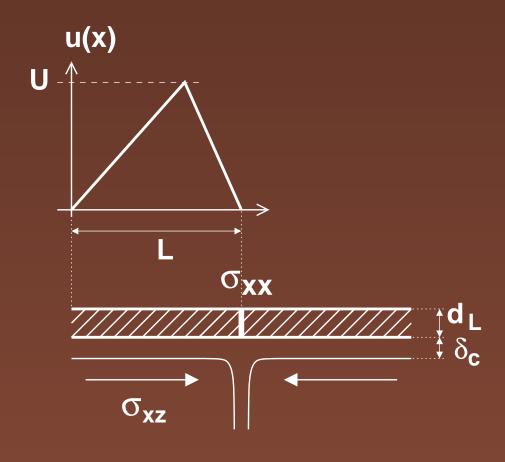


- Shear stress: $\sigma_{xz}(x) = \eta(T_c) \frac{\partial u}{\partial z} = \eta(T_c) \frac{u(x)}{\delta_c}$.
- We need to know:
 - Velocity: u(x),
 - Active boundary layer thickness: δ_c ,
 - Lid thickness: d_L,
 - Temperature below the lid: T_c.

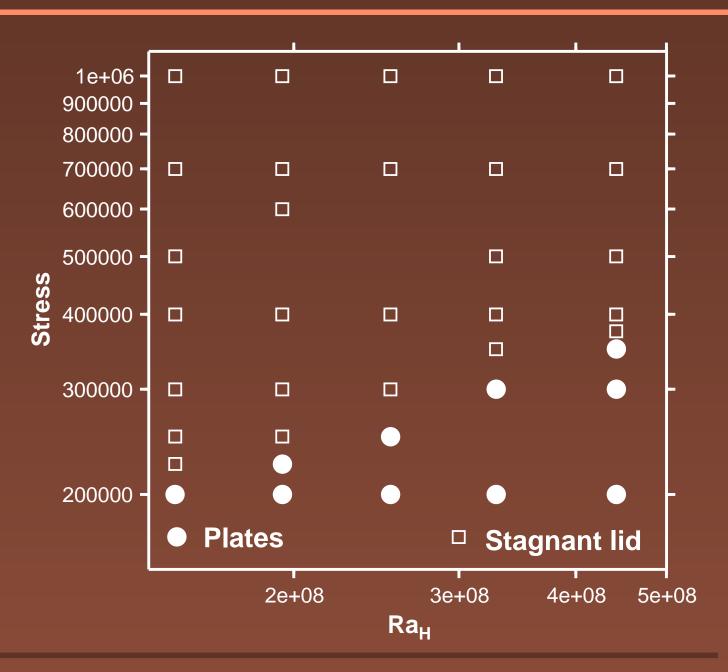


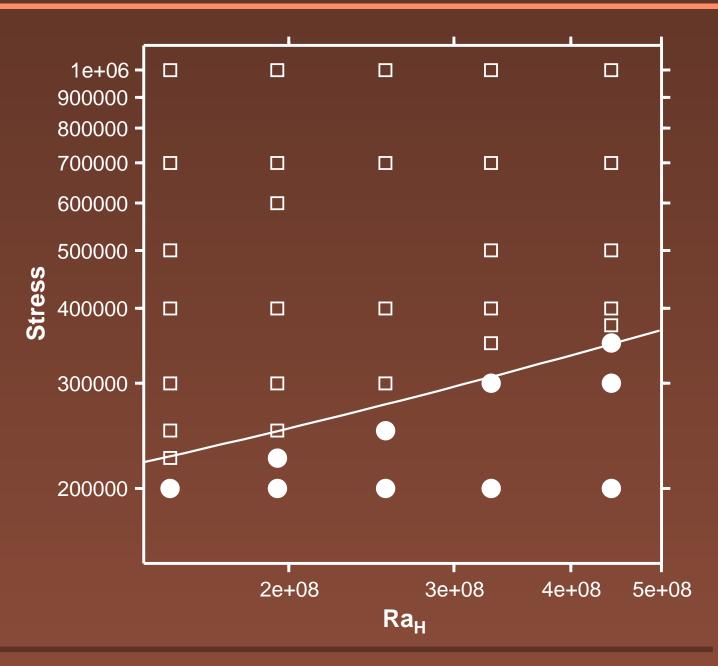


- Viscous temperature scale: $T_i T_c = \gamma \Delta T_{rh}$. (e.g. Davaille and Jaupart, *JGR*, 1994)
- Heat transfer balance: $H = \frac{T_i T_c}{\delta_c} = \frac{T_c T_s}{d_L}$.

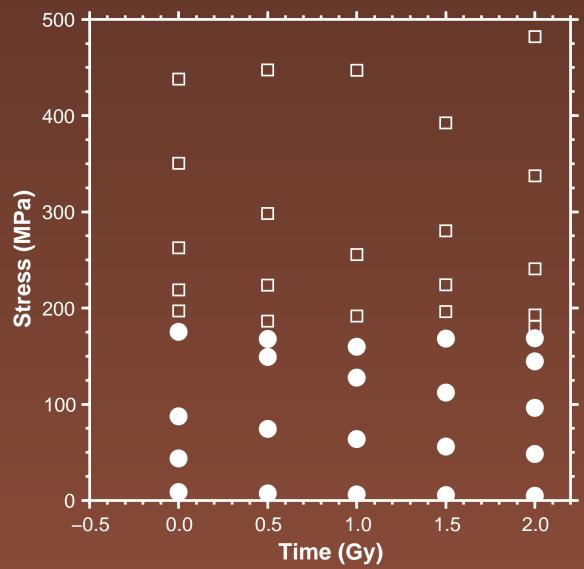


$$| \overline{\sigma_{xx}} = \frac{4}{3} \eta(T_c) \frac{U}{T_c} L H |, \quad \text{with } U, T_c = f(Ra, H, L).$$

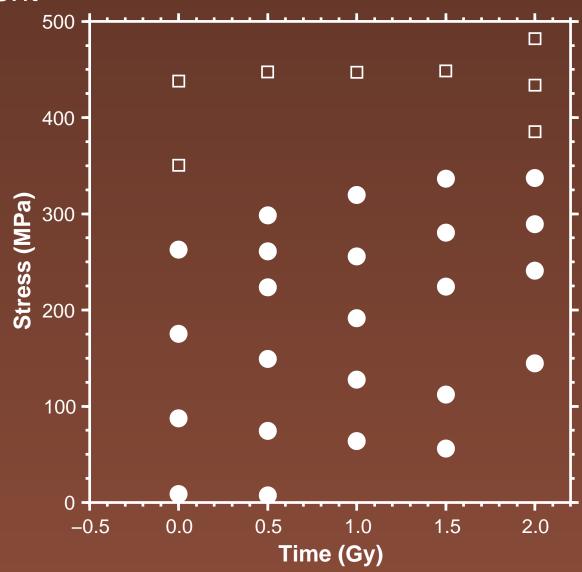




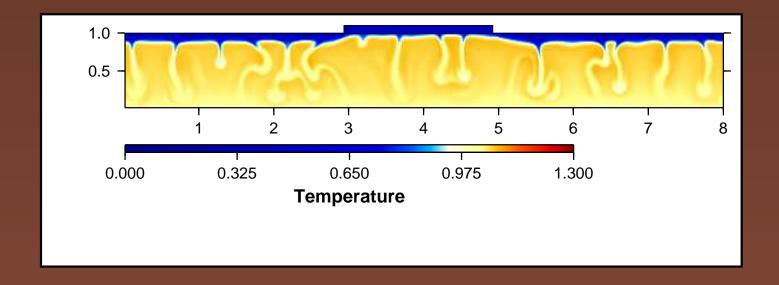
Without continent



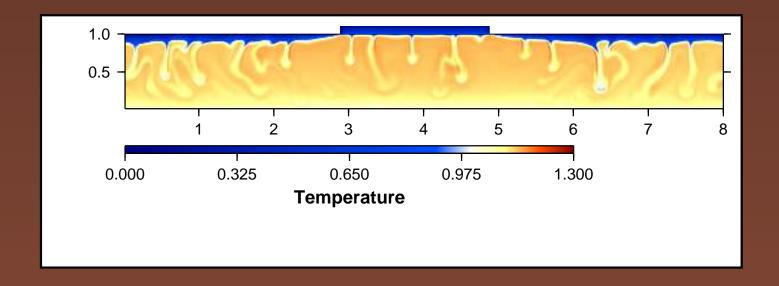
With continent



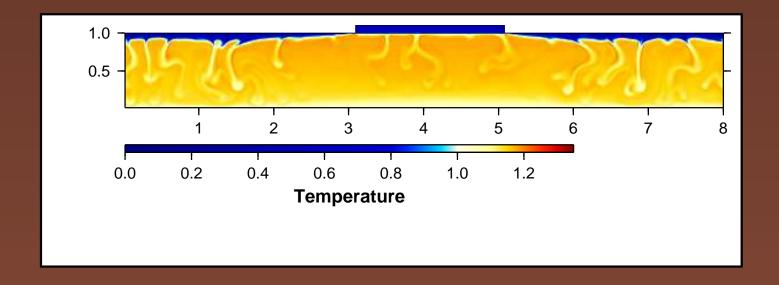
$${\sf Ra} = 7.10^6 \qquad {\sf H} = 22 \quad {\sf t} = 0 \; {\sf Gy}$$



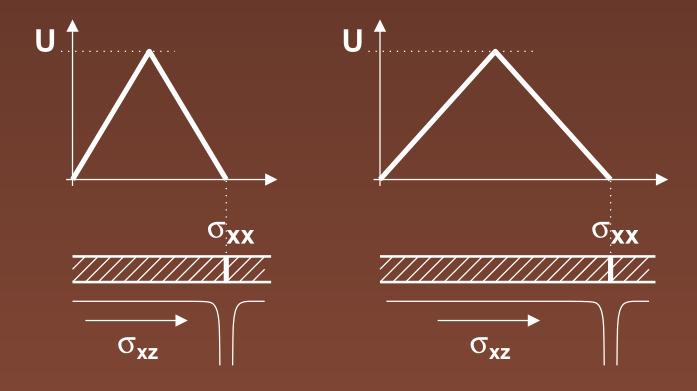
$$Ra = 9.5.10^6$$
 $H = 27$ $t = 1$ Gy



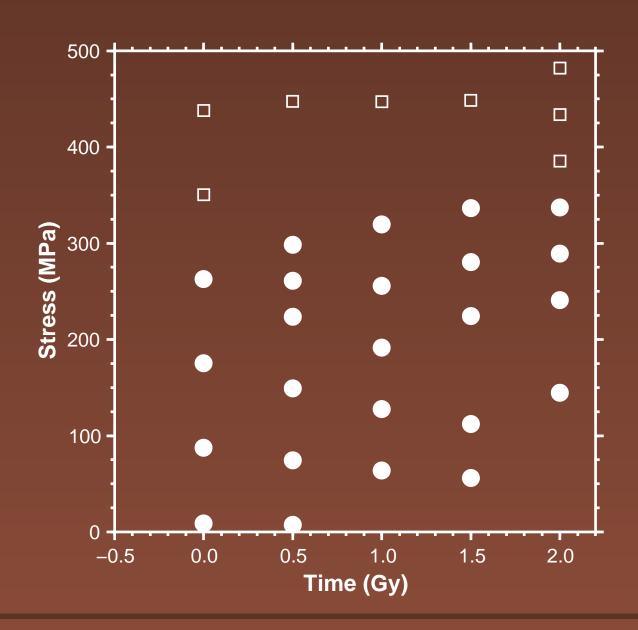
$$Ra = 1.3.10^7$$
 $H = 34$ $t = 2$ Gy



■ Longer wavelength with continent.

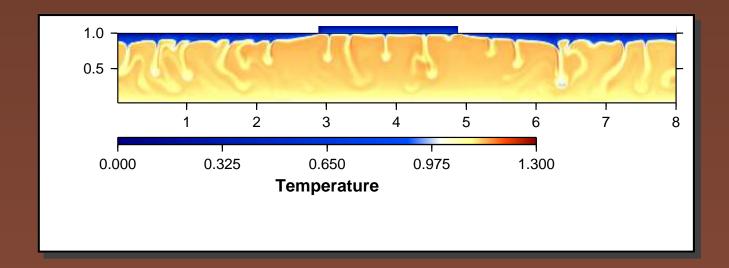


► Viscous drag integrated on longer width.



- Longer wavelength with continent.
- Other effects:
 - Slope in the stagnant lid.
 - Increase in temperature.

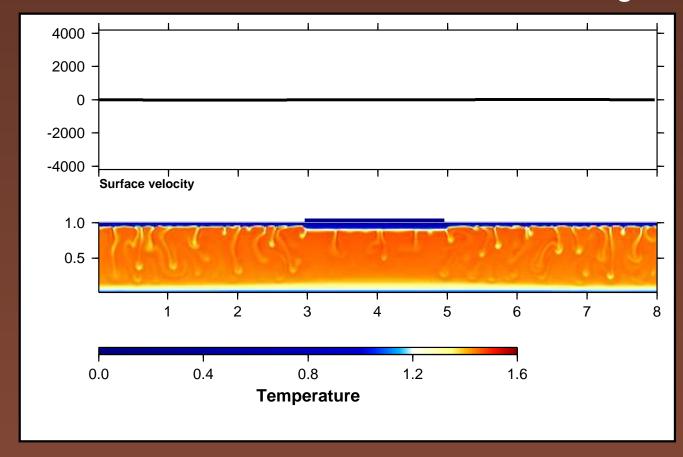
- Longer wavelength with continent.
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 - Slope in the stagnant lid.
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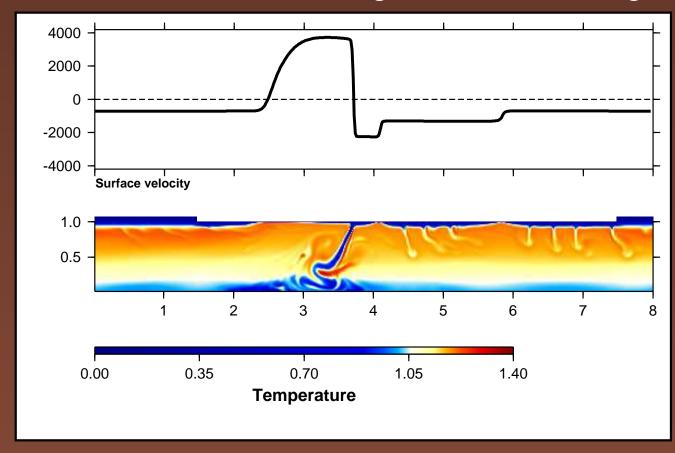
- Longer wavelength with continent.
- Other effects:
 - Slope in the stagnant lid.
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- Continents enhance plate tectonics by modifying the geometry of the flow.

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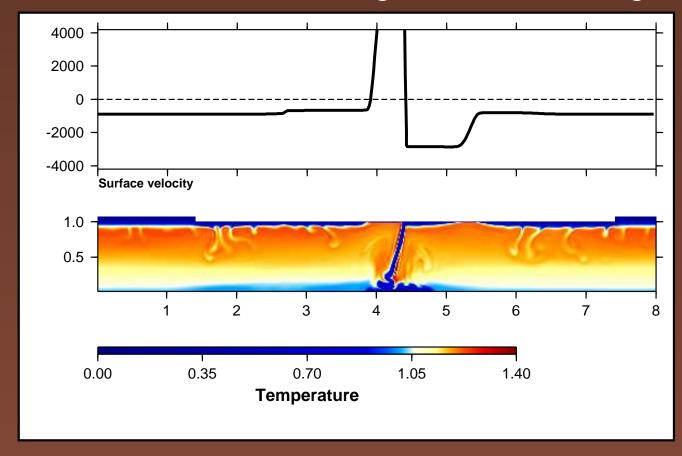
Crust and continental root with low internal heating



Crust and continental root with high internal heating

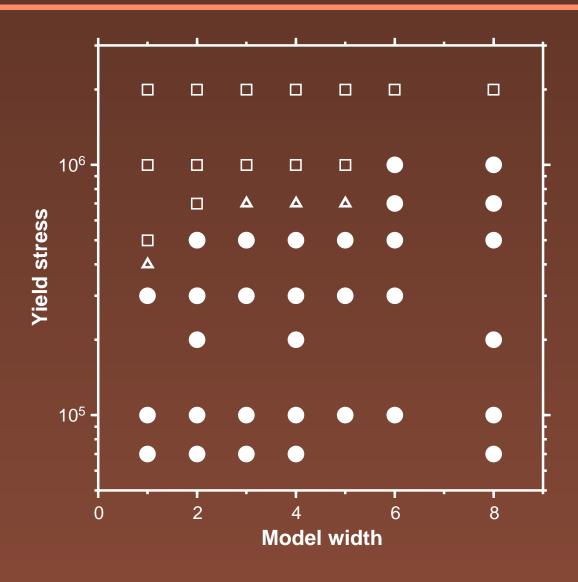


Crust and continental root with high internal heating



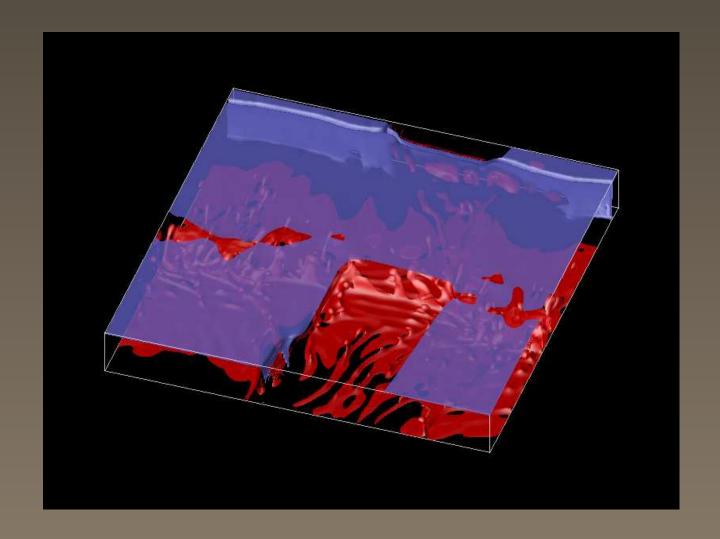
- Plate tectonics is enhanced if continents can provide long wavelength.
- Continental roots do that if the internal heating inside the root is high.

Effect of the box size

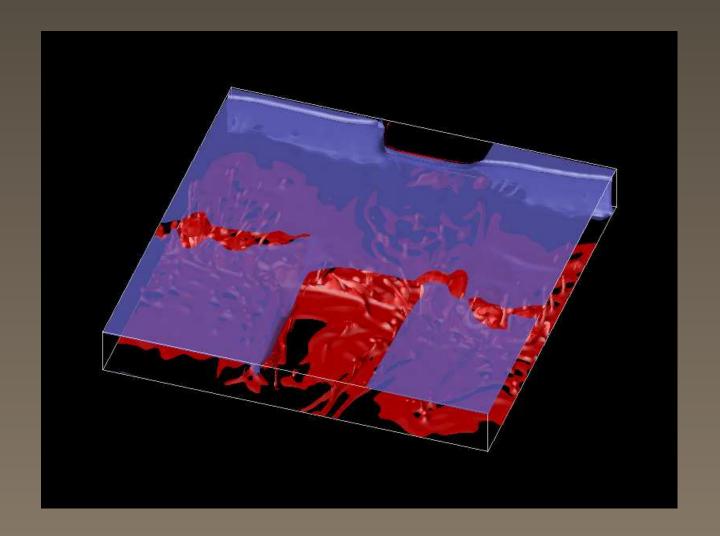


- With models with self-consistent plate tectonics, we can study plate reorganization over time.
- Important time-dependency with the presence of continents.

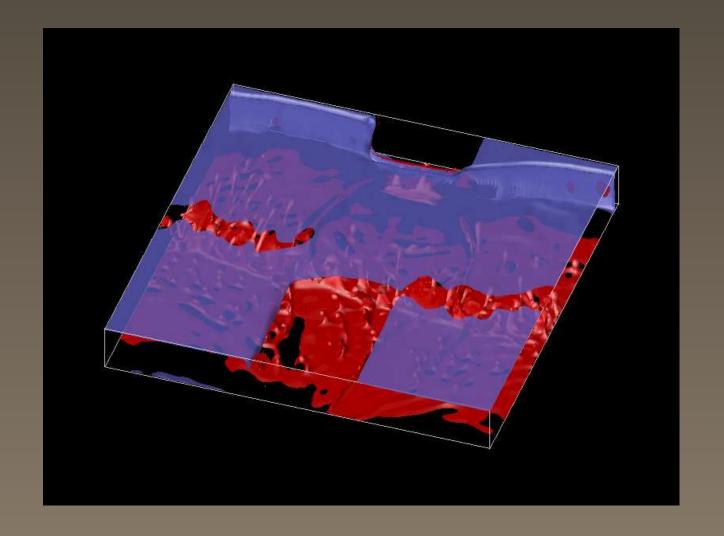
$${
m Ra}=10^7$$
 $\sigma_{
m y}=5.10^5$ Red: T=0.85 - Blue: T=0.35



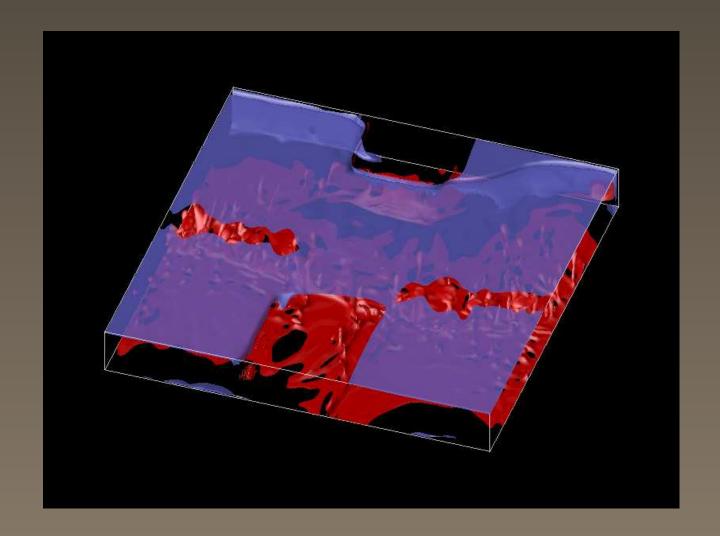
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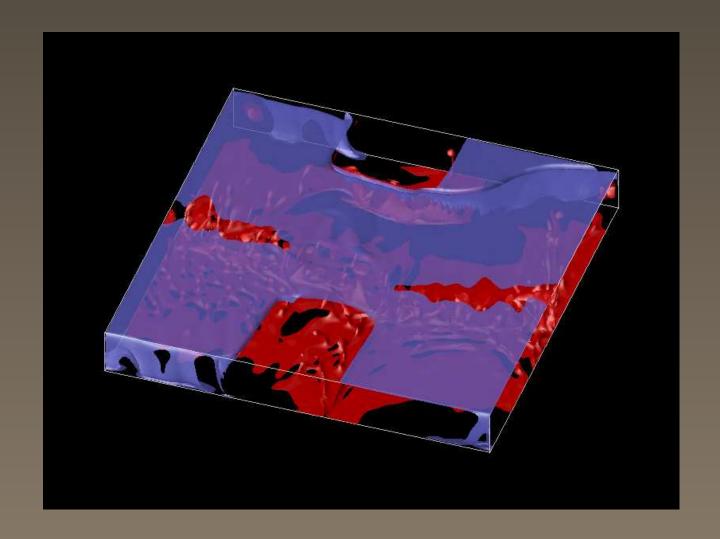
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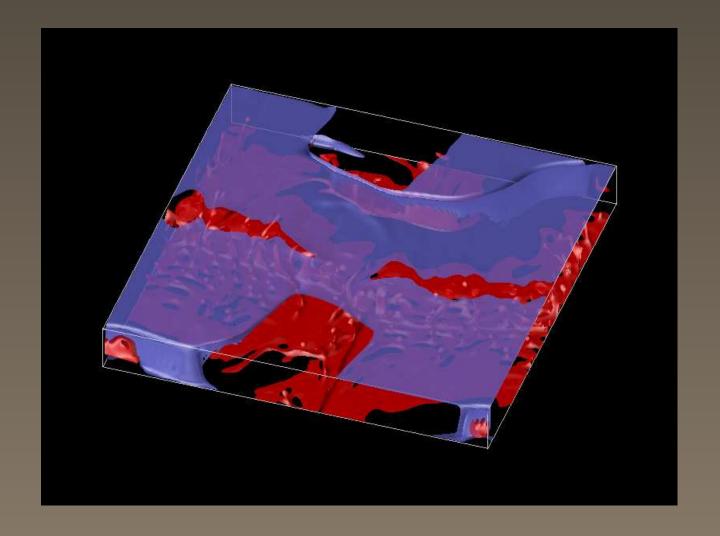
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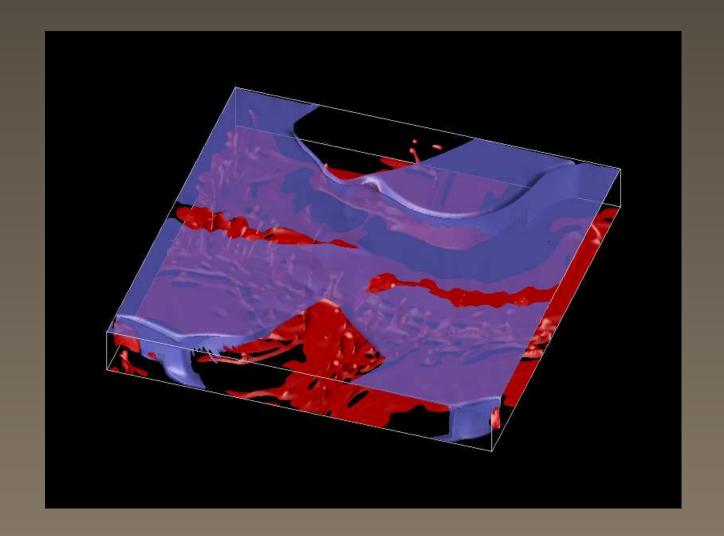
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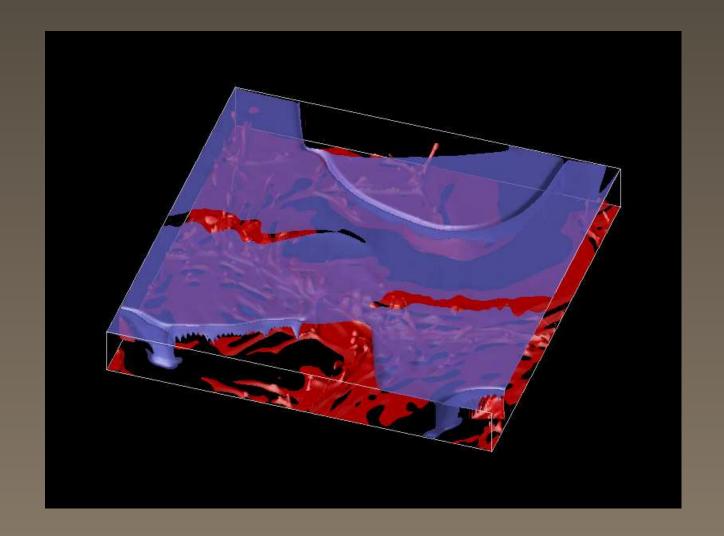
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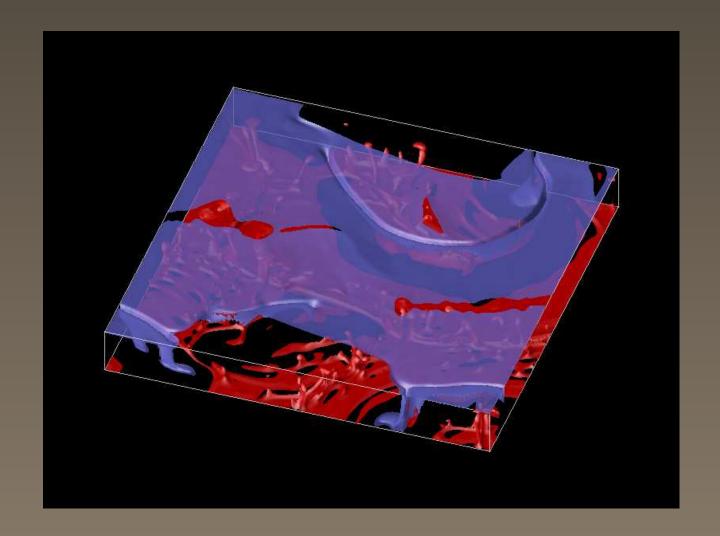
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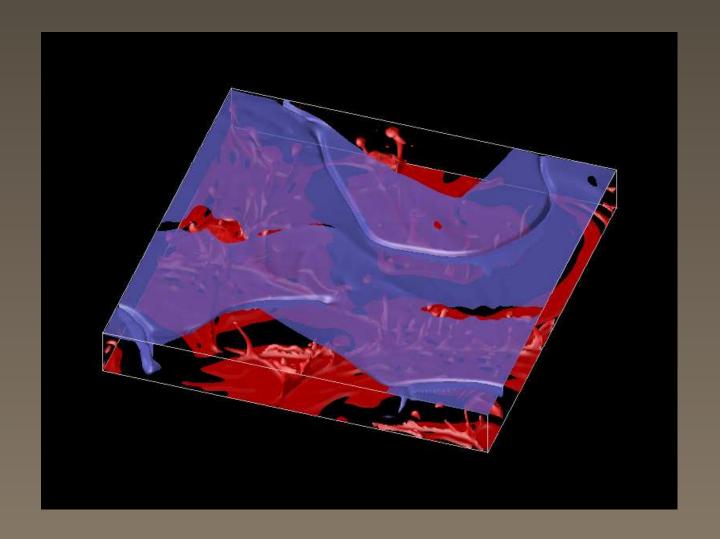
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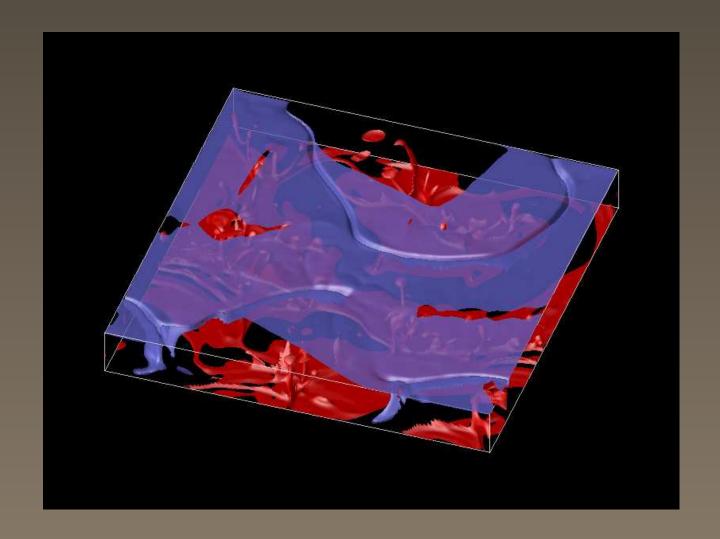
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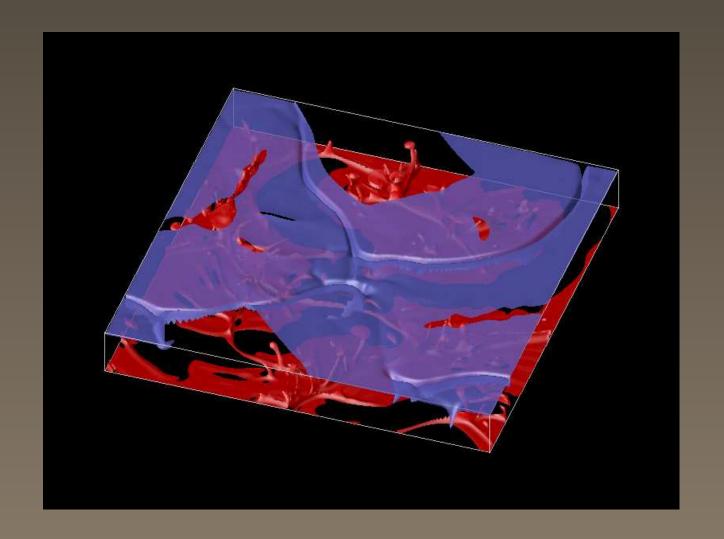
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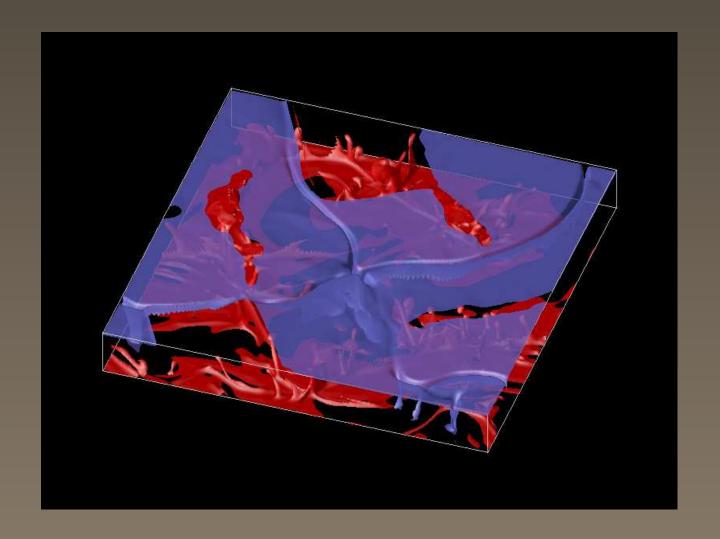
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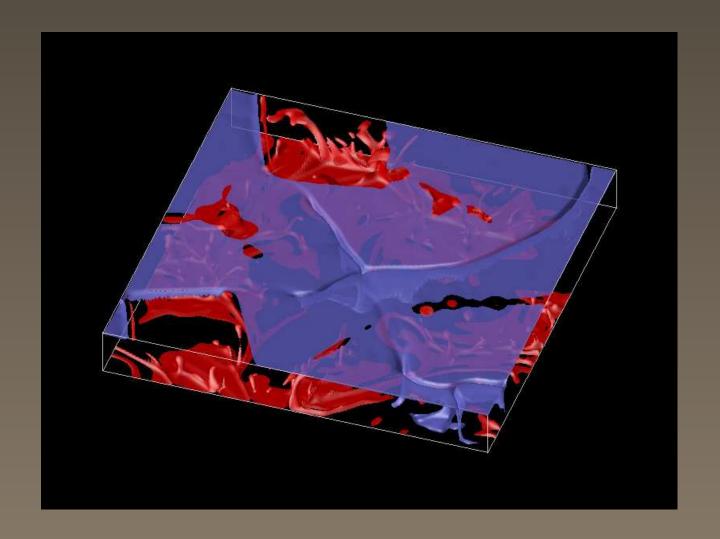
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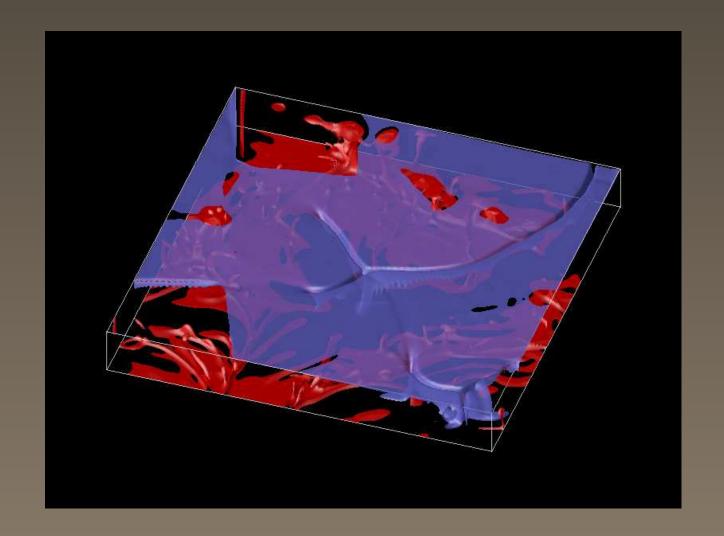
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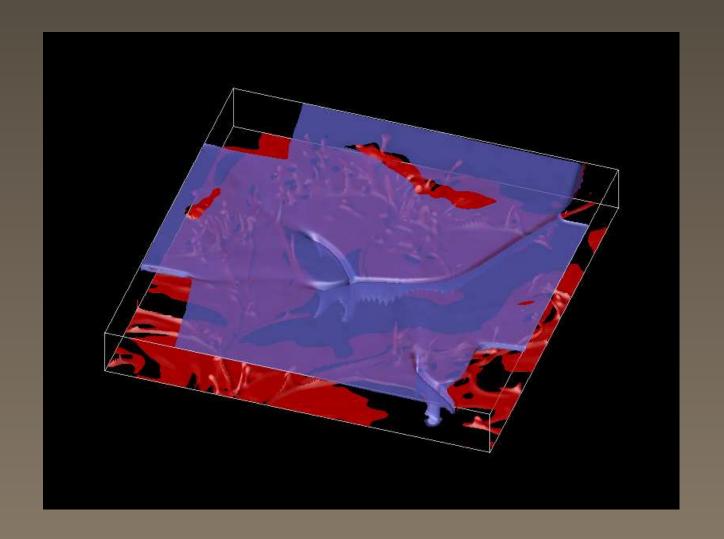
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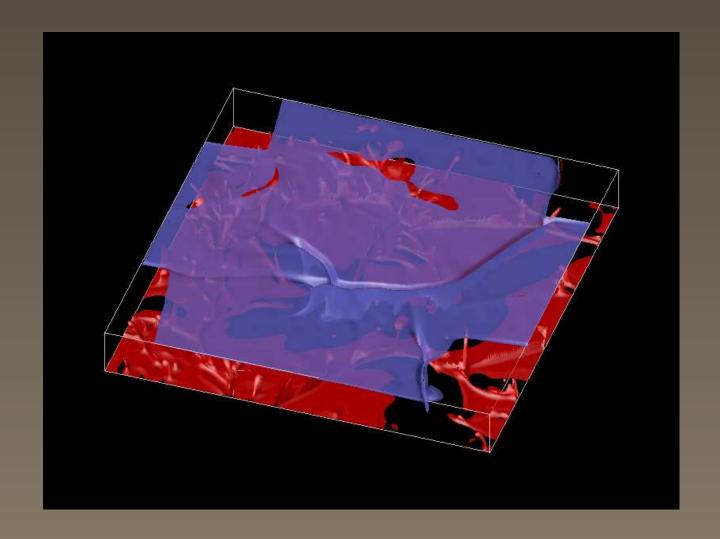
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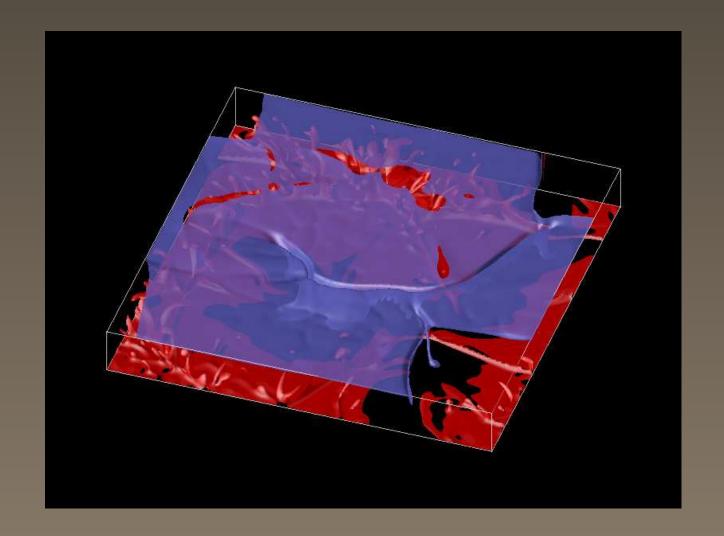
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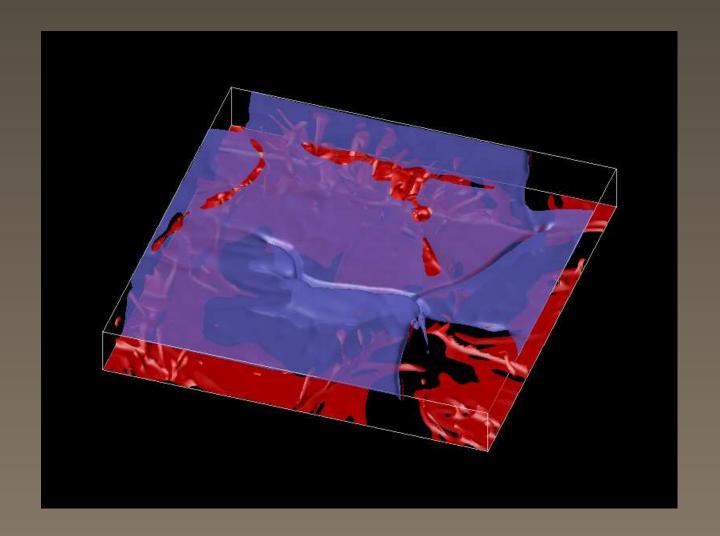
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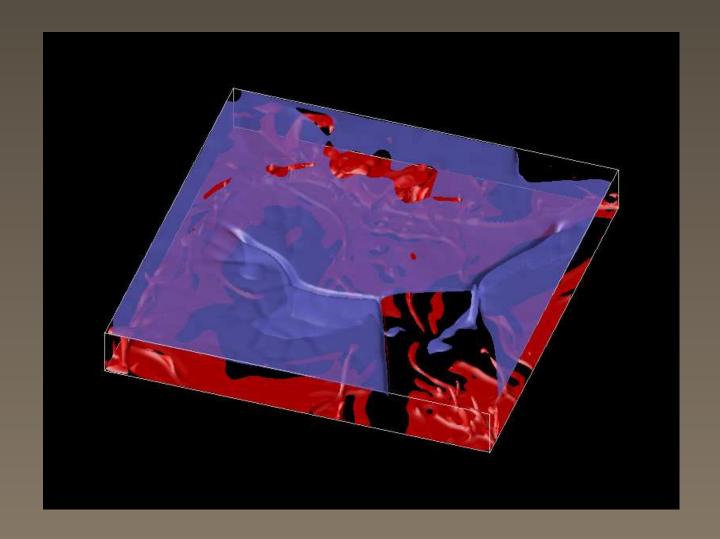
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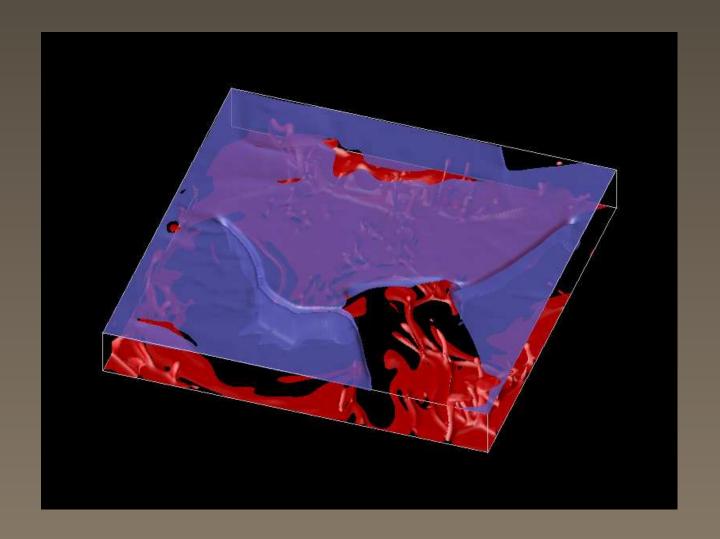
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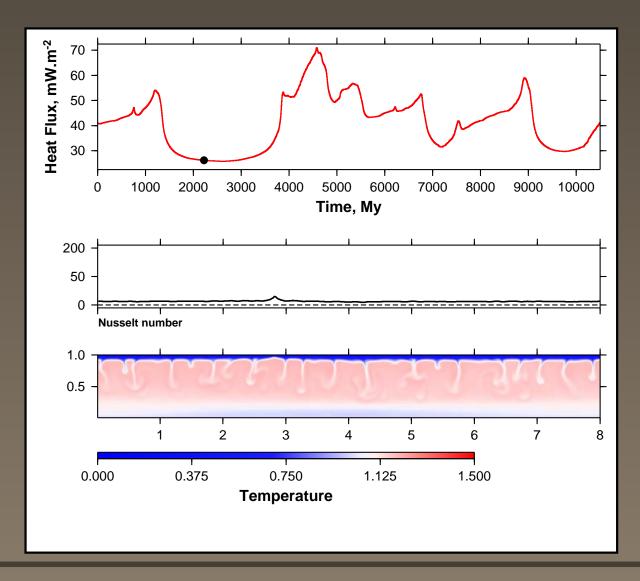


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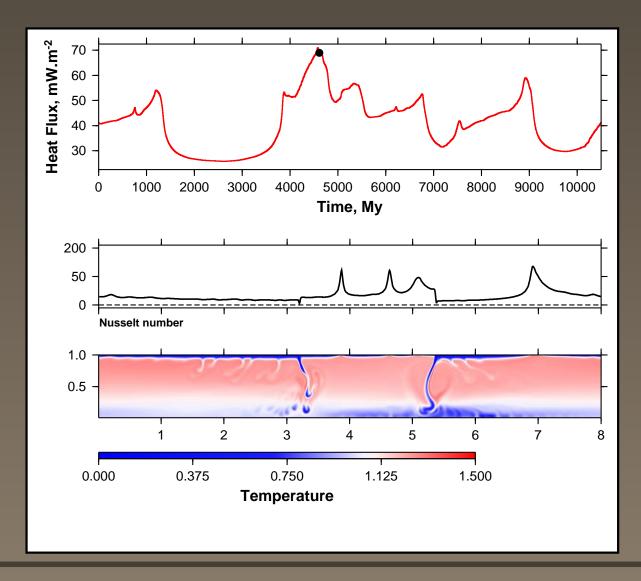


- With models with self-consistent plate tectonics, we can study plate reorganization over time.
- Important time-dependency with the presence of continents.
- ▶ To do with several continents...

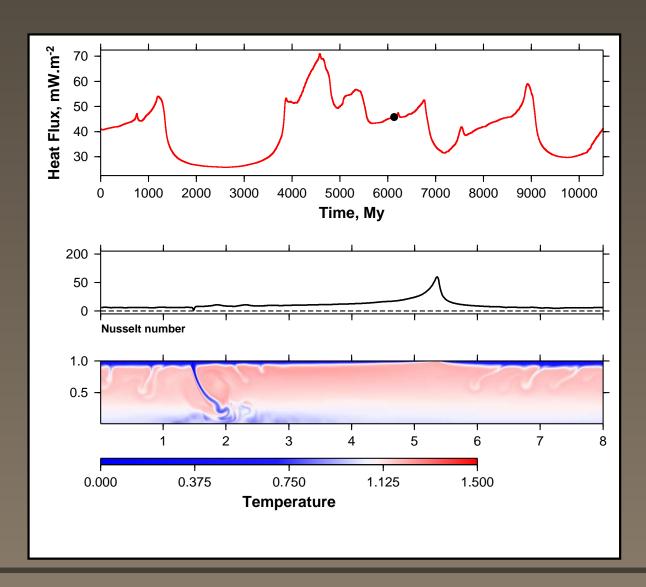
■ Ra = $\overline{7.10^6}$ H = 22 $(1.6.10^{-2} \mu \text{W.m}^{-3})$ $\sigma_{\text{y}} = 2.10^{5} (175 \text{ MPa})$



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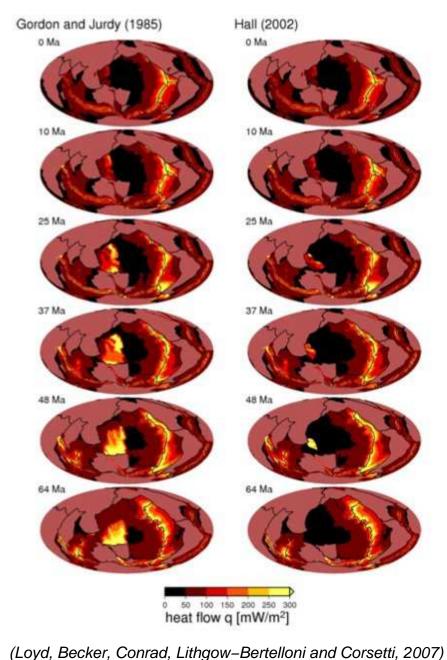


■ Ra =
$$7.10^6$$
 H = $22 (1.6.10^{-2} \mu \text{W.m}^{-3})$ $\sigma_{\text{y}} = 2.10^5 (175 \text{ MPa})$



- Non-monotonicity of plate tectonics and mantle dynamics.
- ► Influence on mantle thermal history. (Grigné et al., JGR, 2005; Gait and Lowman, GJI, 2007; Loyd et al., PNAS, 2007)
 - Geochemical record of this non-monotonic trend.
 (Parman et al., Nature, 2005; Pearson et al., Nature, 2007)

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 - Geochemical record of this non-monotonic trend.
 (Parman et al., Nature, 2005; Pearson et al., Nature, 2007)

- Method used here: viscoplastic rheology yield stress.
- The physics of damage with our approach is somewhat prescribed rather than described (Bercovici, *EPSL*, 2003). To include:
 - Grain size reduction.
 - Healing (grain growth).
 - Incorporation of volatiles.
 - Viscous heating.
 - ...

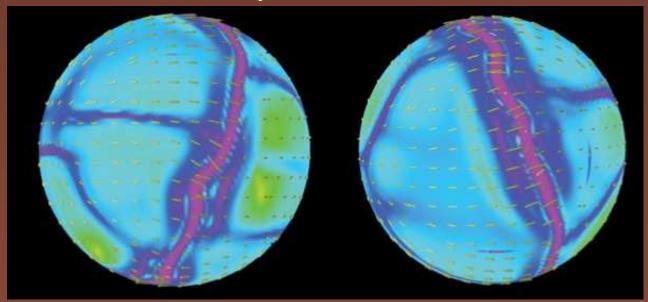
(Two-phase damage theory: e.g. Ricard and Bercovici, *GJI*, 2003; Bercovici and Ricard, *JGR*, 2005)

Another parametrization of yielding? (L.Moresi' talk)

- The effect of the wavelength/geometry of the flow is primordial.
- The Earth is a spherical object.

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- The Earth is a spherical object.

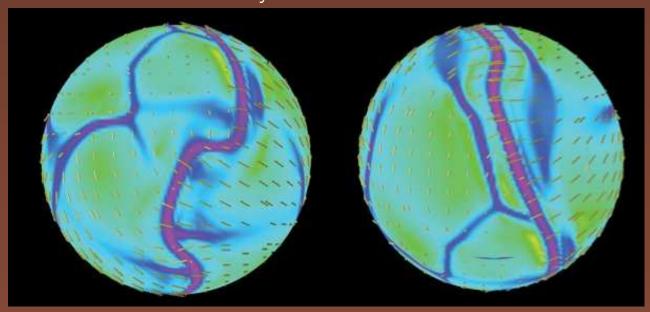
$$\sigma_{\mathsf{y}} = 17 \; \mathsf{MPa}$$



(Models of Hein van Heck. ETH Zürich. Poster)

- The effect of the wavelength/geometry of the flow is primordial.
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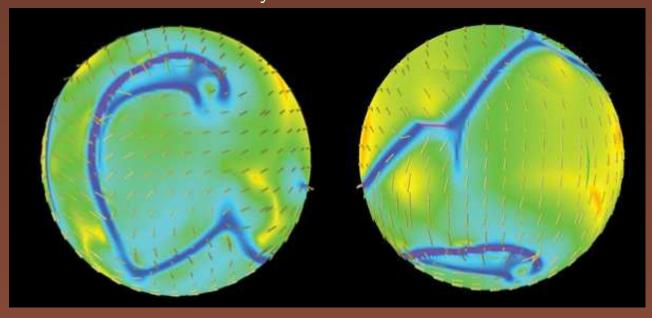
$$\sigma_{\rm y}=34~{
m MPa}$$



(Models of Hein van Heck. ETH Zürich. Poster)

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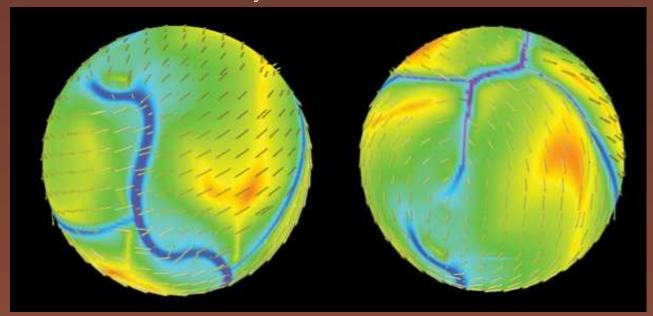
$$\sigma_{\rm v}=69~{
m MPa}$$



(Models of Hein van Heck. ETH Zürich. Poster)

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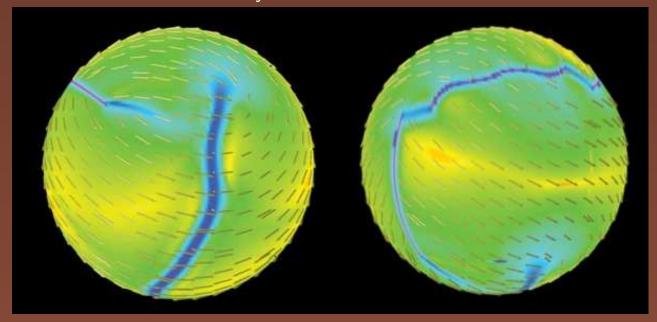
$$\sigma_{\mathsf{y}} = 103 \; \mathsf{MPa}$$



(Models of Hein van Heck. ETH Zürich. Poster)

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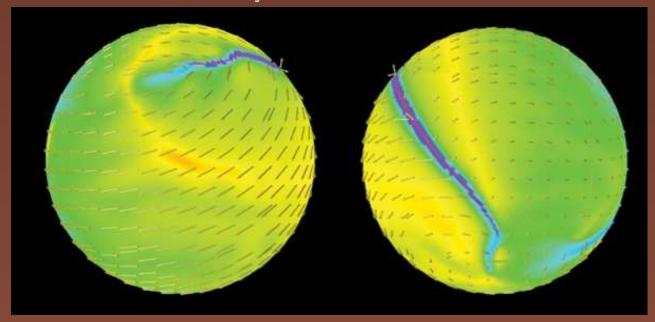
$$\sigma_{\mathsf{y}} = 120 \; \mathsf{MPa}$$



(Models of Hein van Heck. ETH Zürich. Poster)

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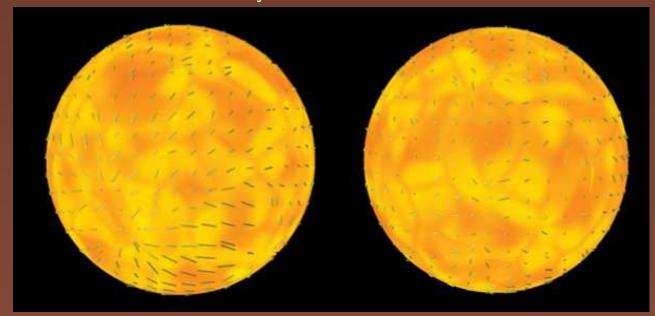
$$\sigma_{\rm y}=243~{
m MPa}$$



(Models of Hein van Heck. ETH Zürich. Poster)

- The effect of the wavelength/geometry of the flow is primordial.
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$$\sigma_{\rm v}=340~{
m MPa}$$



(Models of Hein van Heck. ETH Zürich. Poster)

Final remark

➤ Why is there plate tectonics on Earth and not on other terrestrial planets?

Final remark

- Why is there plate tectonics on Earth and not on other terrestrial planets?
 - Is the Earth less strong than other planets?
 - \rightarrow Effect of water.
 - → Shouldn't it break more?
 - Is there something on Earth that makes it more 'stressed' than other planets?
 - → Effect of heterogeneities.
 - → Something that changes the geometry of the flow?