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Advanced School on Scaling Laws in Geophysics: Mechanical and Thermal Processes in Geodynamics

23 May - 3 June, 2011

Small-scale convection beneath oceanic and continental lithosphere
(Sub-lithospheric small-scale convection)

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Sub-lithospheric small-scale convection

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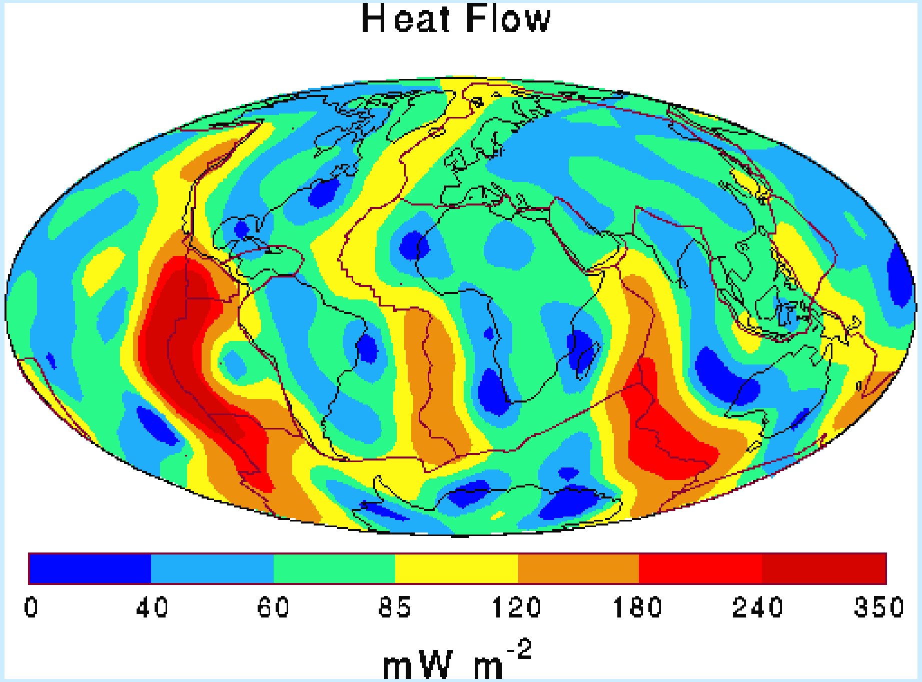
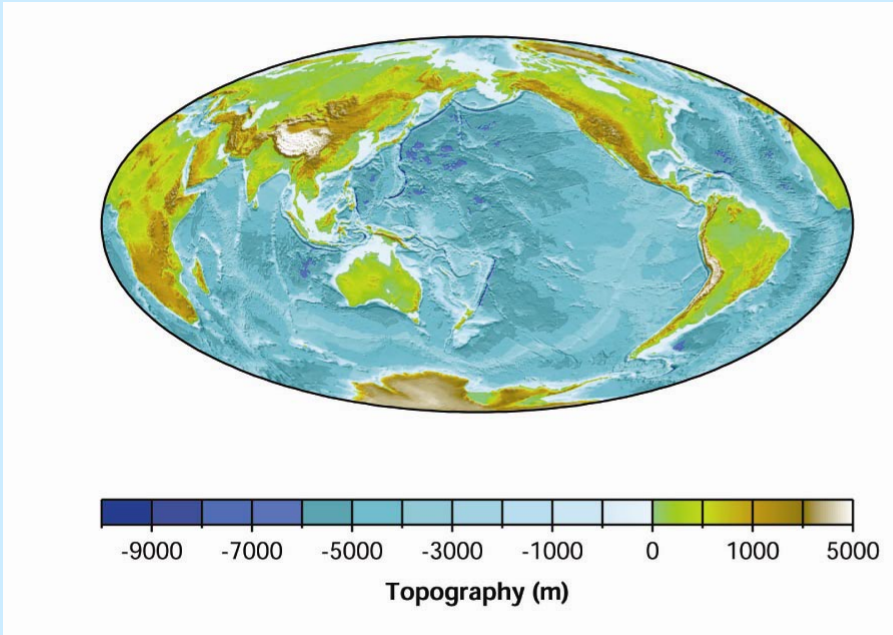
ICTP Advanced School on Scaling Laws in Geophysics
6/2, 2011

Earth's Surface Heat Flux and Topography



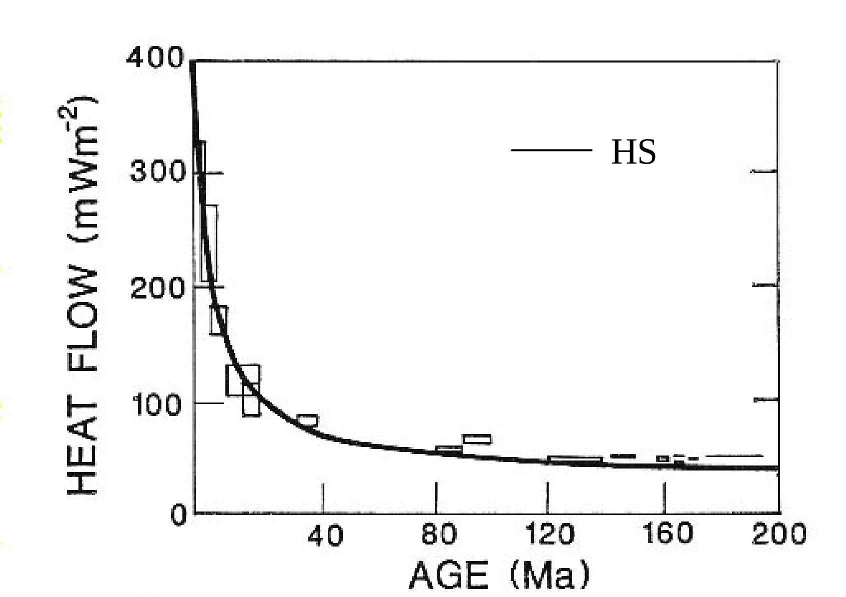
Pollack et al., 1993

Topography



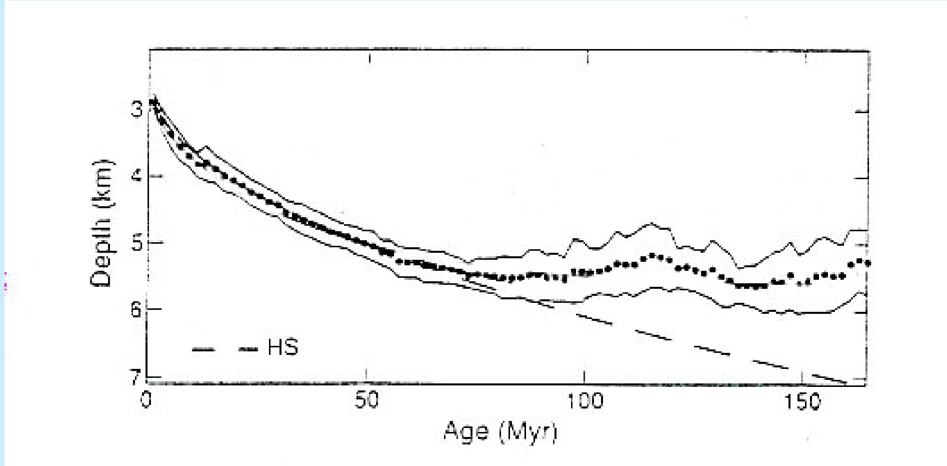
Age-dependent Heat Flux and Ocean Depth

Heat Flux



Lister et al., 1991

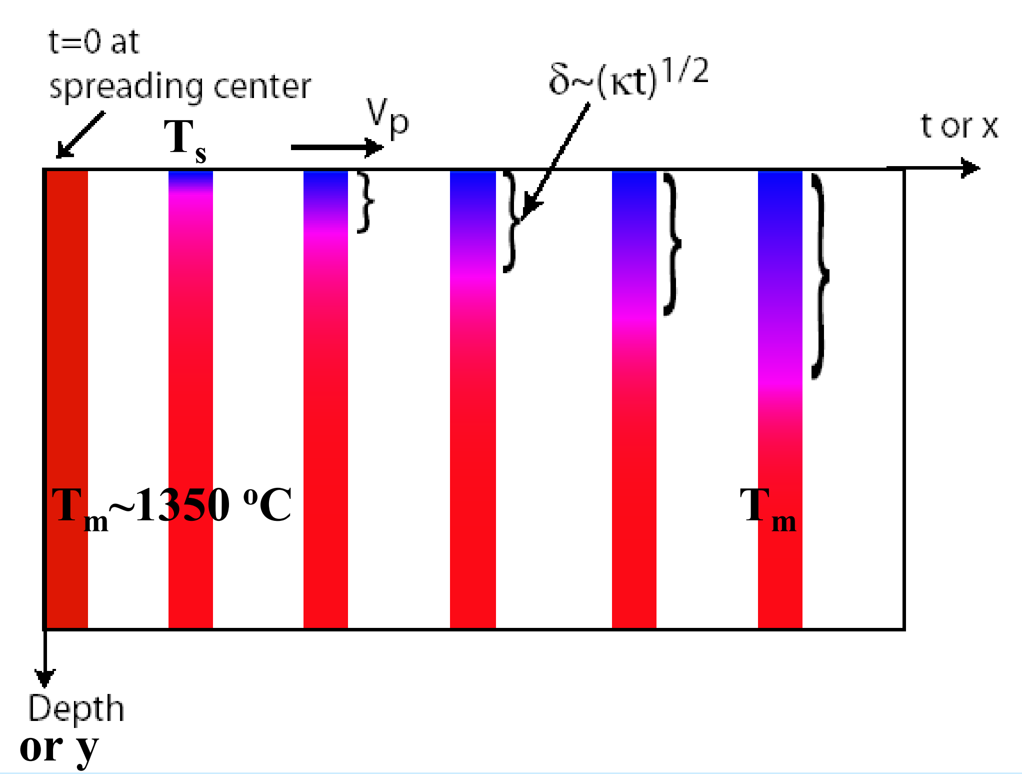
Ocean Depth



Stein & Stein, 1992

A Simple Model for Age-dependent Topography and Heat Flux (a half-space cooling model)

- *Conductive cooling of oceanic lithosphere as it moves away from the spreading centers [Turcotte & Oxburgh, 1967].*



Temperature:

$$T = T_s + (T_m - T_s)\,\mathrm{erf}[y/(4\kappa t)^{1/2}]$$

Heat flux:

$$Q_s \sim (T_m - T_s)/\delta$$

or $Q_s = k(T_m - T_s)/(\kappa t)^{1/2}$

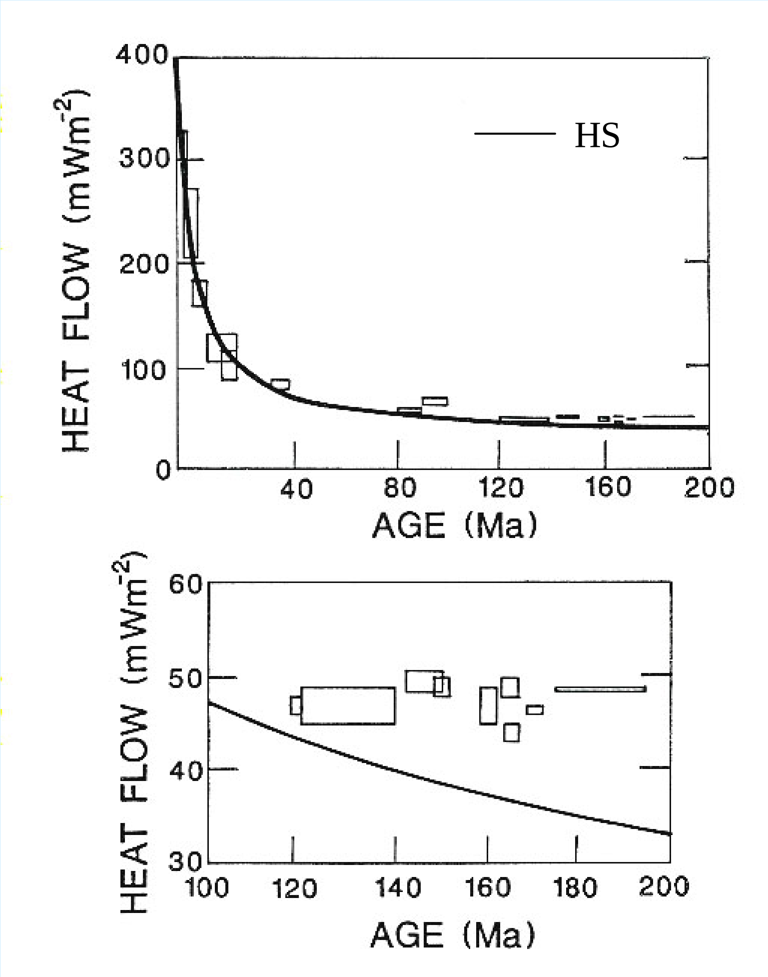
Topography:

$$w = 2b\alpha(T_m - T_s)(\kappa t/\pi)^{1/2}$$

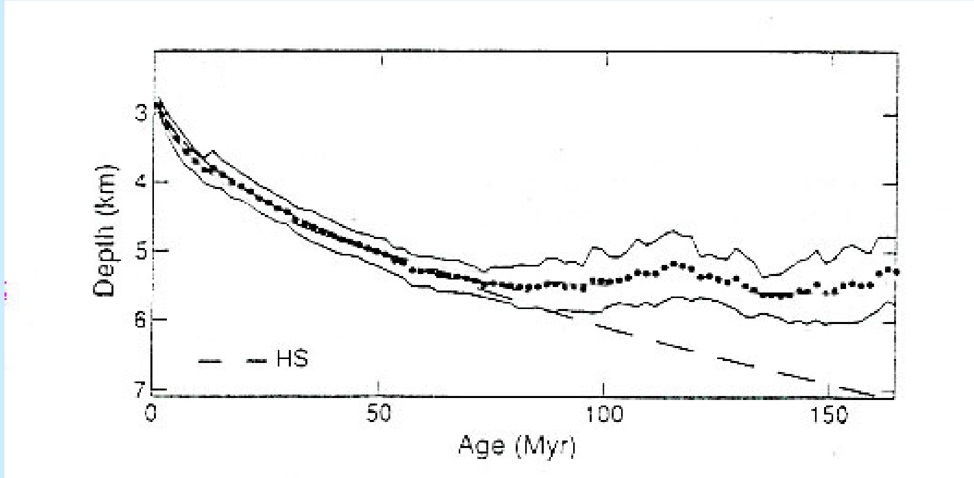
where $b = \rho_m/(\rho_m - \rho_w)$

Deviations from the Half-space Cooling Model at Old Seafloor

Heat Flux



Ocean Depth

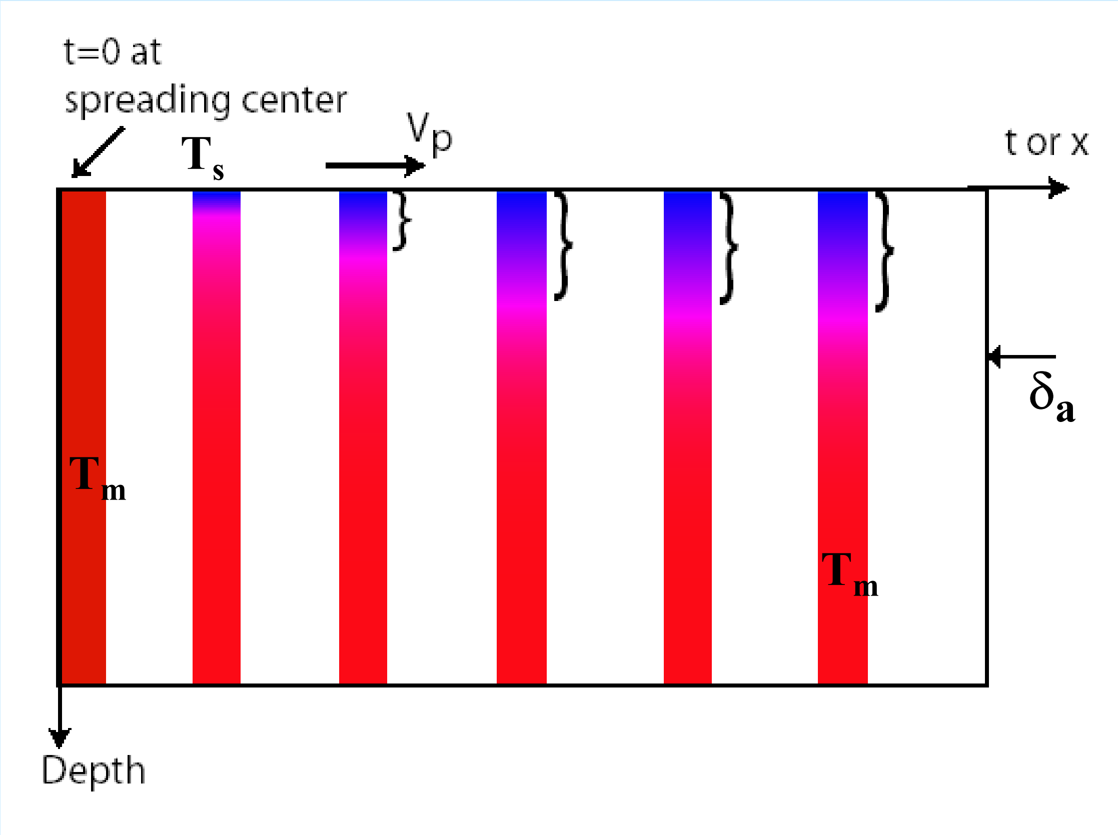


Stein & Stein, 1992

Lister et al., 1991

The Plate Model – a model to fit the data

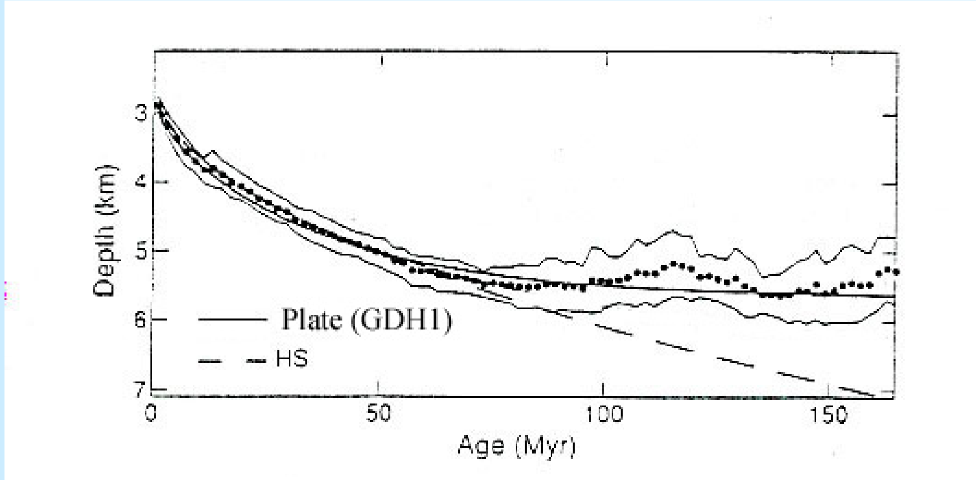
[Parsons & Sclater, 1977; Parsons & McKenzie, 1978]



There is an upper limit on δ, δ_a. And the cooling never reaches to depth of δ_a.

Improved Fit from the Plate Model

Ocean Depth

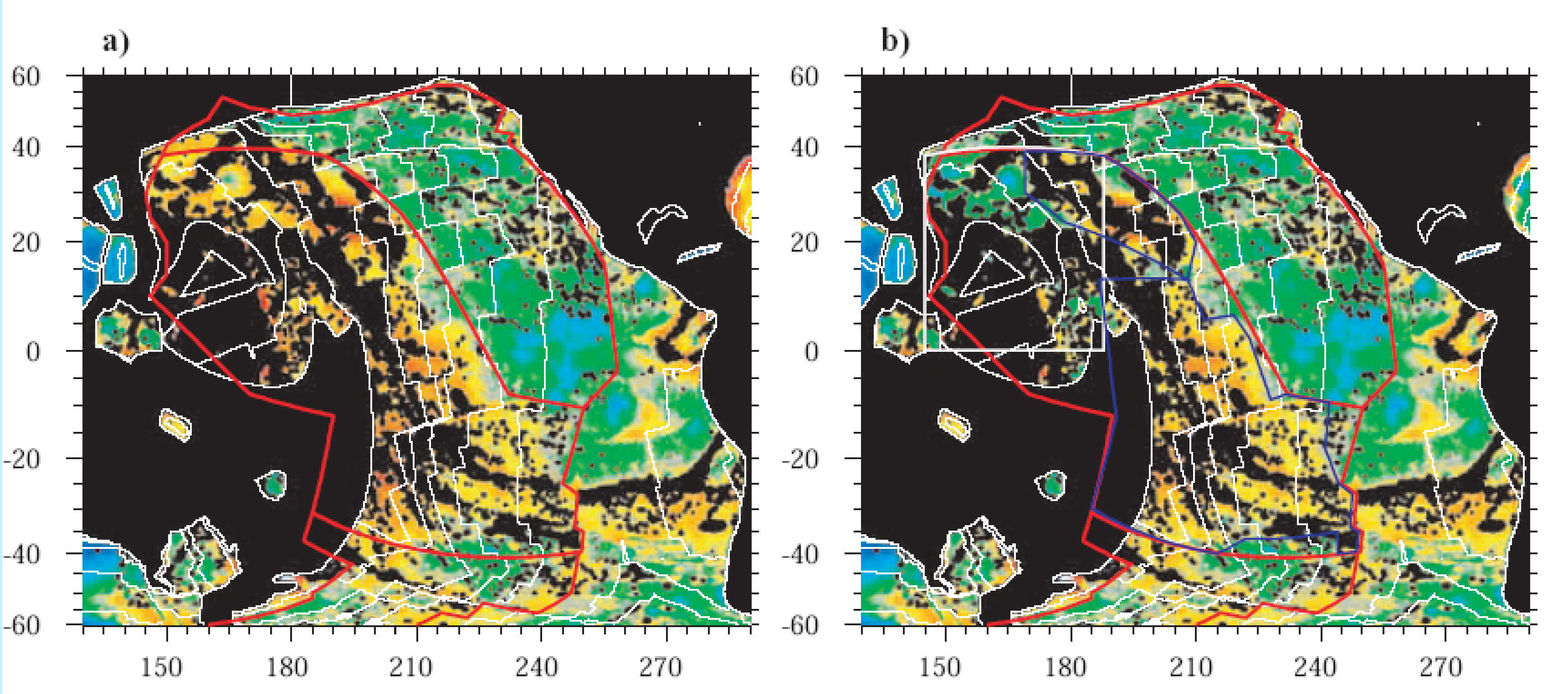


Stein & Stein, 1992

An empirical model!

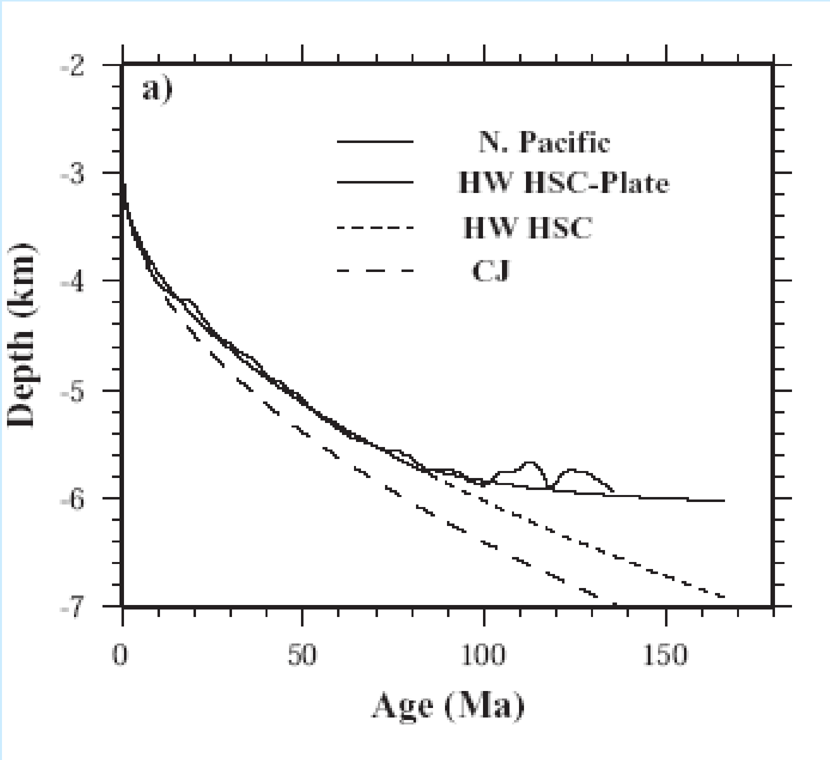
Age is not the only control!

Residual topography – role of mantle upwellings



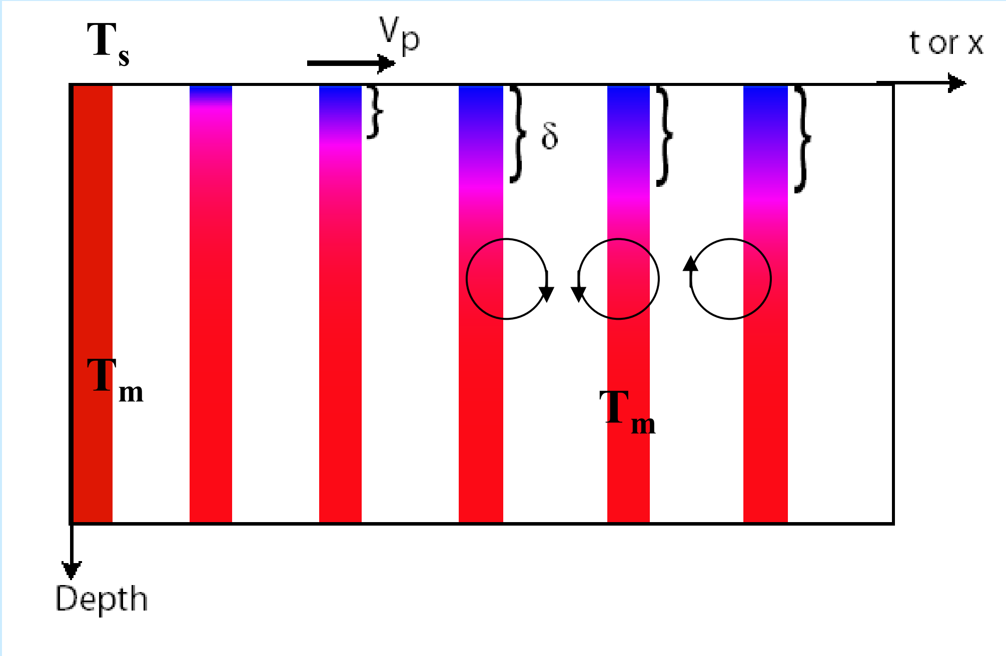
Zhong et al., 2007

However, upwellings may not the only control either.



Zhong et al., 2007

Small-scale Convection (SSC) Below Old Oceanic Lithosphere -- Physical Basis for the Plate Model

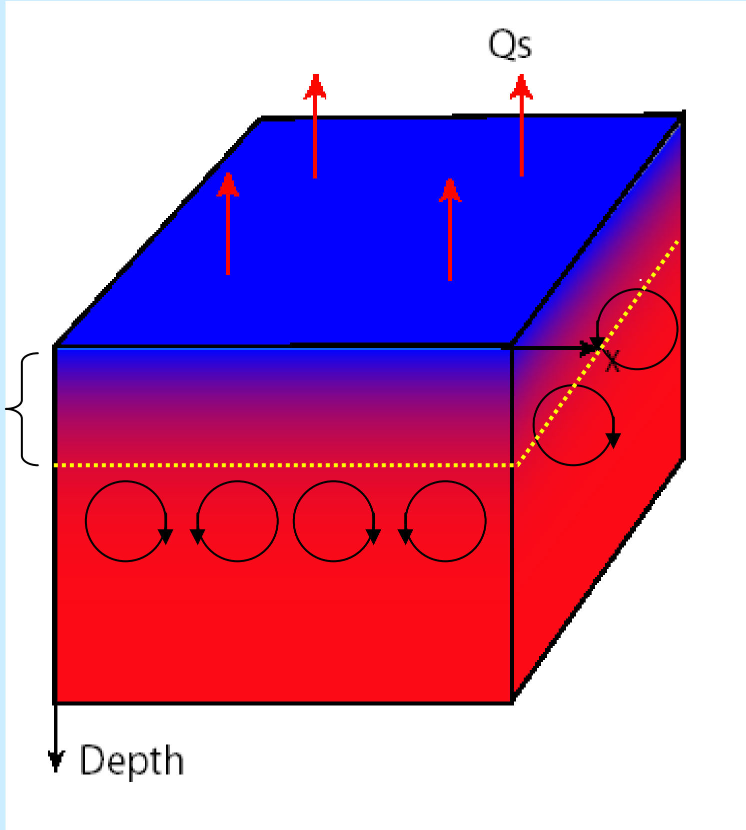


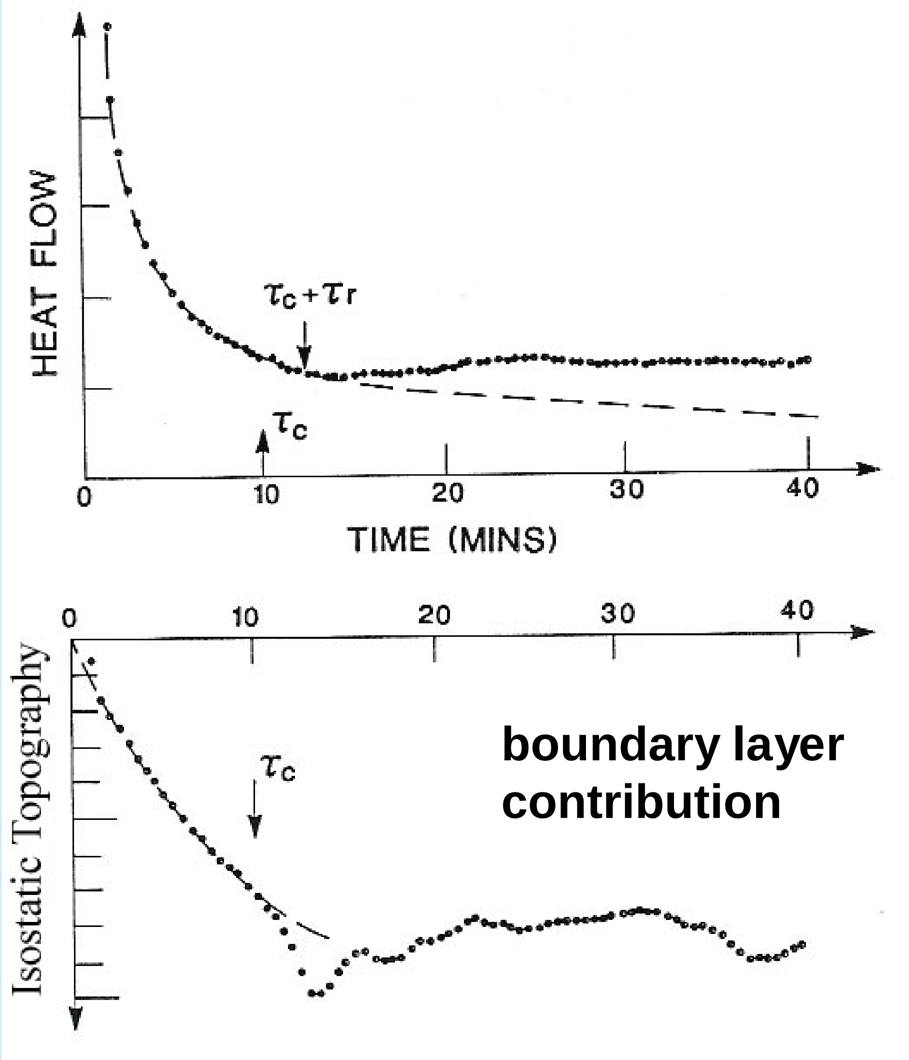
$\delta \sim (\kappa t)^{1/2}$

Rayleigh number: $Ra = \rho g \alpha (T_m - T_s) \delta^3 / (\kappa \eta)$

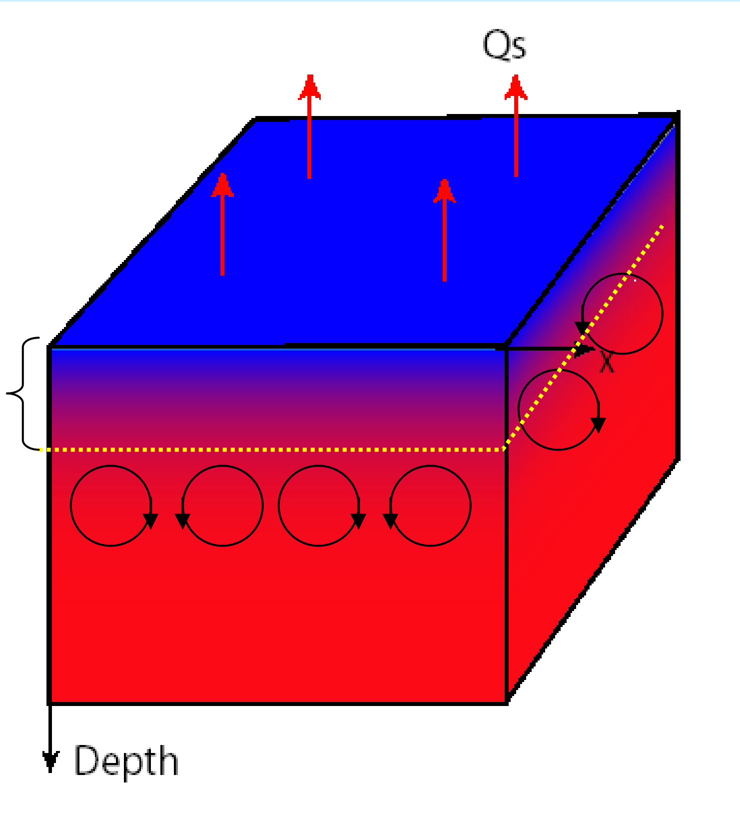
As t increases, δ and Ra increase. When $Ra > Ra_{cr}$, the thermal boundary layer goes unstable and thermal convection starts to happen.

Tank Experiments for Fluids Cooled from Above [Davaille & Jaupart, 1994]





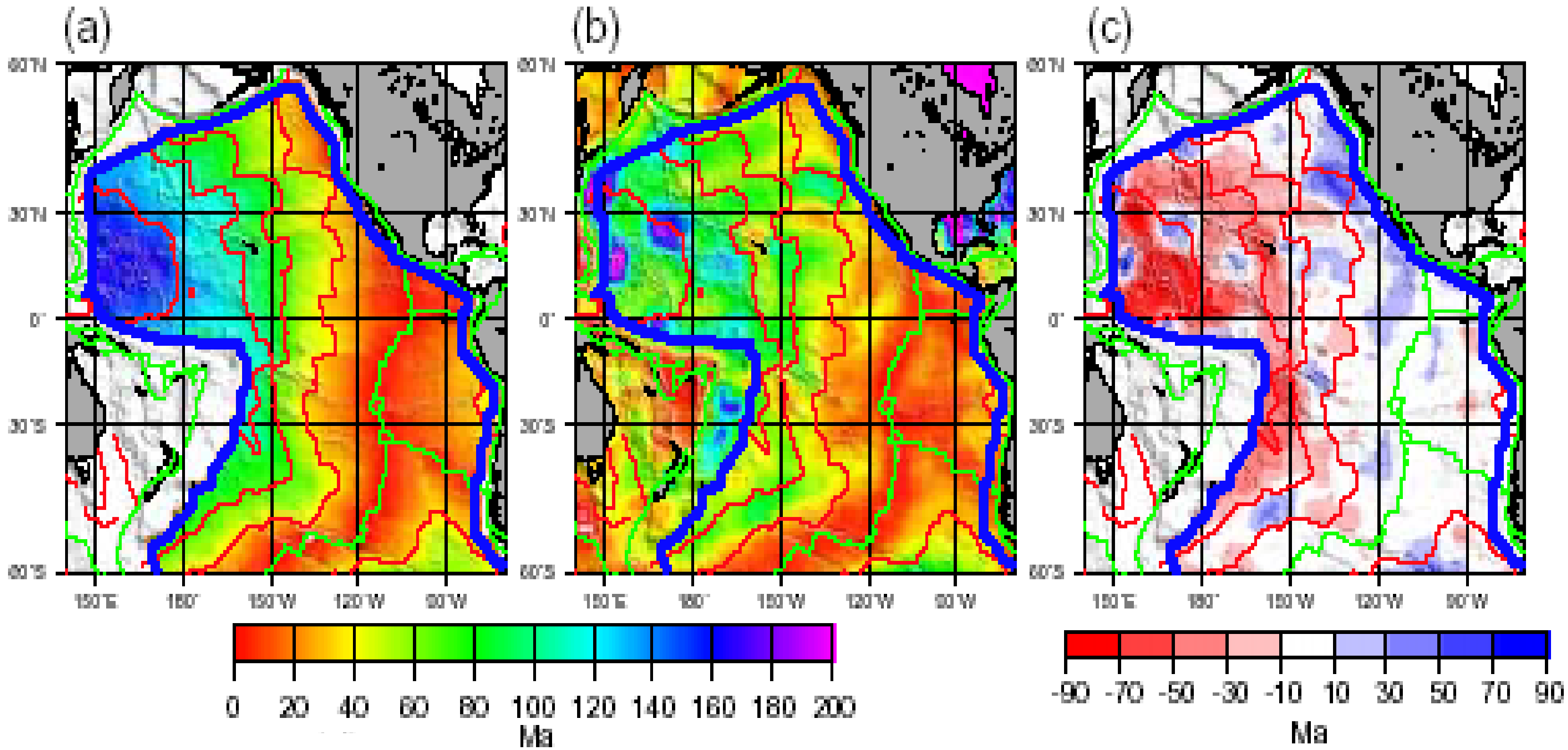
Does Small-scale Convection (SSC) Lead to Reduced Topography?



Increased topography from SSC as argued by O'Connell and Hager [1981] and Davies [1988, 1999].

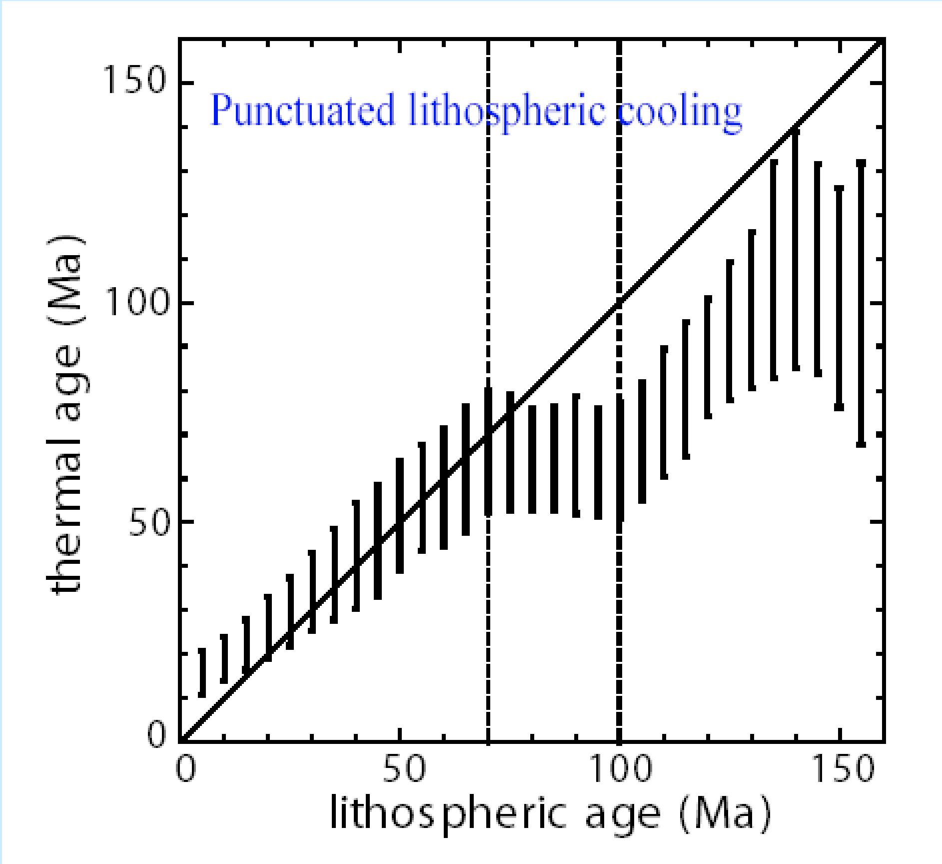
SSC may reheat the lithosphere but it also enhances the cooling of the mantle interior.

Apparent Thermal Age From Surface Wave Tomography



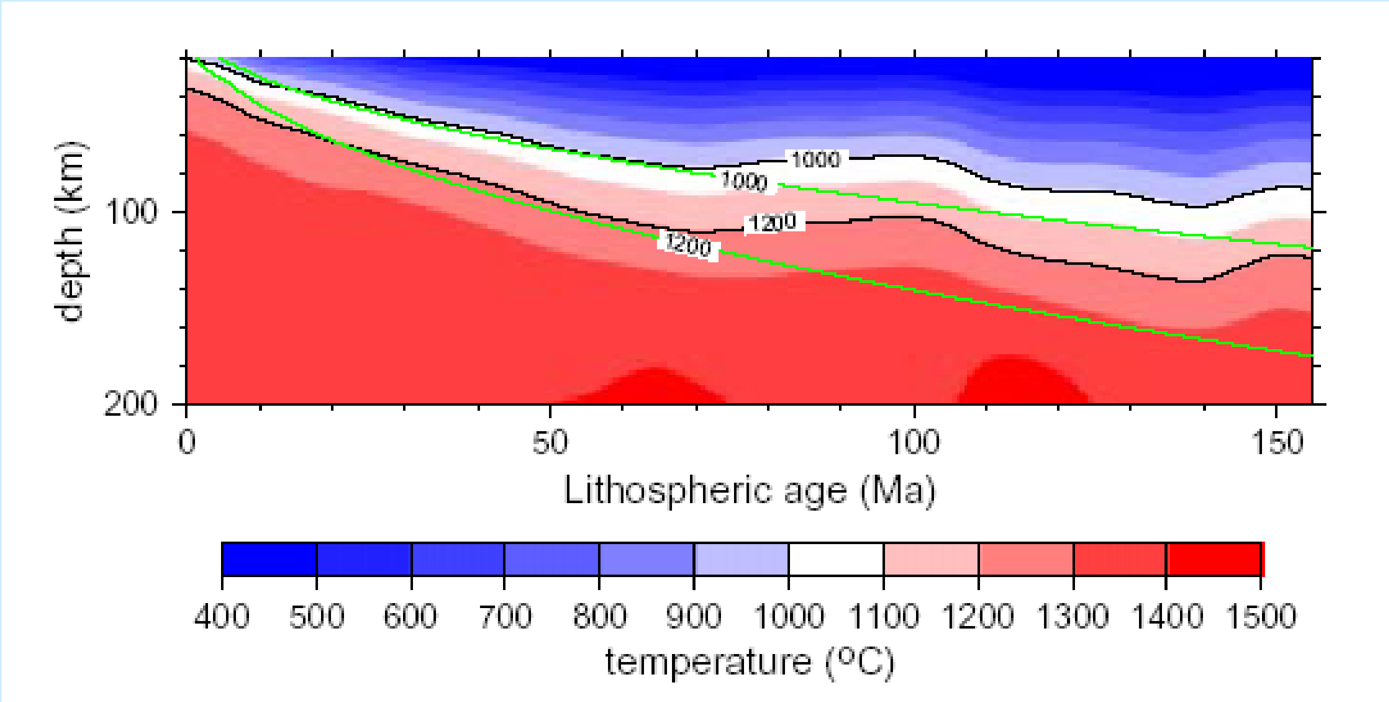
Ritzwoller et al, 2004

Thermal Age vs Lithospheric Age



Ritzwoller et al, 2004

Lithospheric Thermal Structure



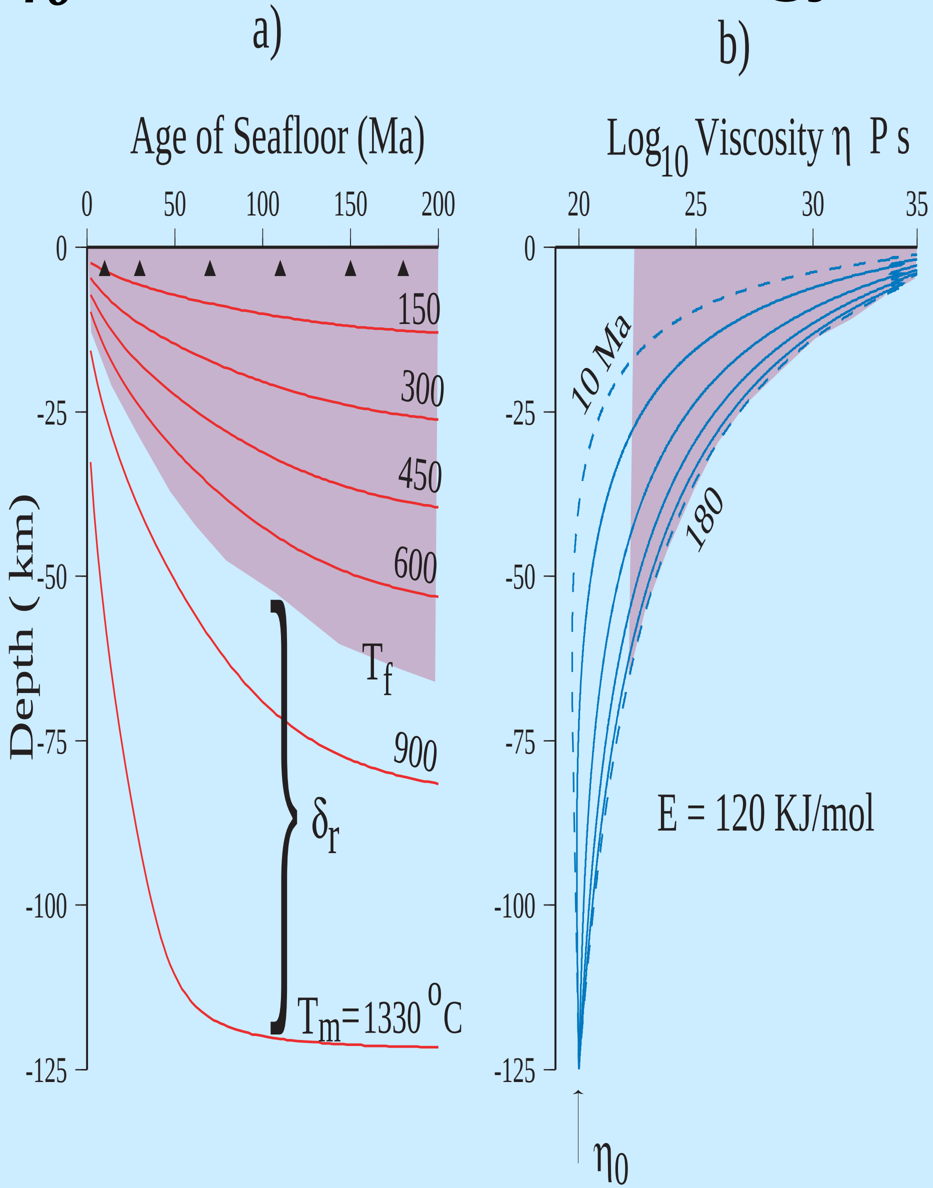
Controlling Parameters: mantle interior viscosity η_0 and activation energy E

$\eta=\eta_0 \exp[E/(RT)-E/(RT_m)]$

Two parameters:

1) E: activation energy,

2) η_0: viscosity at T_m.



What goes unstable?

[Davaille & Jaupart, 1993]

Temperature-dependent viscosity can be written as:
$\eta = \eta_0 \exp[E(1-T)]$.

The fluid can participate in convection only if its viscosity η_c satisfies (i.e., cannot be too viscous):

$$\frac{\eta_c}{\eta_0} < C \quad (\sim<10).$$

This implies that

$$\frac{\eta_c}{\eta_0} = \exp[E(1-T_c)] < C.$$

$$E(1-T_c) < \ln C \quad \text{or}$$

$$T_c > \frac{C'}{E}.$$

That is, only the fluid with temperature that is greater than a certain value can participates in convection. The threshold temperature *Tc* depends on activation energy E.

Controlling Parameters: mantle interior viscosity η_0 and activation energy E

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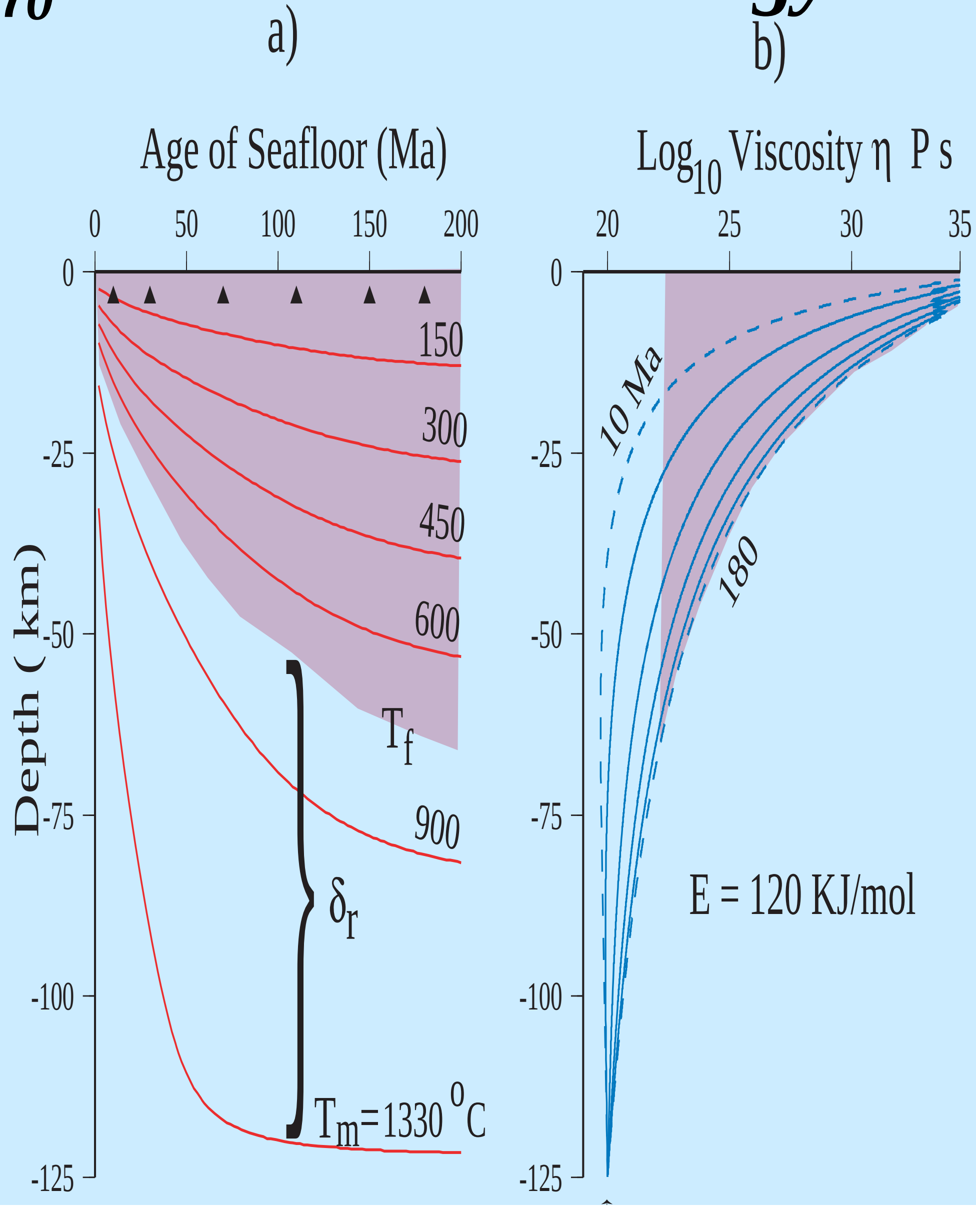
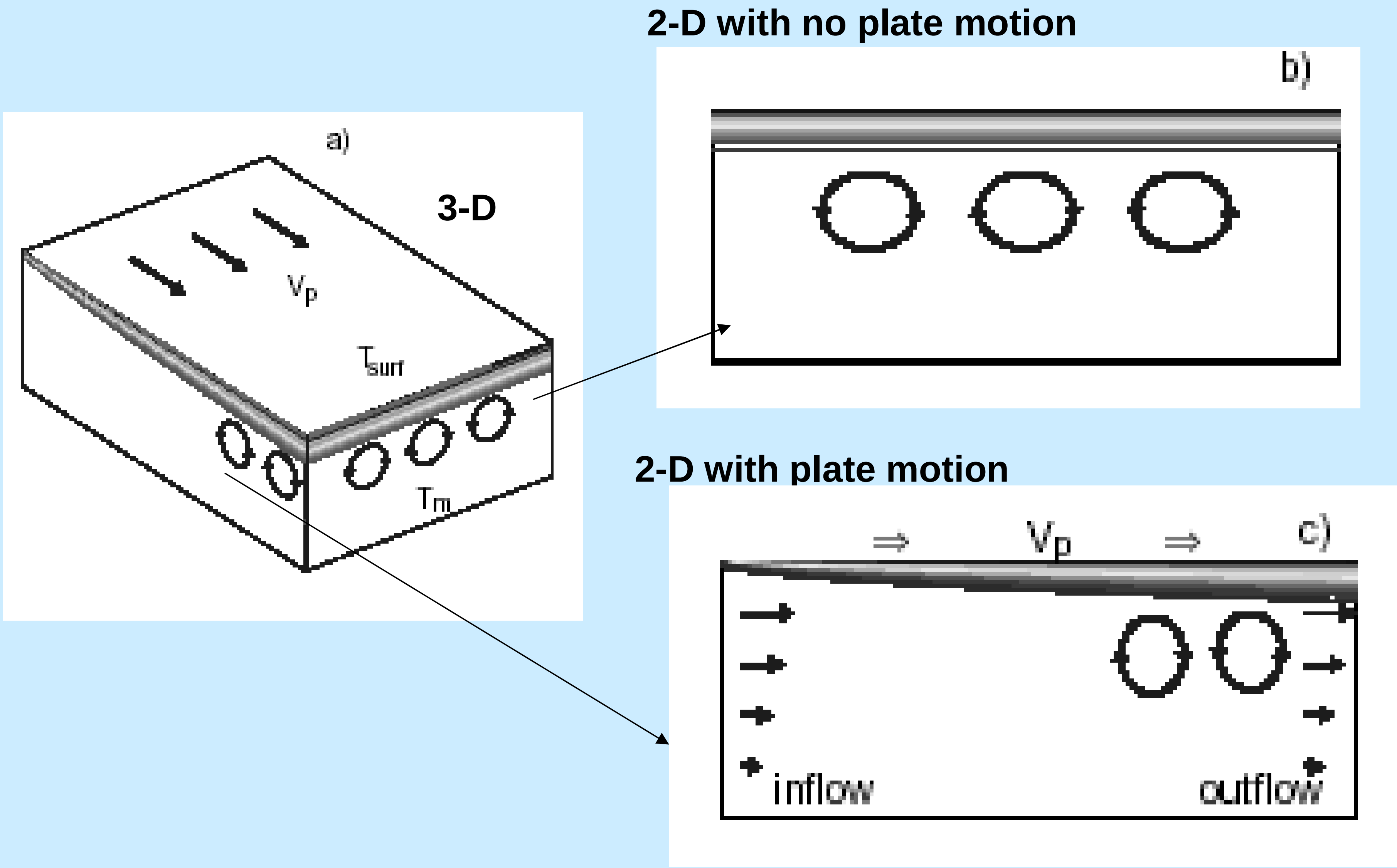


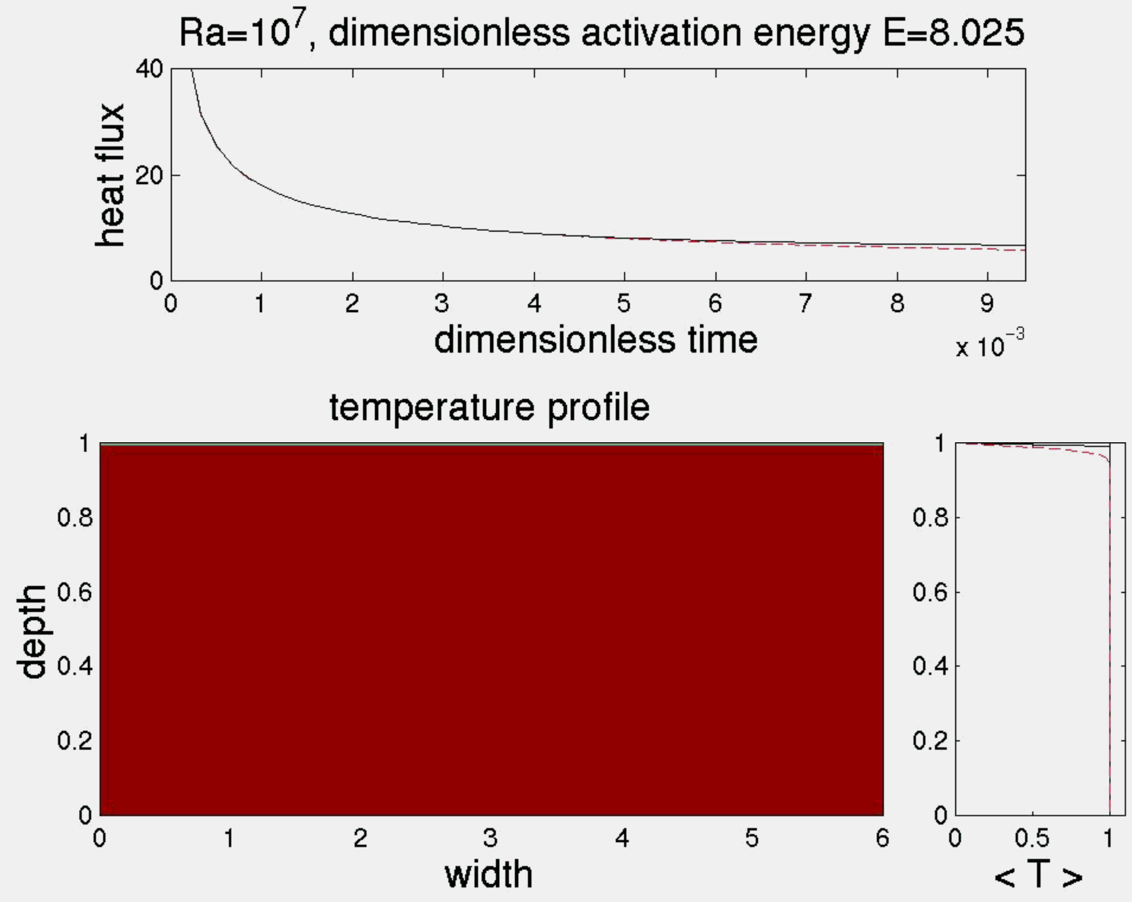
Numerical Modeling of SSC



SSC from 2D Models

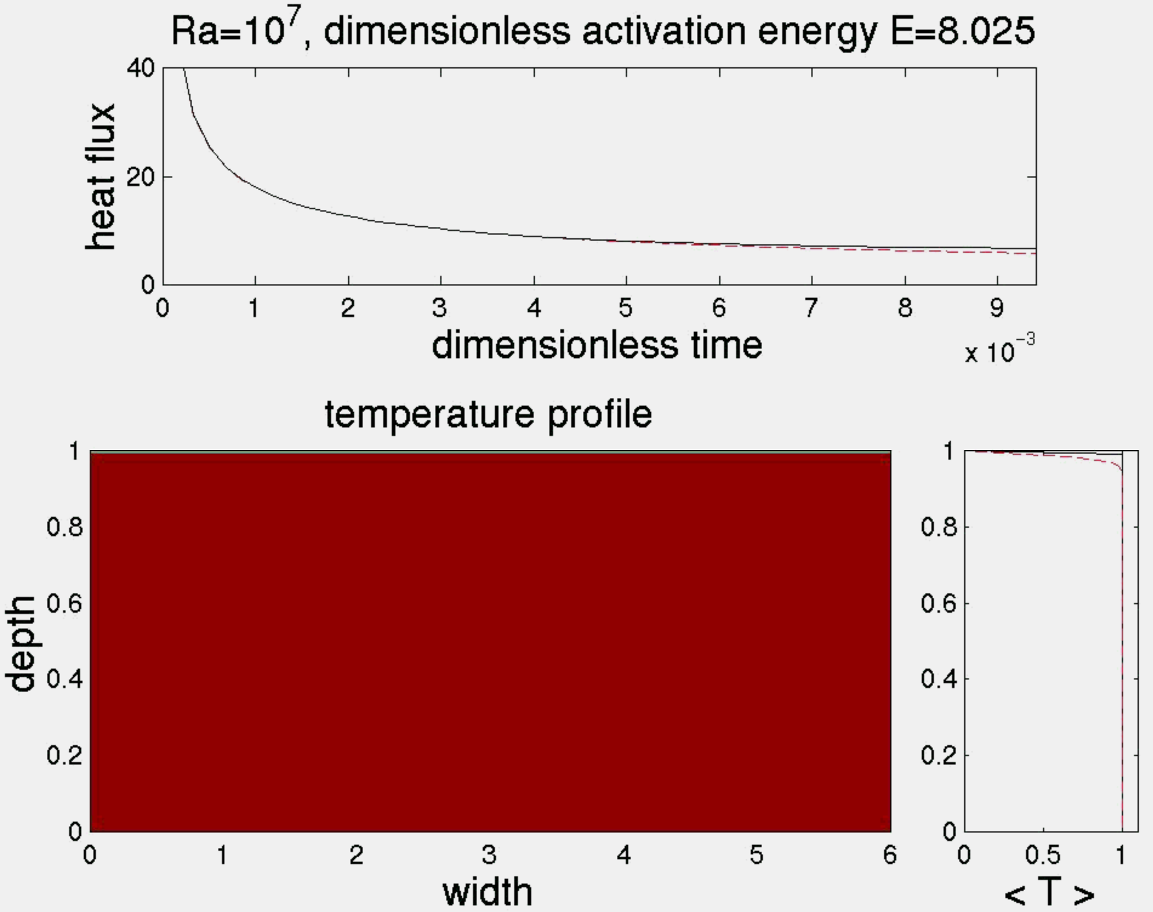
(Huang et al., 2003)

Ra=ρgαΔTd³/(κη₀)



SSC from 2D Models

(Huang, et al., 2003)



Onset time for small-scale convection – a simple analysis

$$Ra_\delta = \frac{\rho g \alpha \Delta T \delta^3}{\eta \kappa} \sim Ra_{cr}, \qquad \delta \sim (\kappa t)^{1/2}$$

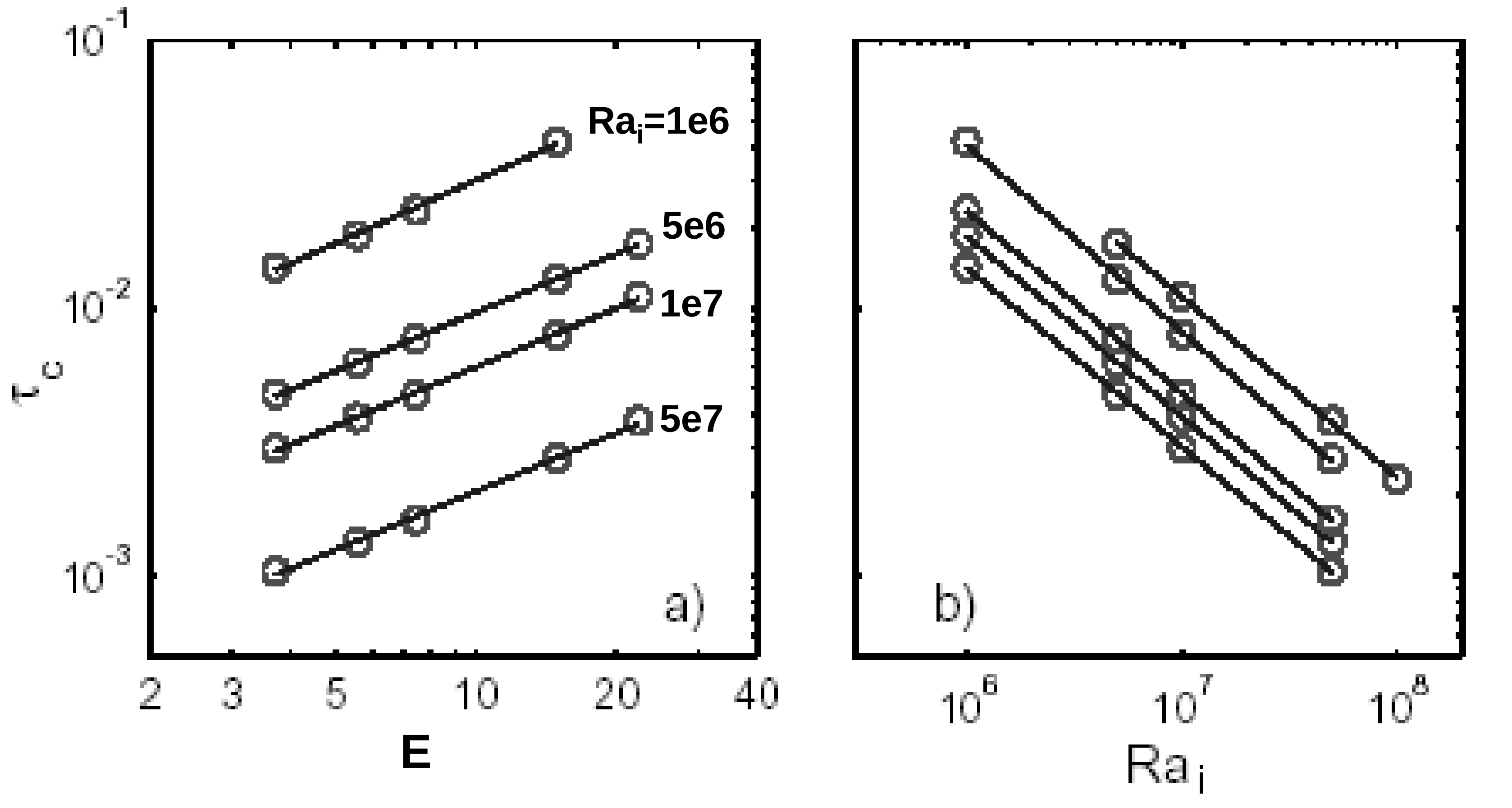
At $t=\tau_c$, $\delta=\delta_c$, instability occurs, and

$$Ra_\delta = \frac{\rho g \alpha \Delta T {\delta_c}^3}{\eta \kappa} \sim Ra_{cr}.$$

$$\delta_c \sim \left(\frac{\eta \kappa Ra_{cr}}{\rho g \alpha \Delta T}\right)^{1/3} \sim (\kappa \tau_c)^{1/2}.$$

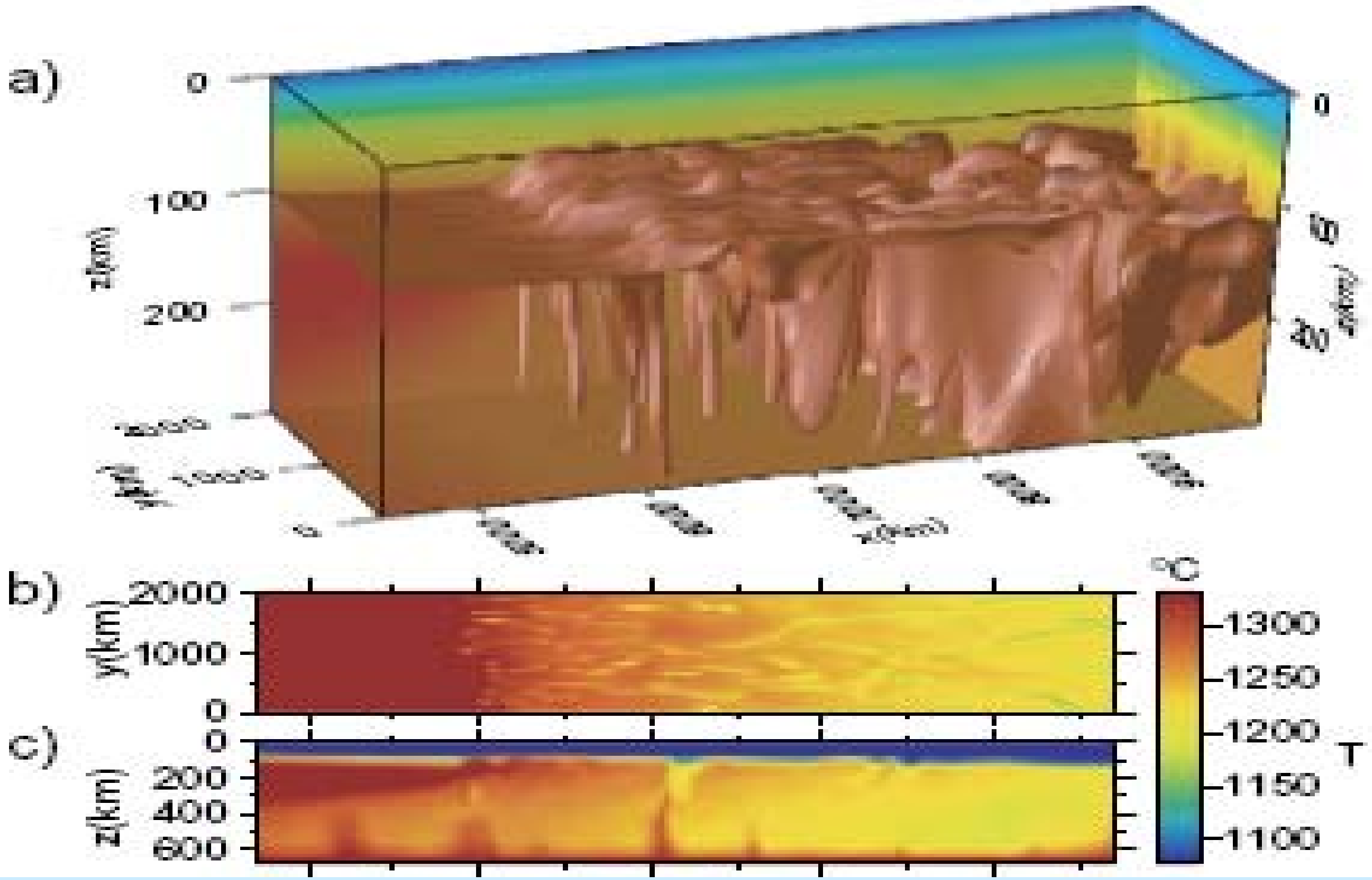
$$\tau_c \sim \frac{d^2}{\kappa}\left(\frac{\eta \kappa Ra_{cr}}{\rho g \alpha \Delta T d^3}\right)^{2/3} \sim \frac{d^2}{\kappa} Ra^{-2/3}.$$

Numerically Determined Scaling for Onset Time: $\tau_c \sim Ra_i^{-2/3} E^{0.74}$



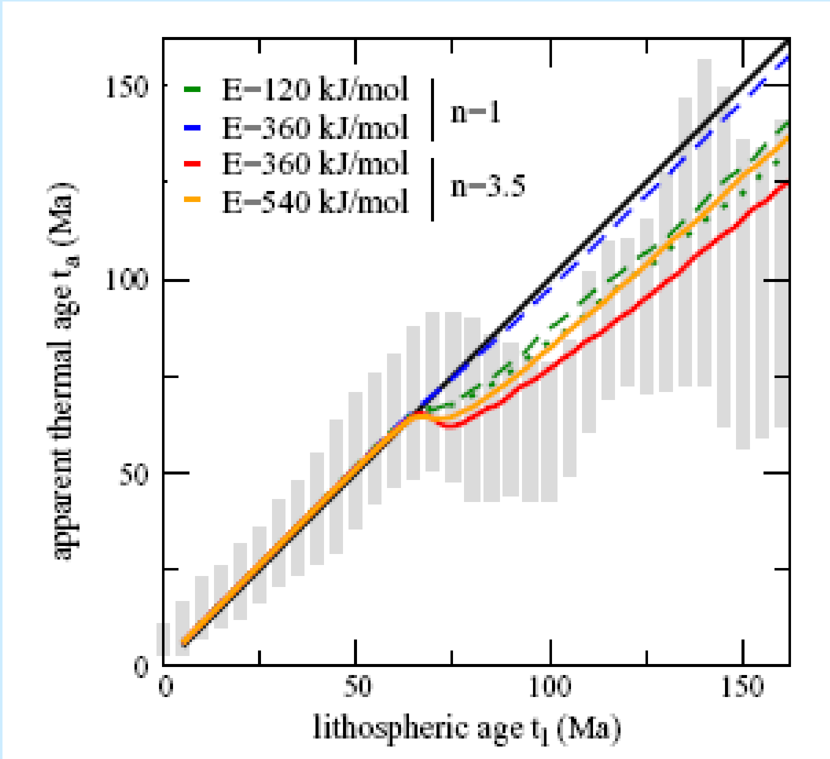
Huang et al., 2003

3-D modeling of SSC



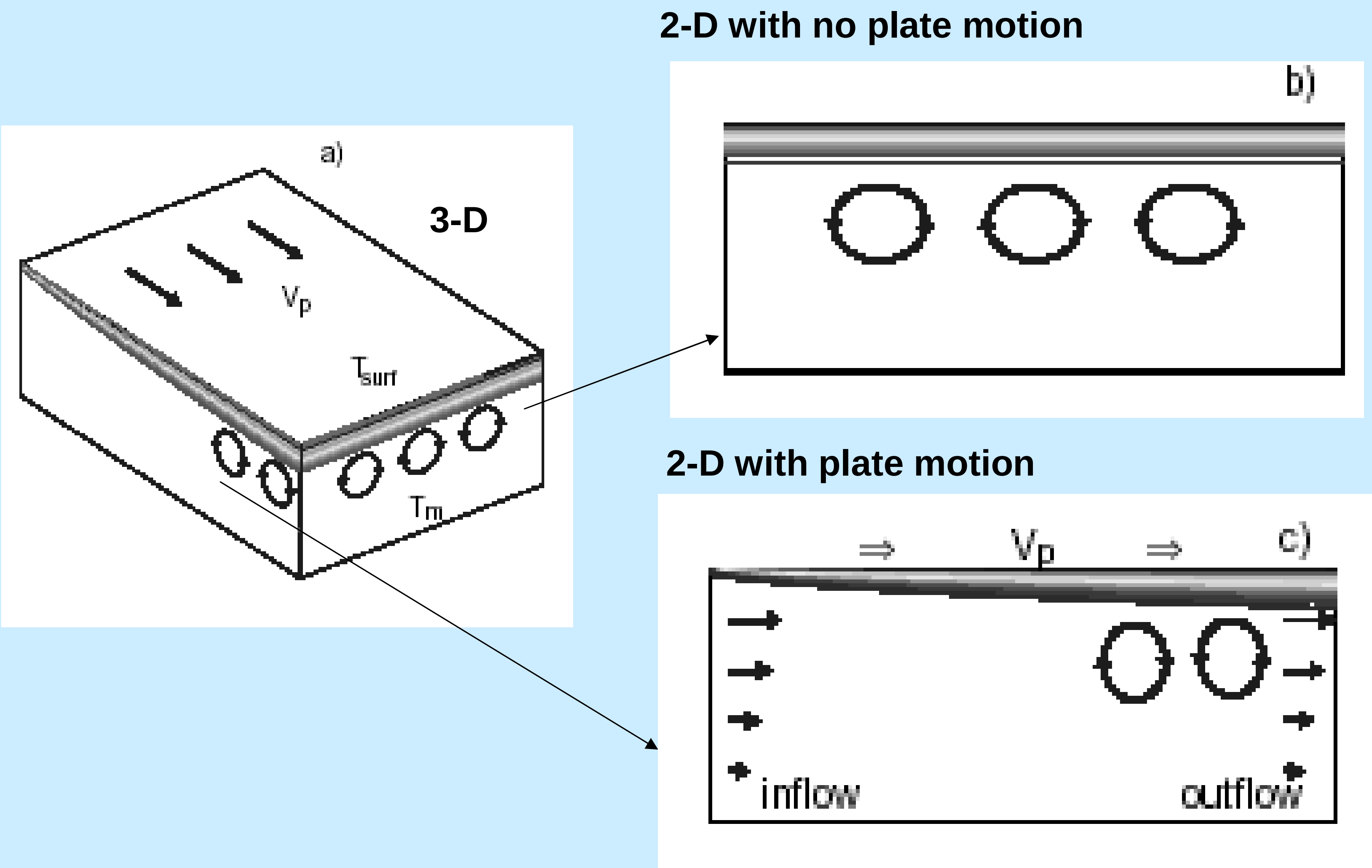
Van Hunen et al., 2005

Constraints on mantle rheology

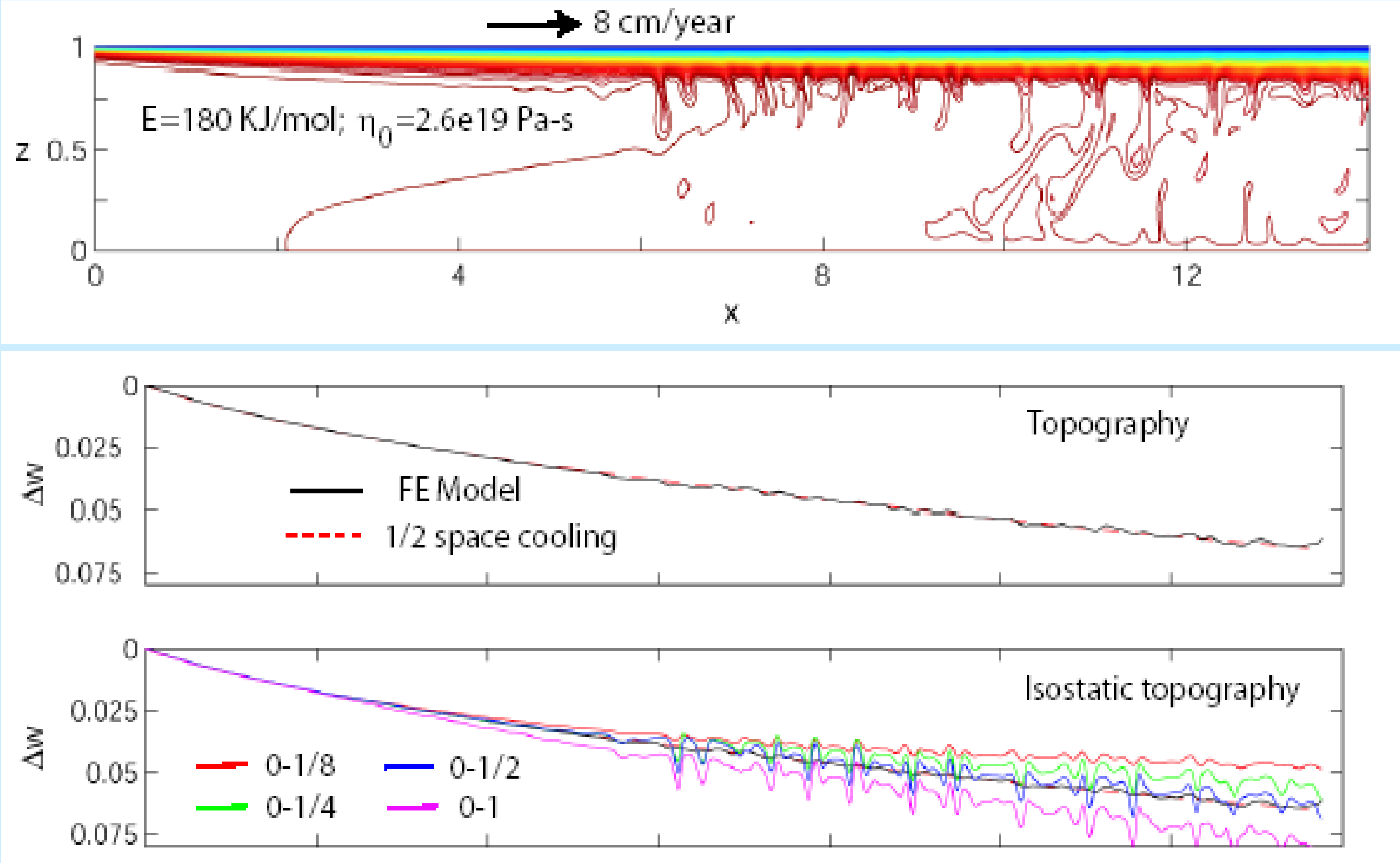


Van Hunen, et al., 2005

Numerical Modeling of SSC

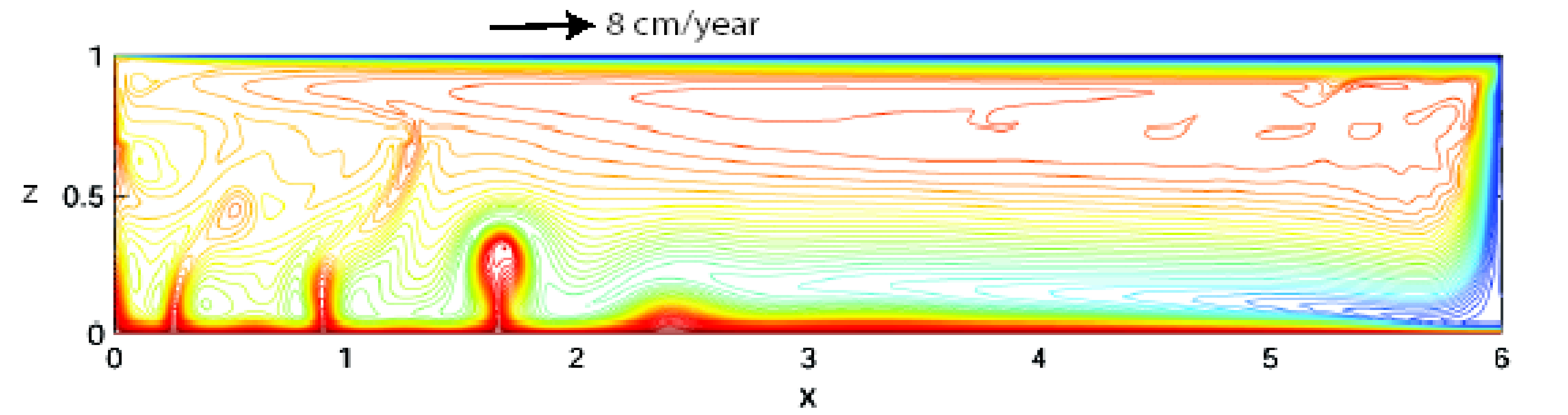


2D Model with Flow-through Boundary Conditions [Huang & Zhong, 2005]

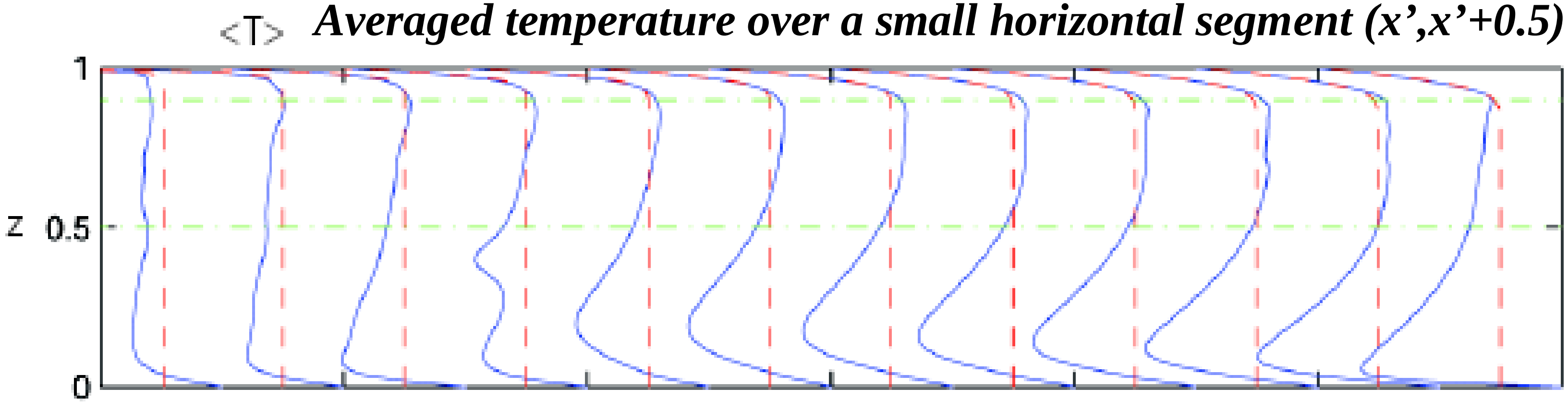


Trapped Heat Below Old Lithosphere – Convection Models in Closed Box

45% internal heating; E=120 KJ/mol; η_a=1.1e20 Pa-s with X60 for the lower mantle



Averaged temperature over a small horizontal segment (x’,x’+0.5)



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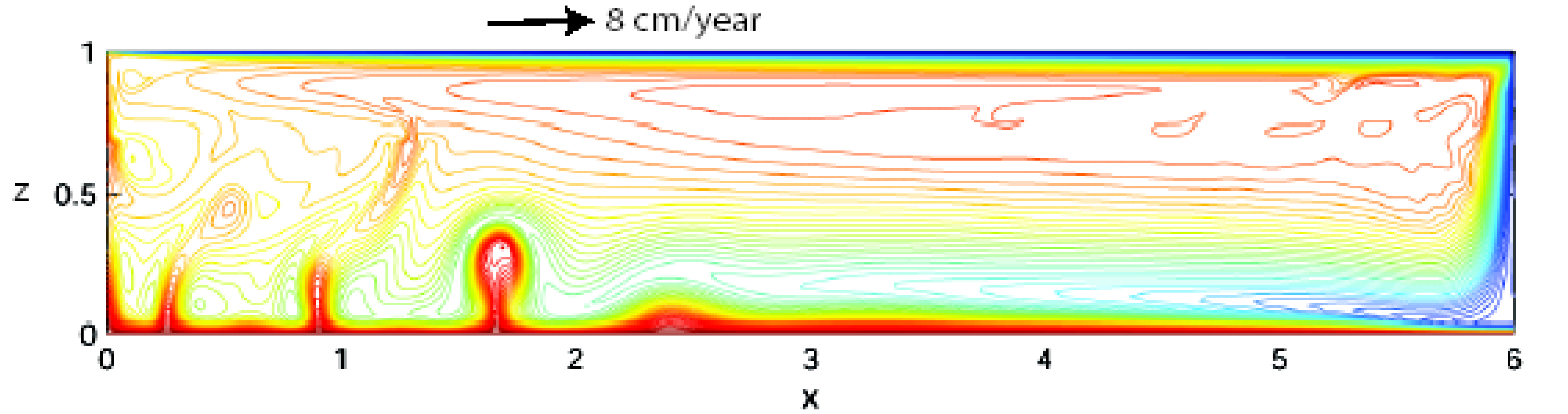
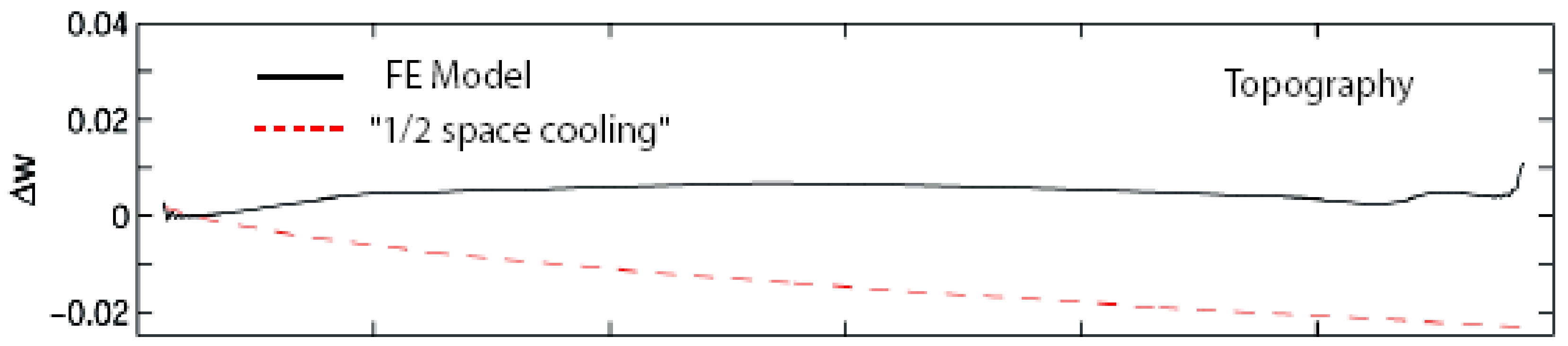
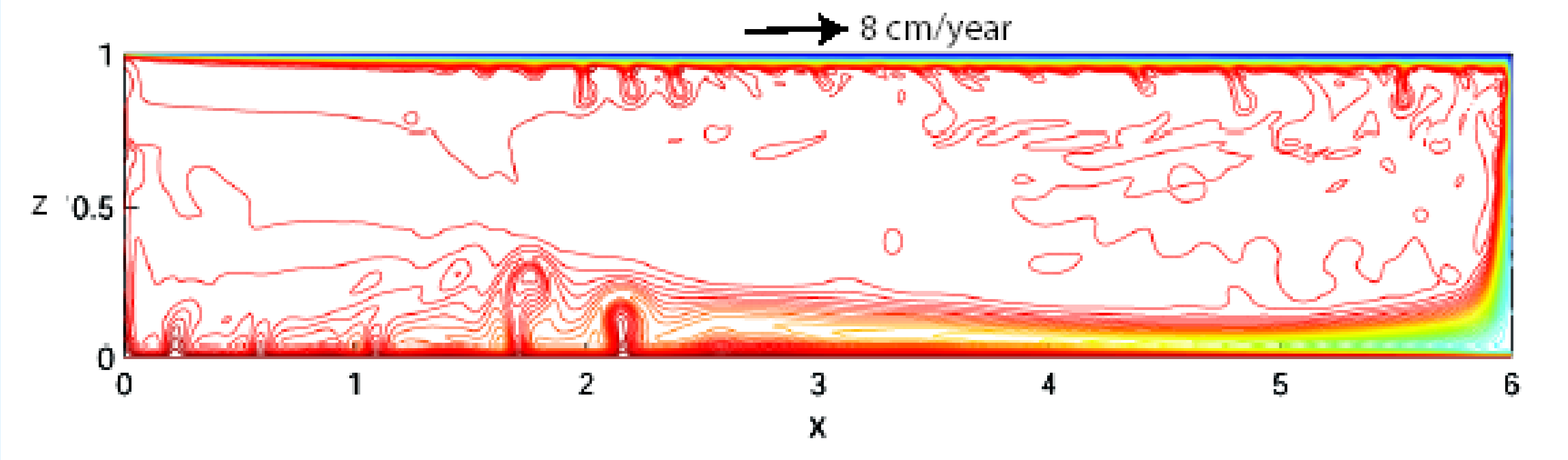


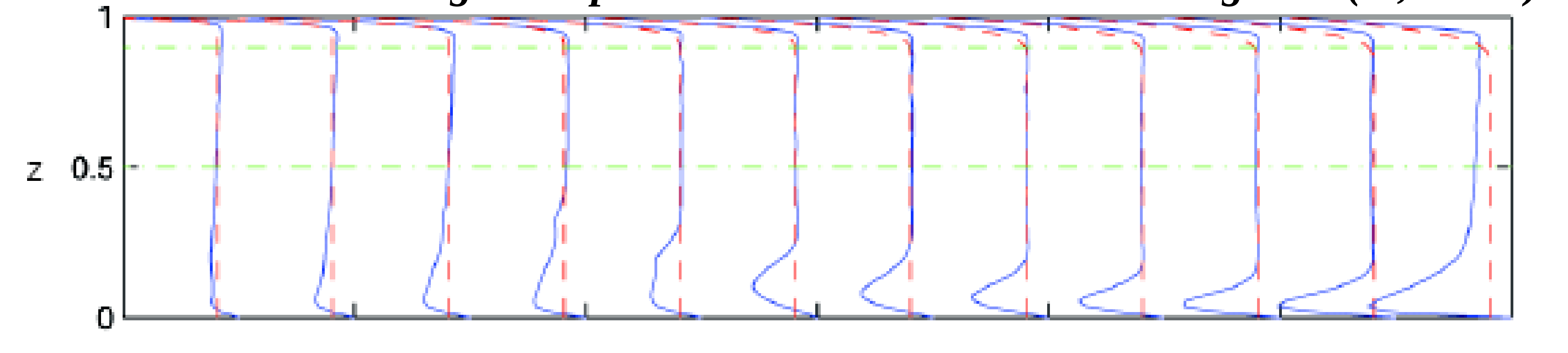


Trapped Heat + SSC

60% internal heating; E=120 KJ/mol; η_a=2.6e19 Pa-s with X60 for the lower mantle



<T> ***Averaged temperature over a small horizontal segment (x',x'+0.5)***



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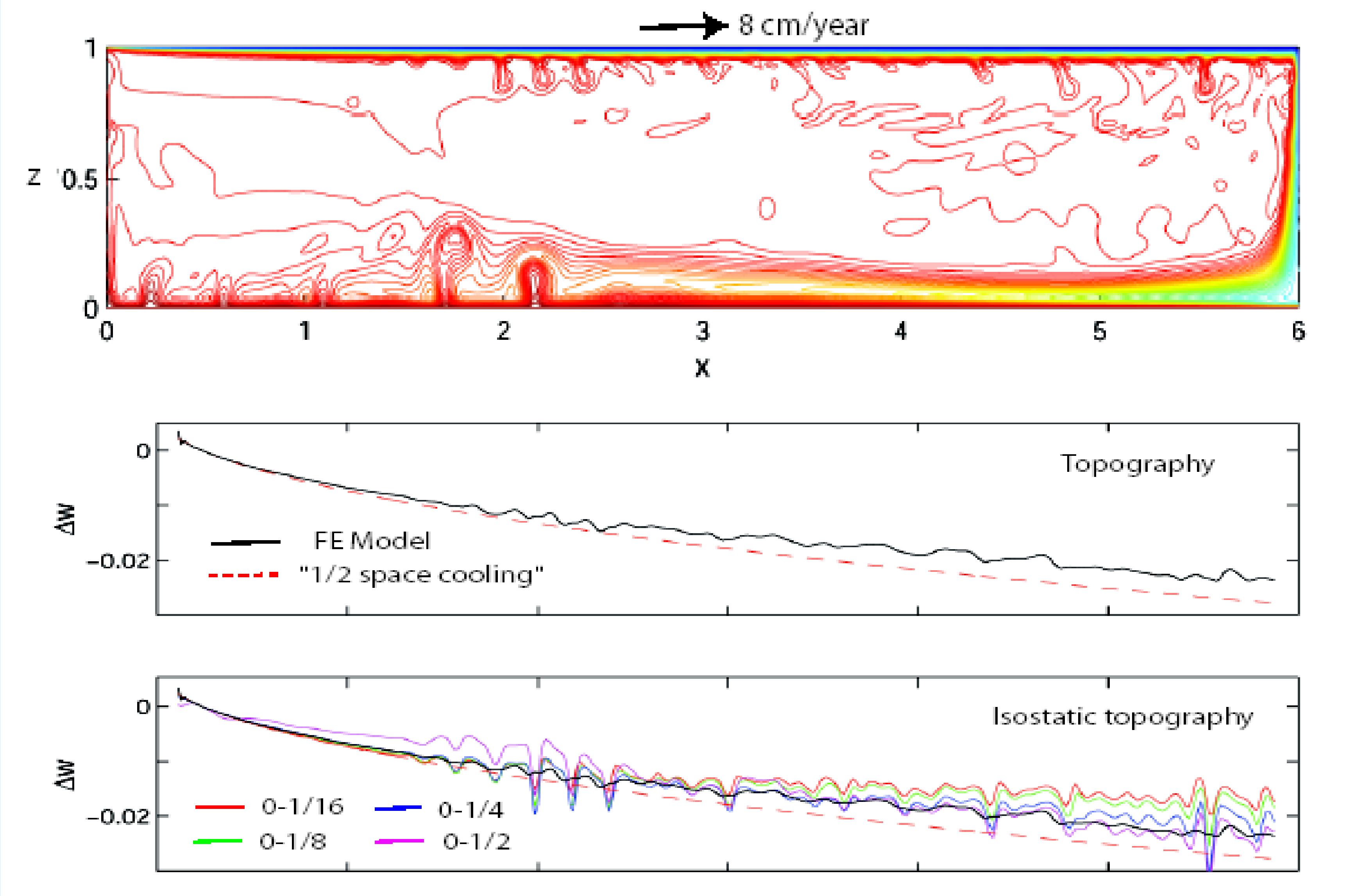

Summary

- ***Trapped heat plus sublithospheric scale convection leads to conditions resembling the plate model and explains the deviation of heat flux and topography from the ½ space cooling model.***
- ***Seismic evidence for sublithospheric small convection that can also provide constraints on activation energy.***