Mantle Geotherms from Geodynamics

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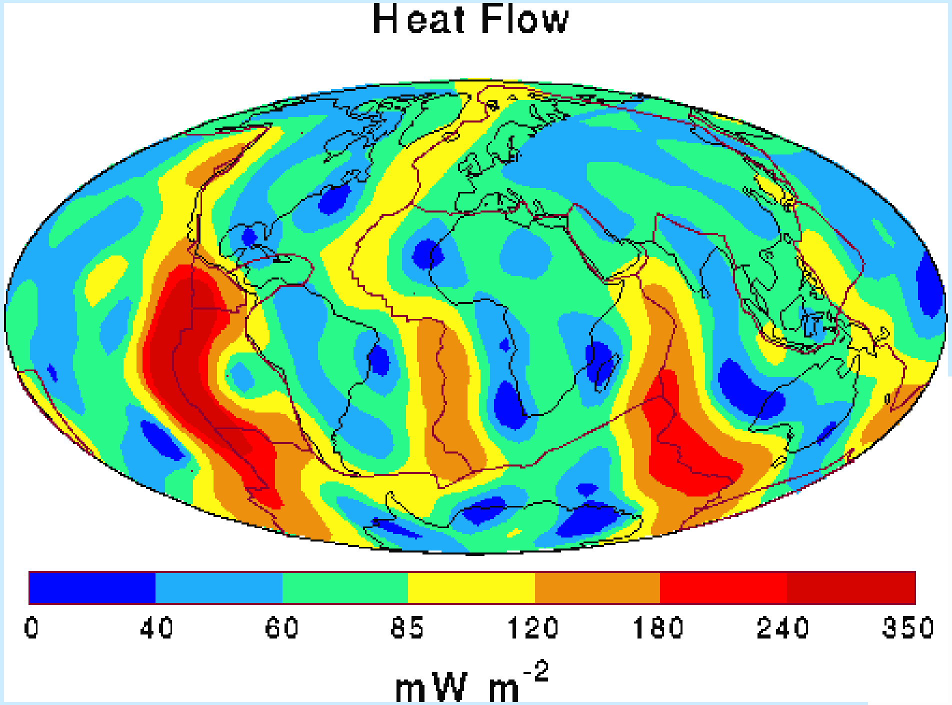
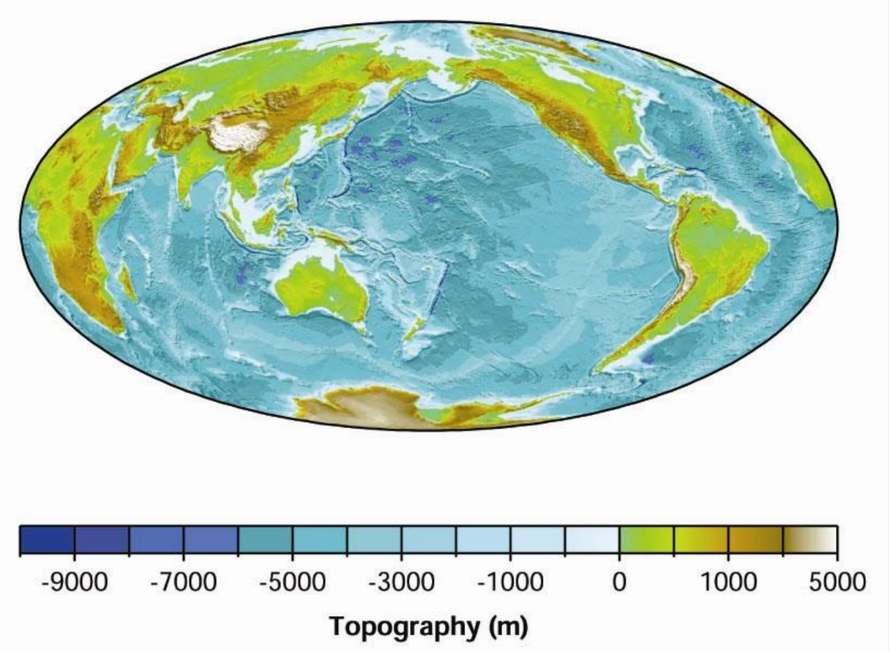
For CIDER Geotherms workshop

Earth's Surface Heat Flux and Topography



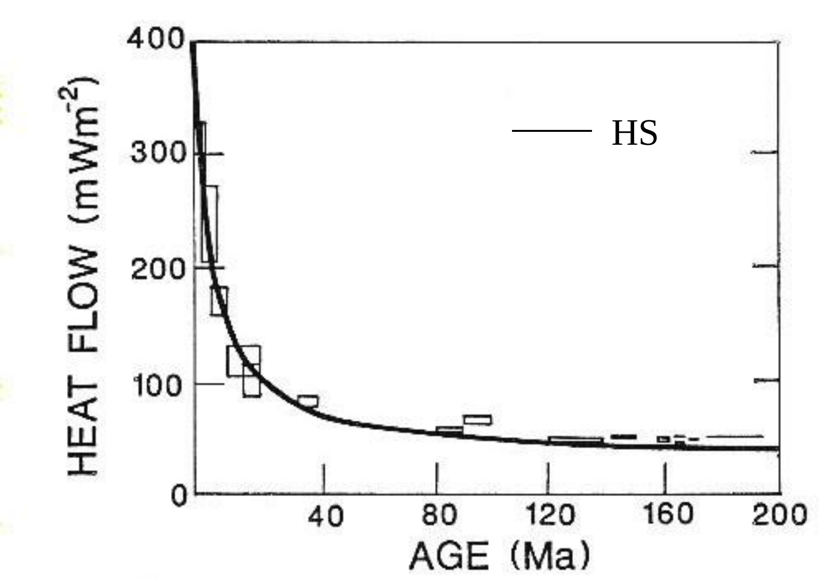
Pollack et al., 1993

Topography



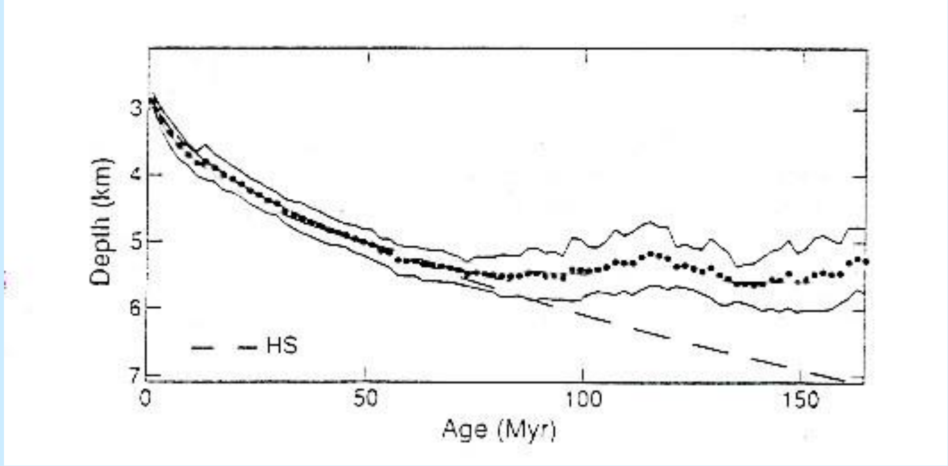
Age-dependent Heat Flux and Ocean Depth

Heat Flux



Lister et al., 1991

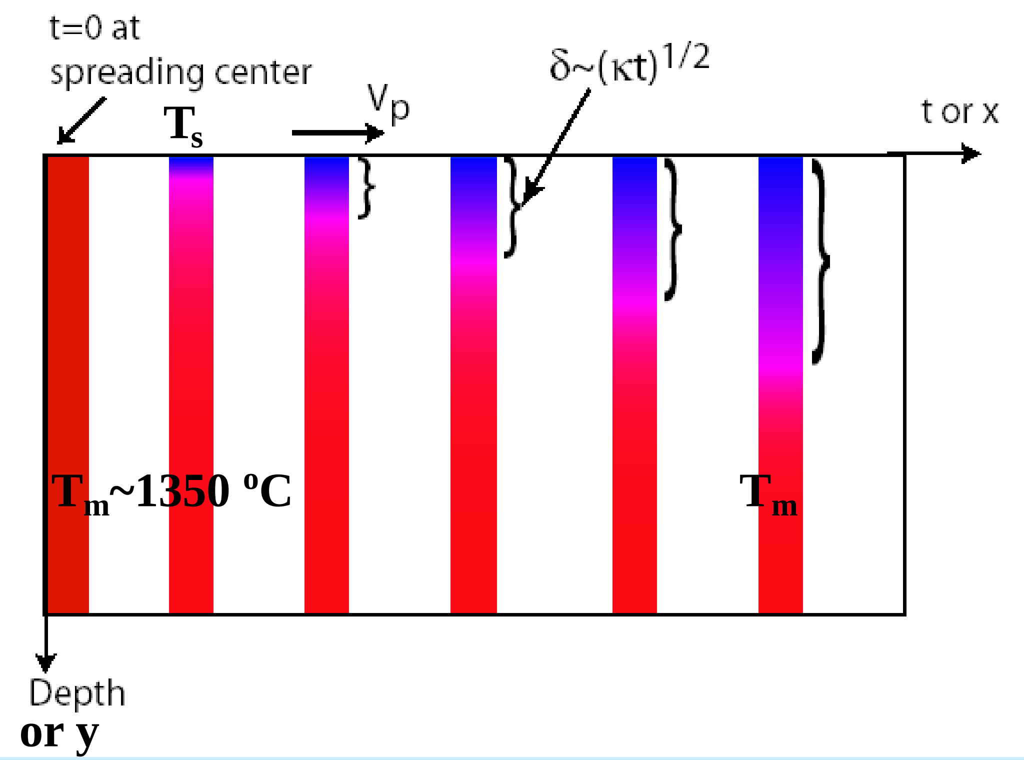
Ocean Depth



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

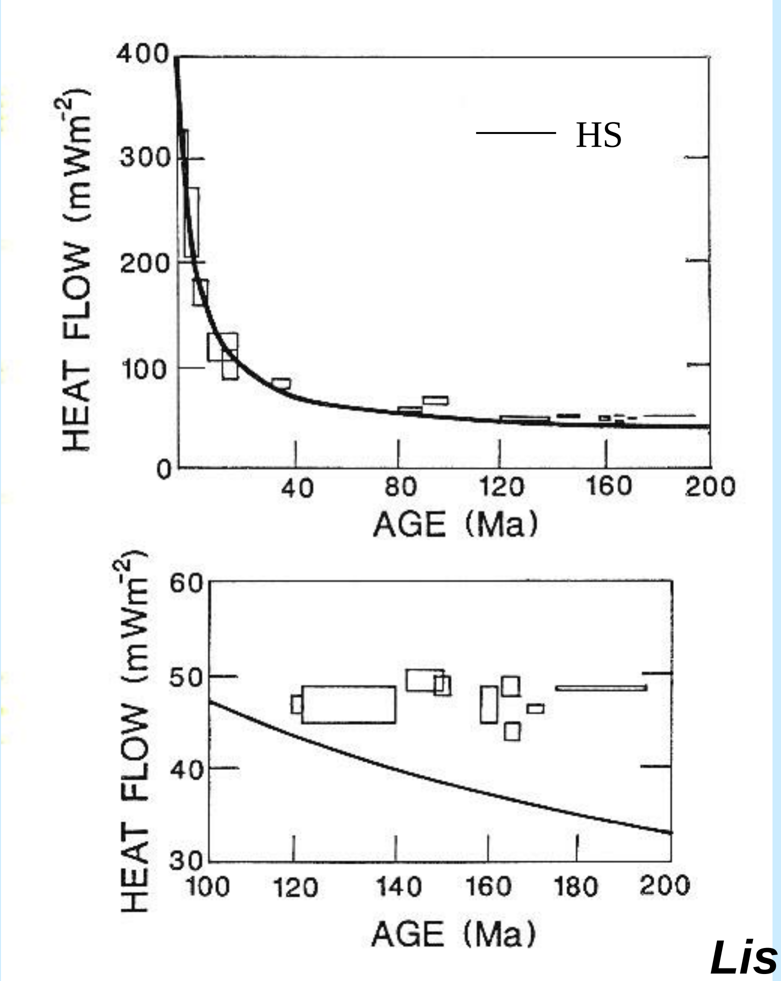
Topography:

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

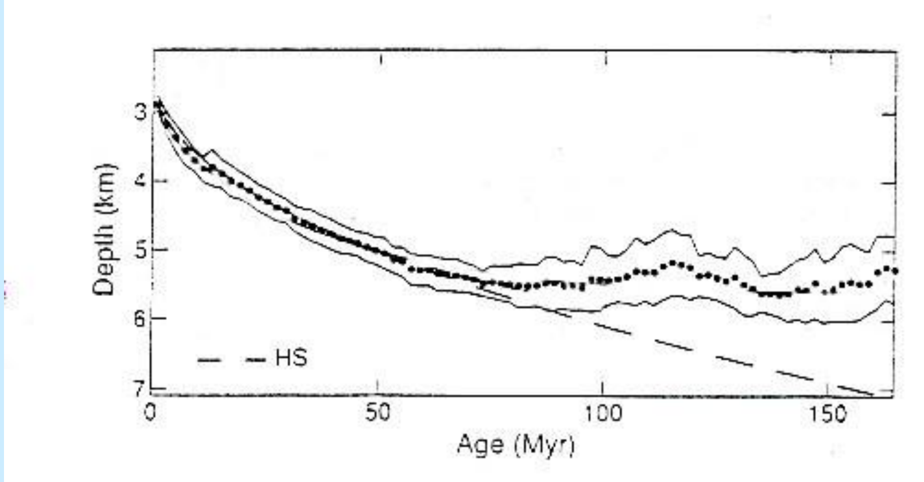
where $b = \rho_m/(\rho_m - \rho_w)$

Deviations from the Half-space Cooling Model at Old Seafloor

Heat Flux



Ocean Depth

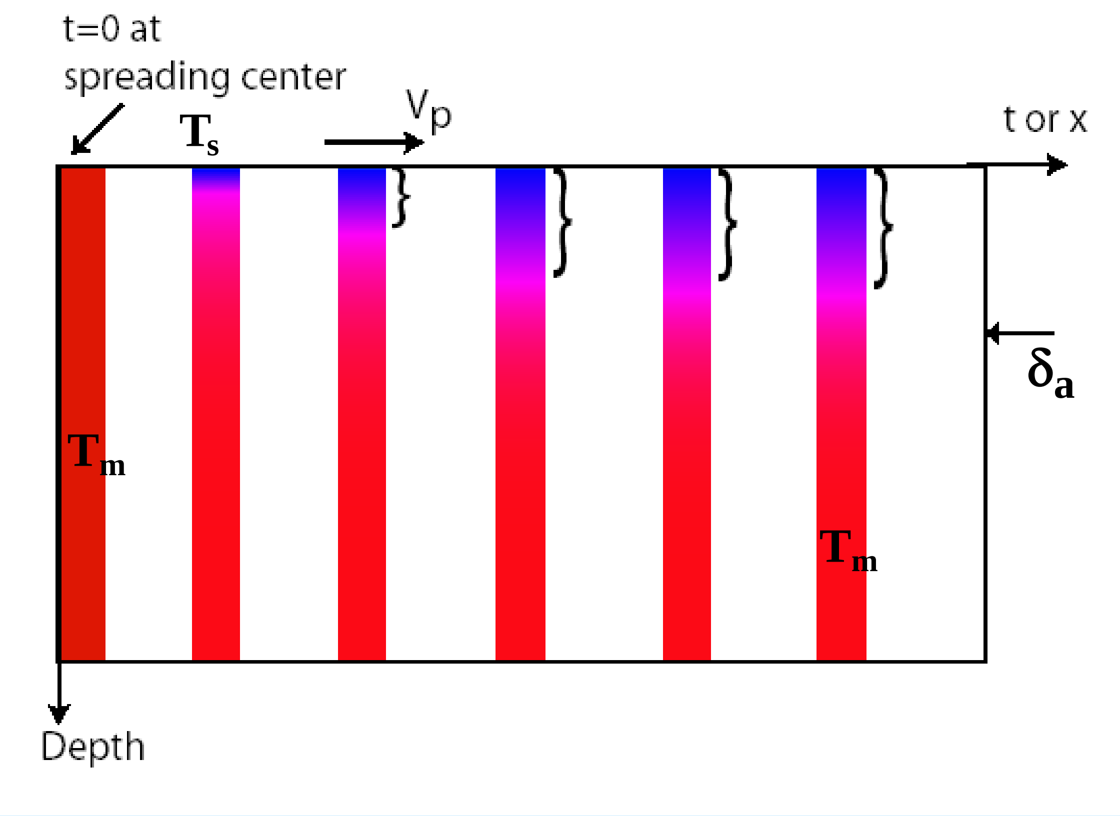


Stein & Stein, 1992

Lister et al., 1991

The Plate Model – a revised model to fit the data

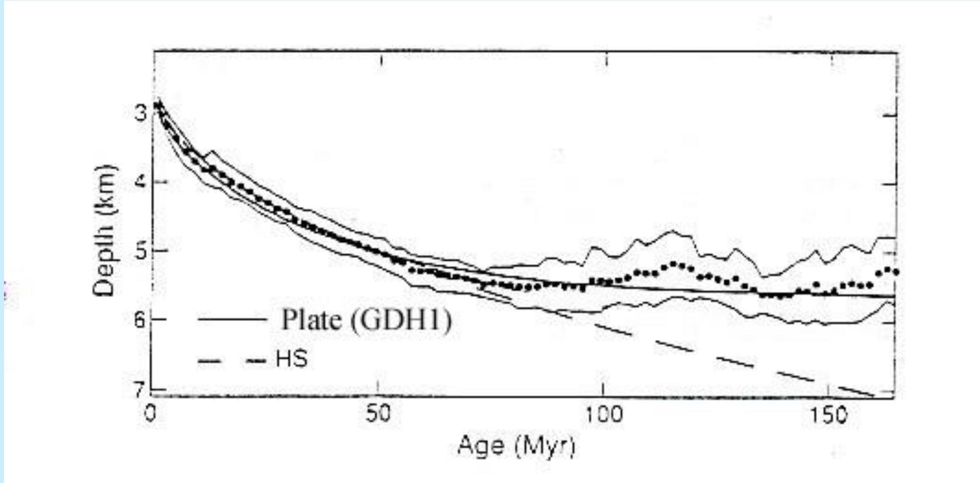
[Parsons & Sclater, 1977; Parsons & McKenzie, 1978]



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

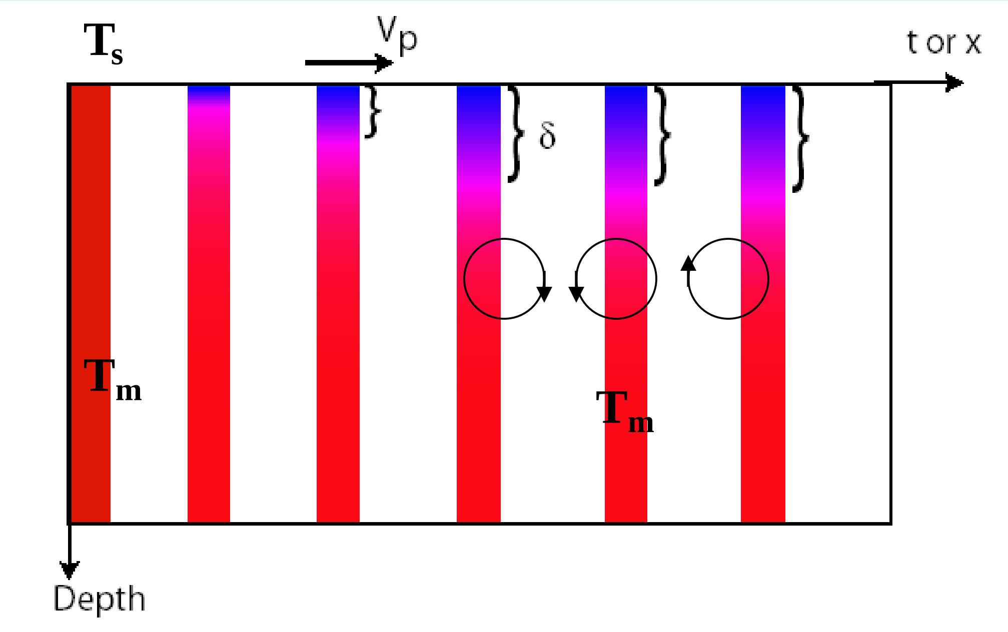
Ocean Depth



Stein & Stein, 1992

An empirical model!

Small-scale Convection (SSC) Below Old Oceanic Lithosphere -- Physical Basis for the Plate Model [Parsons and McKenzie, 1978]

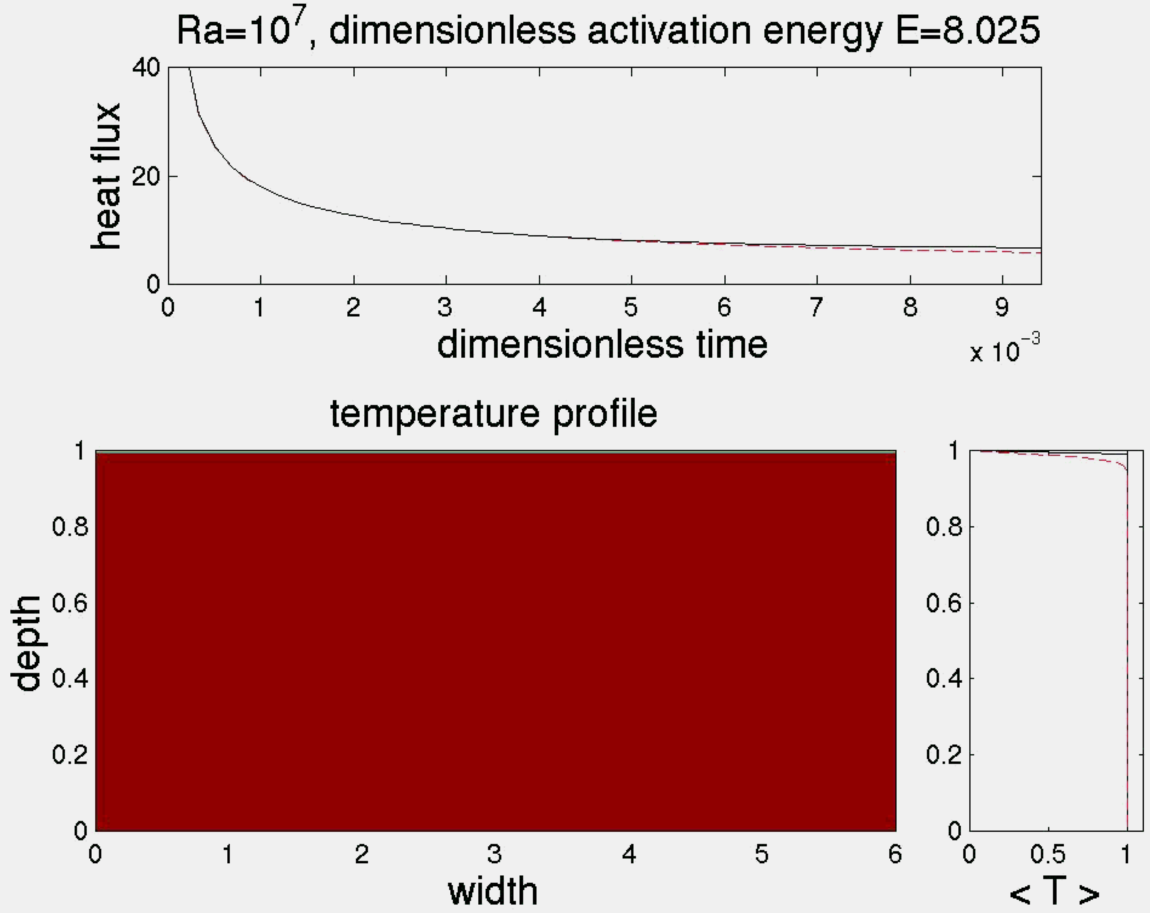


$\delta \sim (\kappa t)^{1/2}$

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.

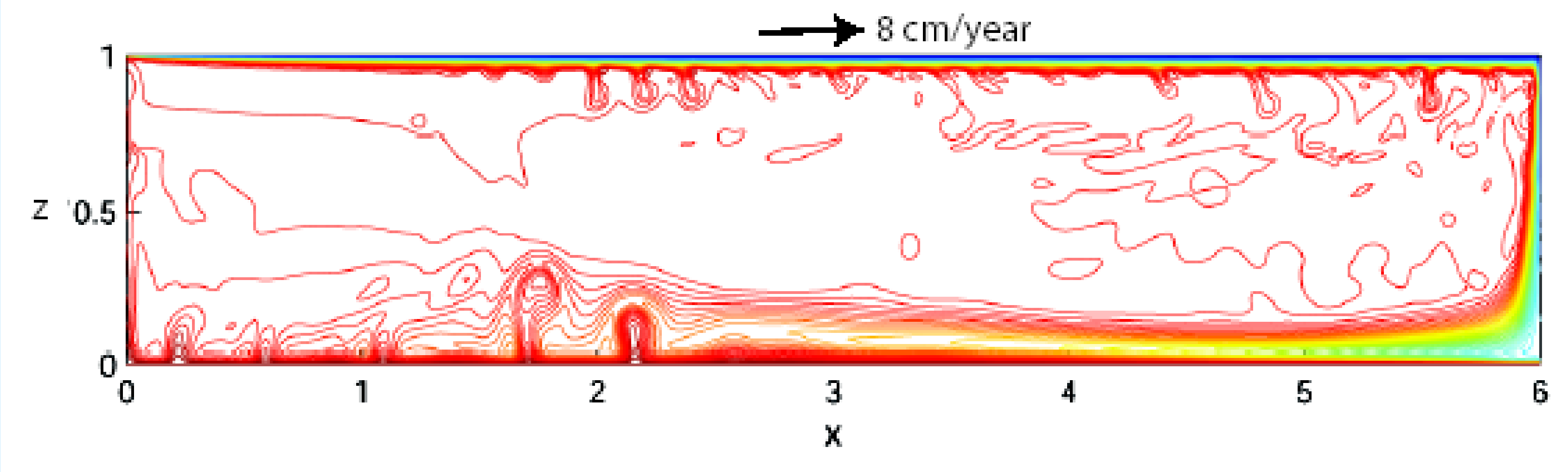
SSC from 2D Models (Huang et al., 2003)

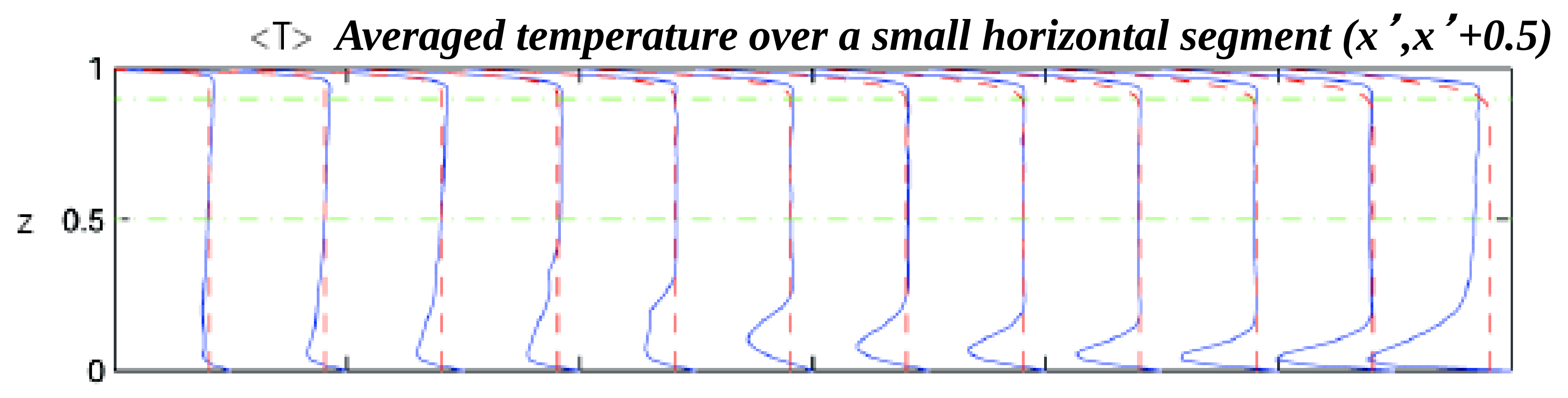


O'Connell & Hager [1981] pointed out that this vertical exchange of heat from SSC may cause "deepening" not "flattening" in ocean depth.

2D model with SSC

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

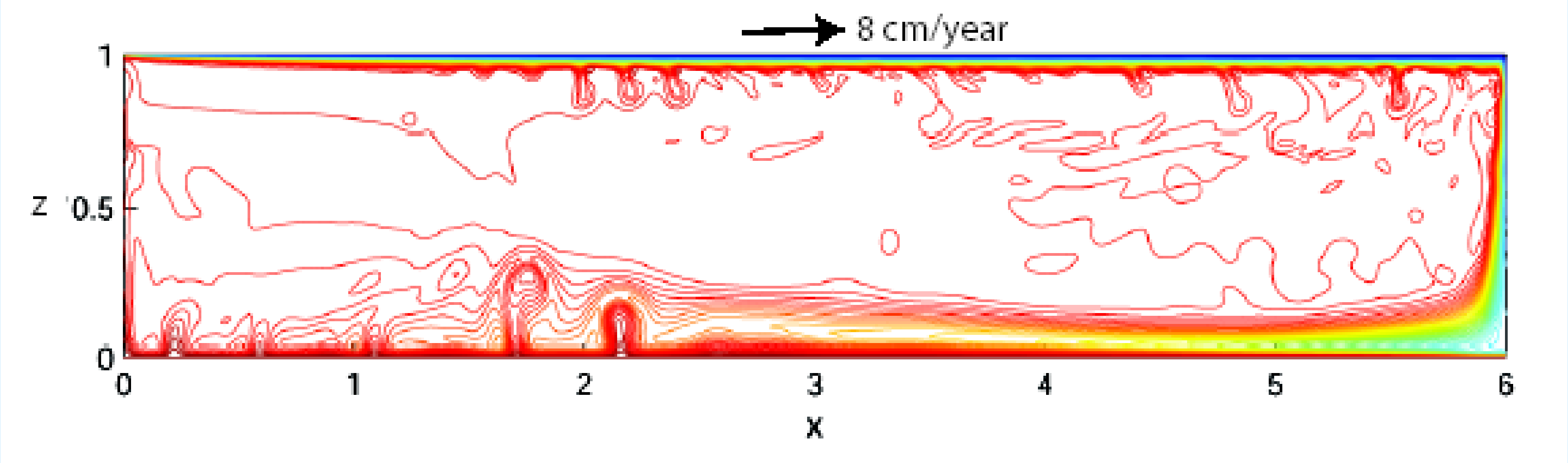


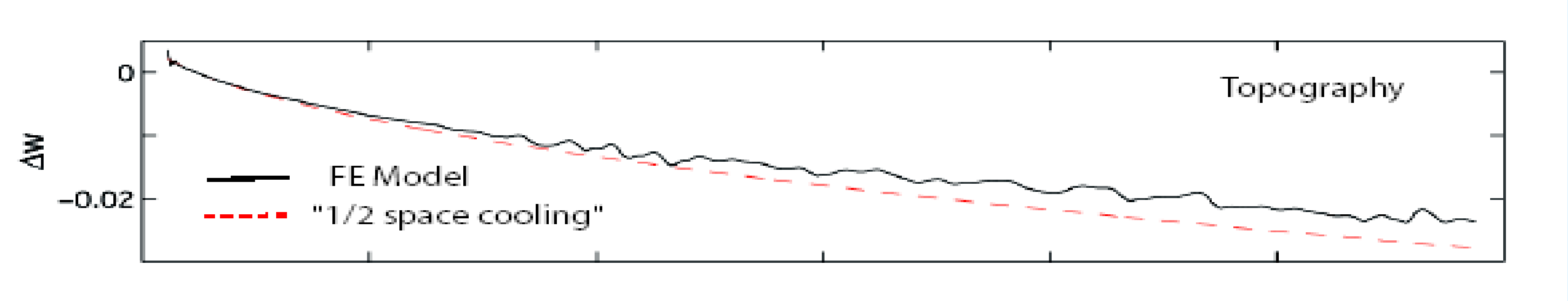


Averaged temperature over a small horizontal segment (x′,x′+0.5)

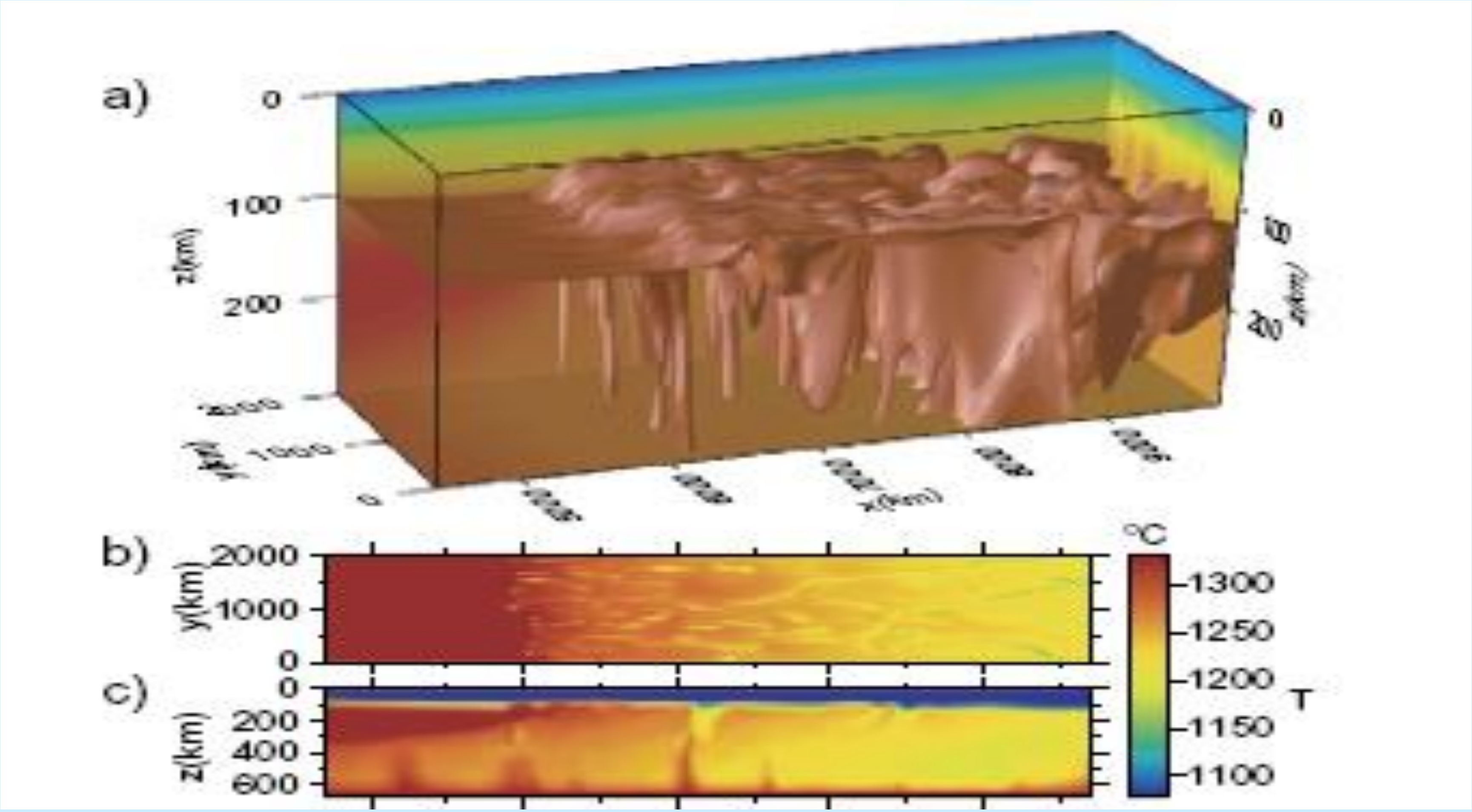
2D model with SSC

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





3-D modeling of SSC



Van Hunen et al., 2005

Summary on lithospheric geotherms

- ***For oceanic lithosphere: The plate model and ½ space cooling model are two end-members. The truth is somewhere between.***

- ***For continental lithosphere: Complications with tectonics/volcanism/composition [Jaupart et al., 2007; Lee et al., 2011; Carlson et al., 2005; Rudnick et al., 1999].***

Convective mantle geotherms

- ***Follow adiabatic gradient.***

$$(dT/dz)_s = \alpha g T / C_p,$$

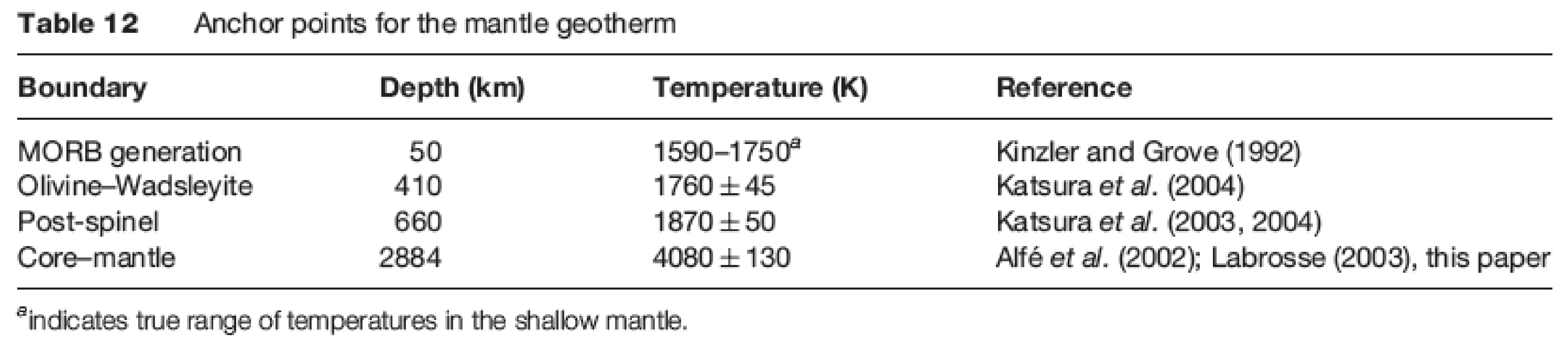
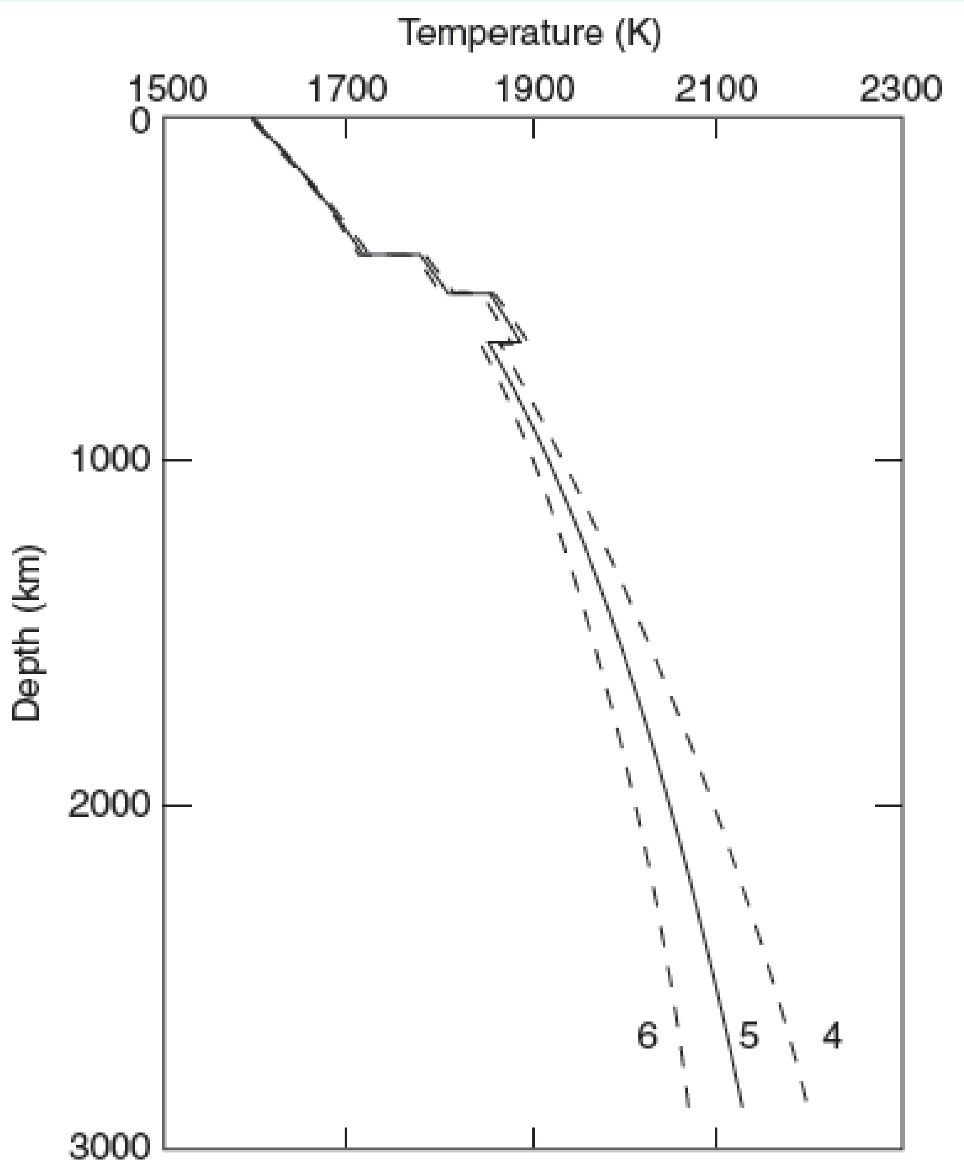


Table 12 Anchor points for the mantle geotherm

Boundary	**Depth (km)**	**Temperature (K)**	**Reference**
MORB generation	50	1590–1750[a]	Kinzler and Grove (1992)
Olivine–Wadsleyite	410	1760 ± 45	Katsura *et al.* (2004)
Post-spinel	660	1870 ± 50	Katsura *et al.* (2003, 2004)
Core–mantle	2884	4080 ± 130	Alfé *et al.* (2002); Labrosse (2003), this paper

[a] indicates true range of temperatures in the shallow mantle.

Jaupart et al., 2007

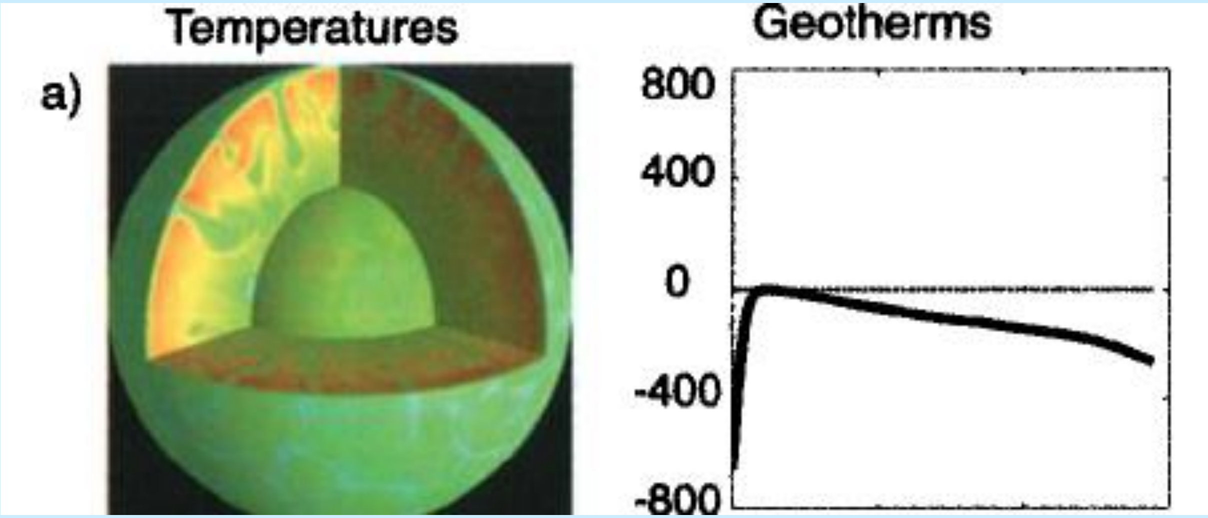


Katsura et al., 2004; Jaupart et al., 2007

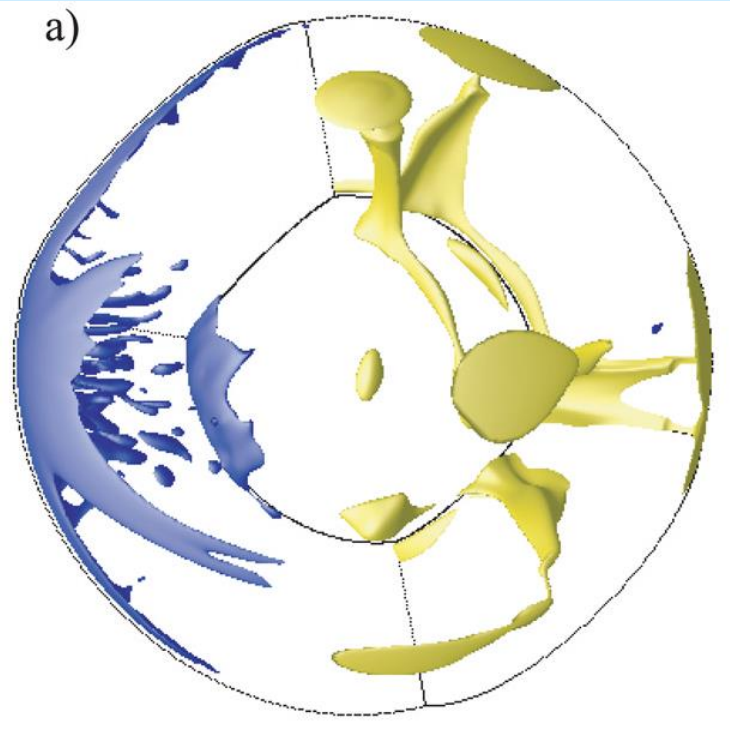
Sub-adiabatic temperature?

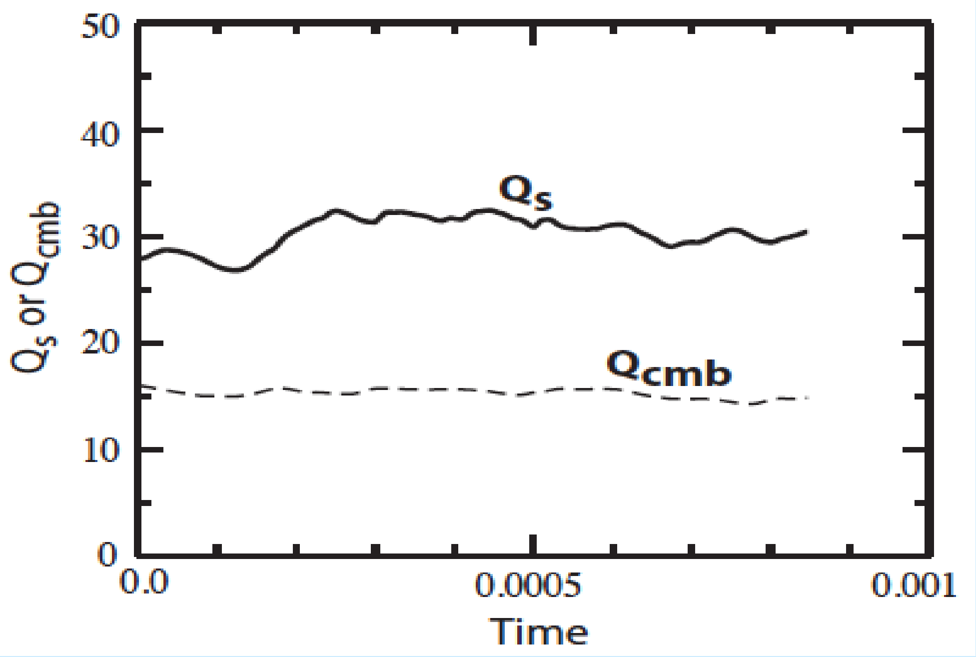
Jeanoz and Morris [1987] suggested ~400-500 K sub-adiabatic temperature in the lower mantle.

Bunge et al. [2001] seemed to support this view.



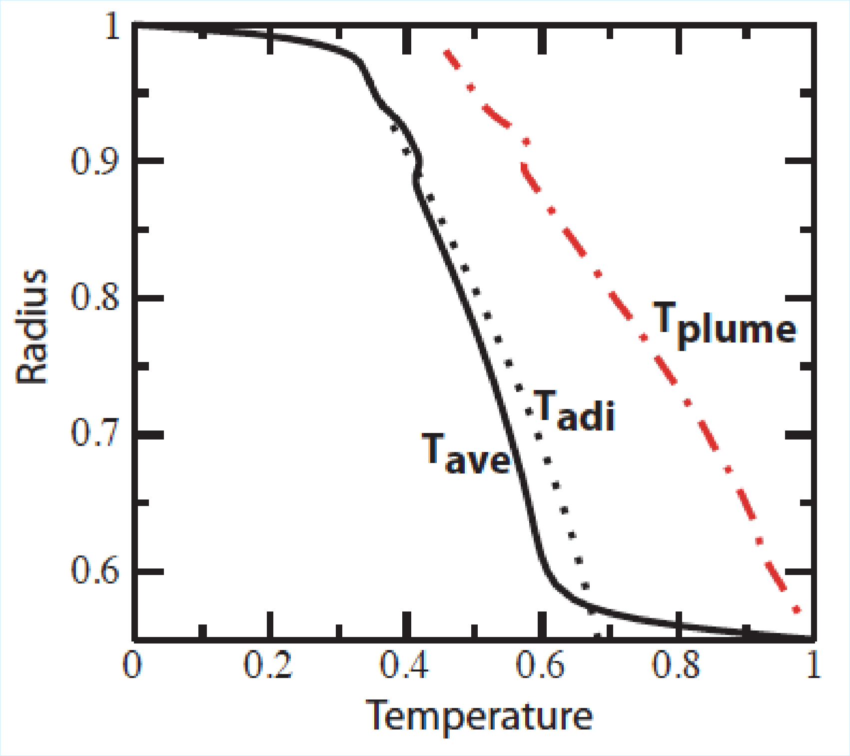
3-D convection model for plume dynamics

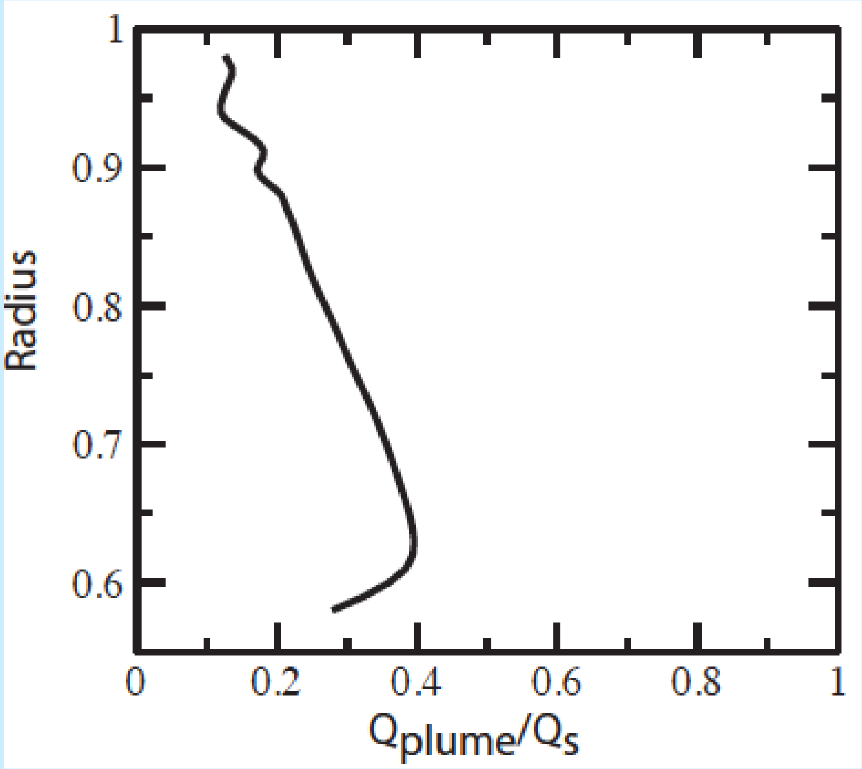




Zhong, 2006; Leng and Zhong 2008.

Temperature and Q_{plume} vs depths

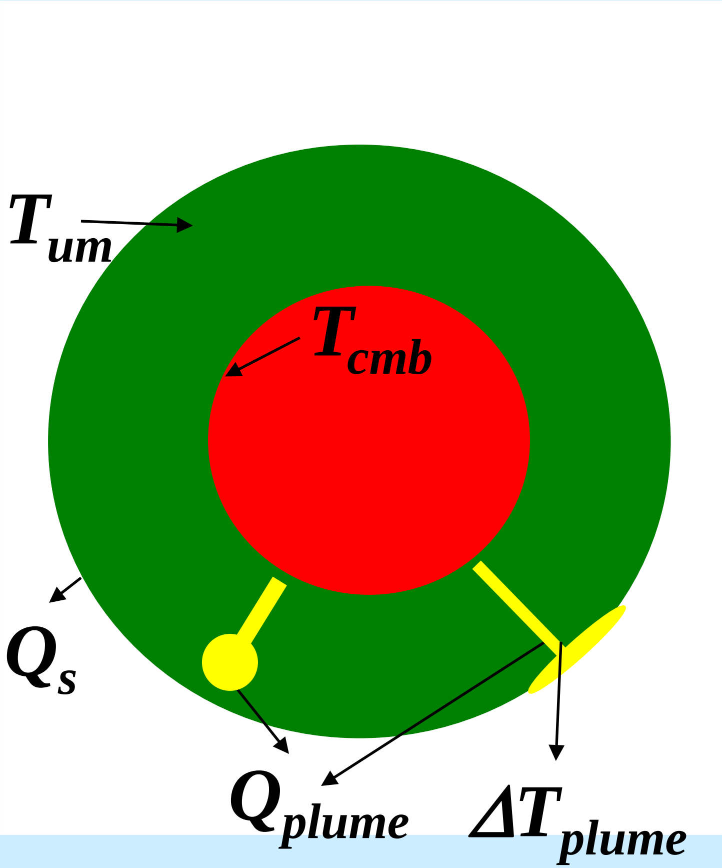




1) Sub-adiabatic temperature is <0.05 (200 K, for T_{cmb}~4000 K)

2) Plume excess temperature decreases as plumes rise. This may place constraints on CMB heat flux, using inferred plume flux by Davies [1988] and Sleep [1990].

Observations in the UM: Plume excess temperature, plume heat flux, and UM and CMB temperature [Zhong, 2006]



1) T_{um}*~1280 °C,* T_{cmb}*~3400±500 °C*

→ T_{um}/T_{cmb} *~0.338-0.455*

2) ΔT_{plume}*~250-350 K*

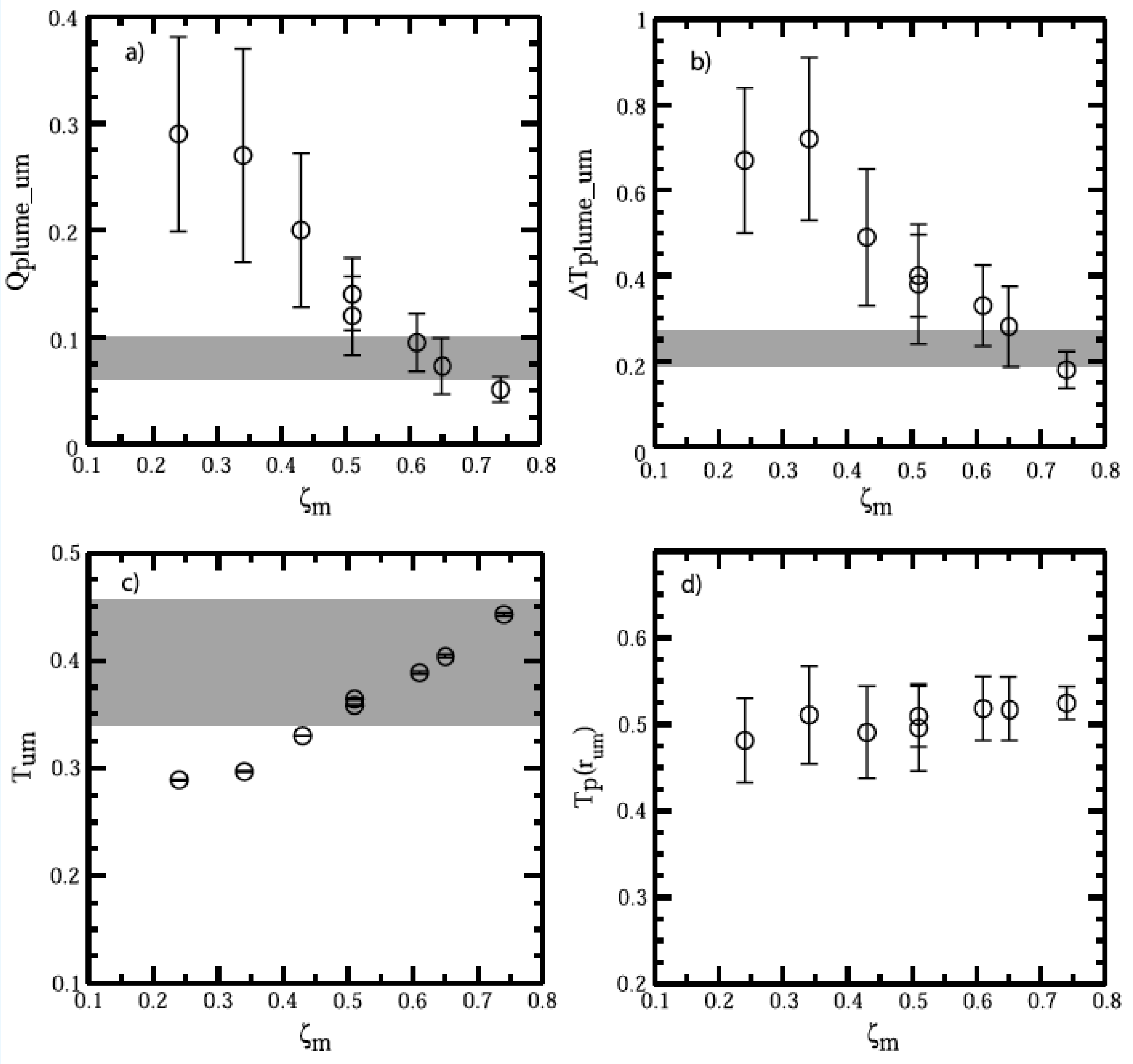
→ $\Delta T_{plume}/T_{um}$ *~ 0.19-0.27*

3) Q_{plume} *~ 2.4-3.5 TW*

→ Q_{plume}/Q_s **~6-10%**

[Davies, 1988; Sleep, 1990].

Plumes constrain the internal heating ratio to be ~70%



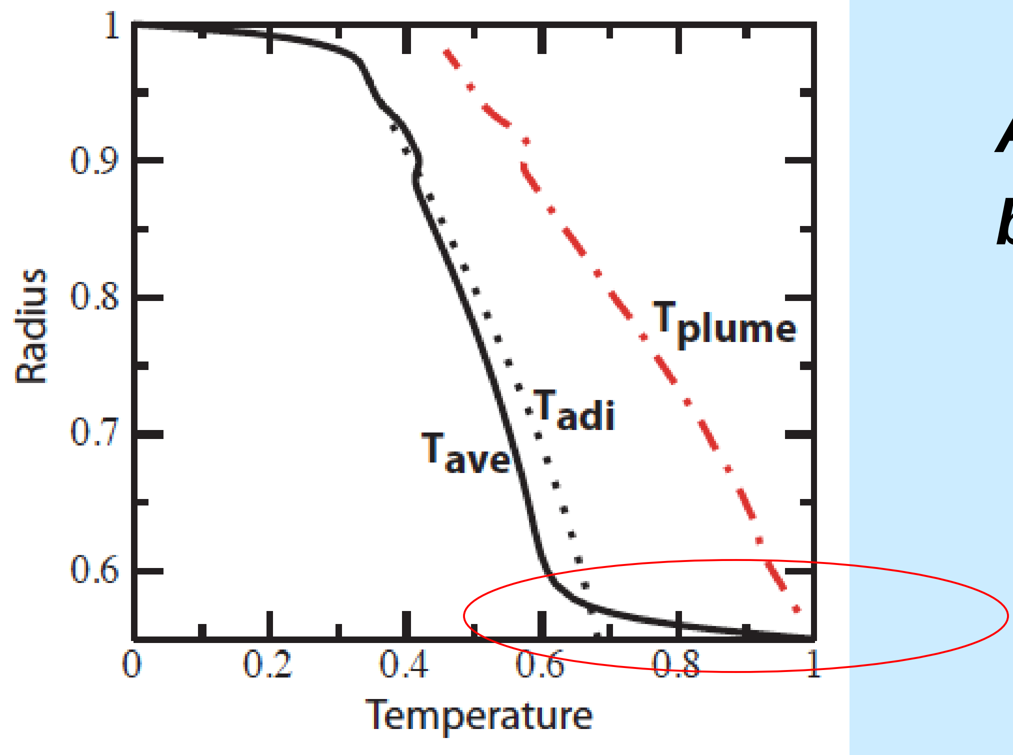
Q_{cmb}~30%Q_s
~10 TW

Summary on convective mantle geotherms

- ***Follow adiabats with <200 K subadiabatic temperature in the lower mantle.***

- ***A plume would follow its own adiabat with a steeper slope due to its high temperature (important for some problems, e.g., plume flux).***

Geotherms in the CMB region

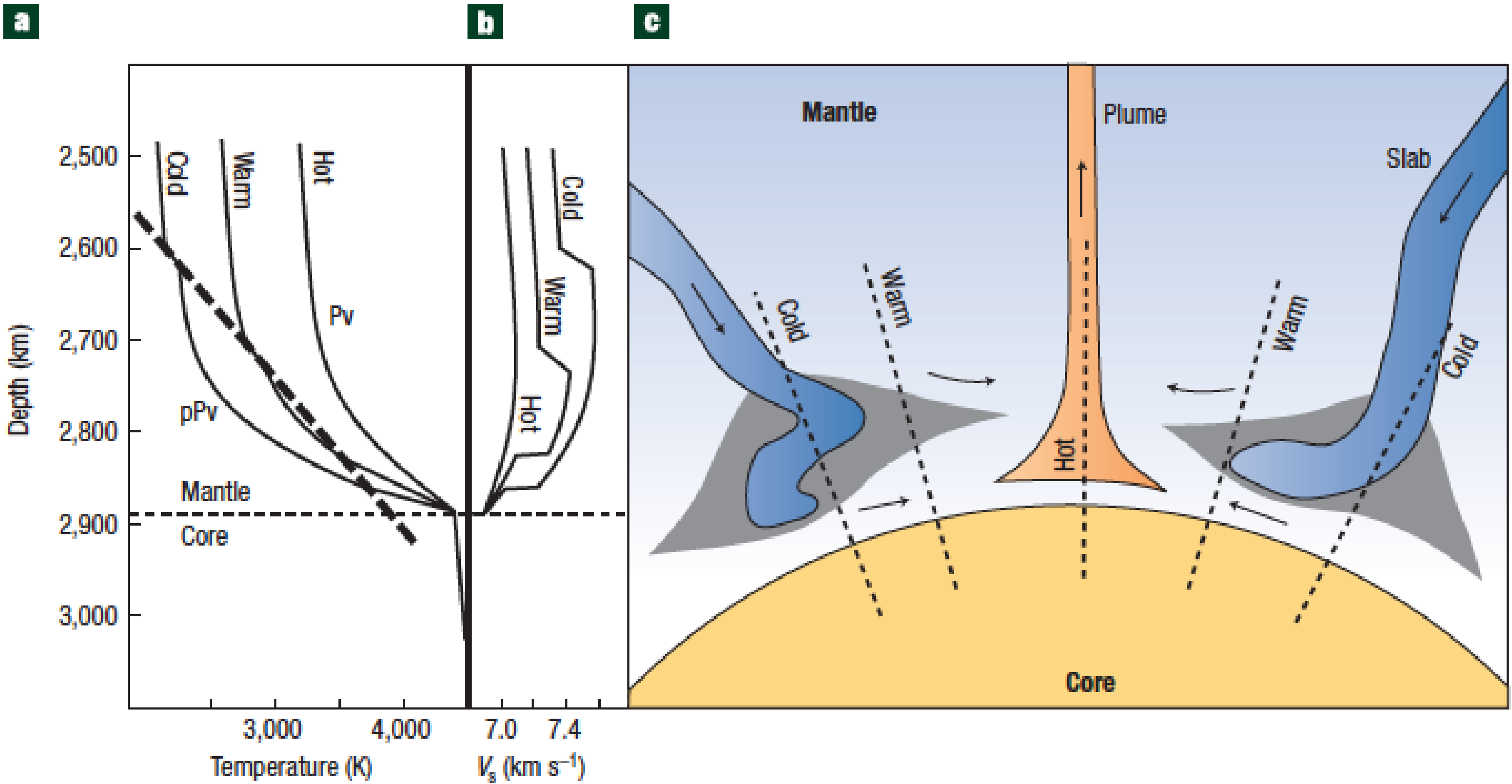


Another thermal boundary layer

We need temperature anchors from melting or phase change (e.g., post-perovskite).

Also CMB heat flux is useful (from plume estimate, geodynamo, post-perovskite, …).

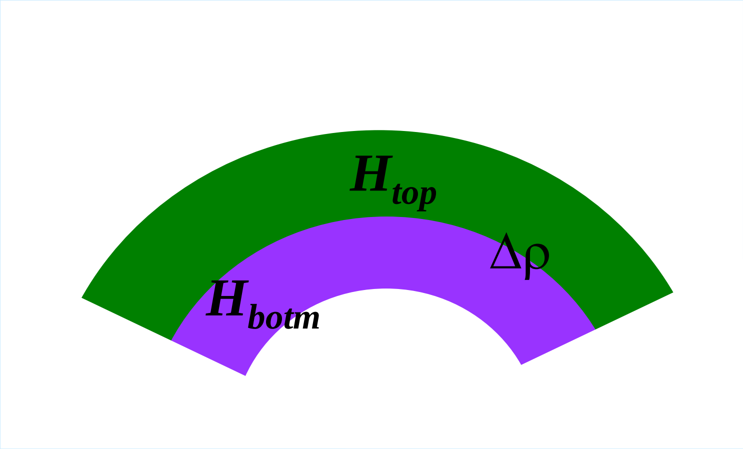
Post-perovskite phase change



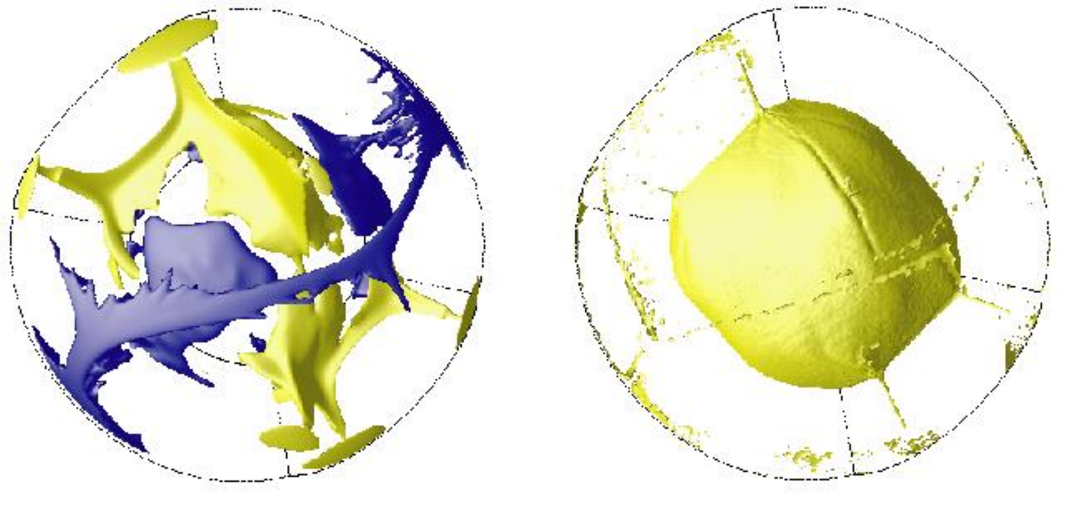
Lay et al., [2008]; Hernlund et al., [2005]

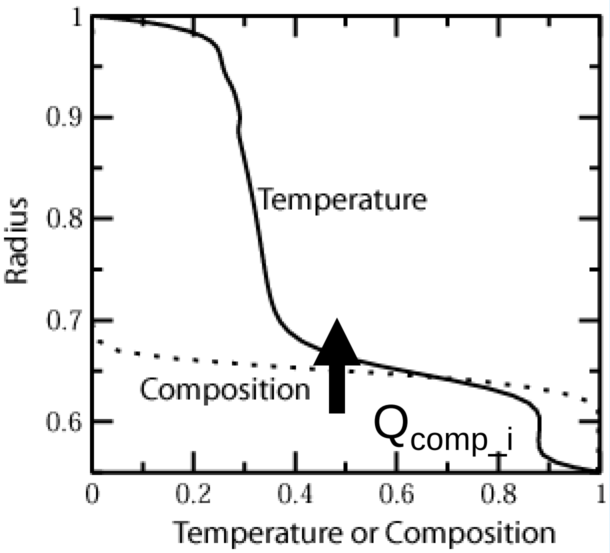
However, post-perovskite phase change may not be a global feature (unlike 410- and 670-km).

Two-layer thermochemical models



Thermochemical piles?





Yet another thermal boundary layer