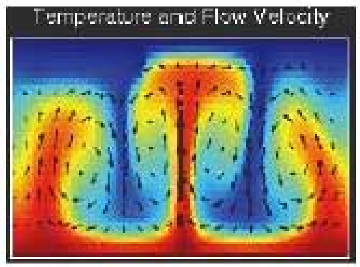
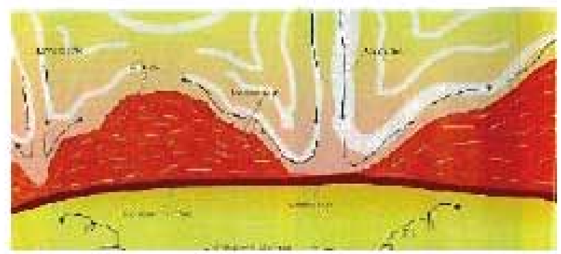
Harvard – MIT Joint Seminar/Lecture series: Spring 2005

Thermal and Chemical Evolution of the Earth





INTRUCTORS:
MIT (course 12.570):
Prof. Rob van der Hilst
Prof. Bradford Hager

Harvard (course EPS 260):
Prof. Richard O'Connell
Prof. Jeremy Bloxham

Results from EPS 260/MIT 12.570 in 1998

Two Earth-shaking papers!!!

Image removed due to copyright considerations.
Please see:

Becker, T. W., J. B. Kellogg, and R. J. O'Connell. "Thermal constraints on the survival of primitive blobs in the lower mantle". *EPSL* 171, no. 351 (1999).

Image removed due to copyright considerations.
Please see:

Kellogg, J. B., and R. J. O'Connell. "The effects of toroidal motion and layered viscosity on mixing in three dimensions, *EOS Trans AGU*, 80, F, 1999.

Thermal and chemical evolution of the Earth

Issues:

- Current heat flow: magnitude and mode
- Heat sources: Initial heat and radiogenic
- Heat from core: geodynamo & conduction
- Heat transfer in Earth: Style of convection
- Evidence for layers in mantle
- Boundary layers: Lithosphere and CMB and ???
- Models of evolution: parameterized convection

Thermal evolution:

Chondritic coincidence:
'chondritic' values of heat sources are
roughly equal to present day heat flow

Time constant for Earth temperature changes
depends on mode of heat transfer
and style of convection.

Terrestrial heat flux

$J_{ave} = 100$ mW/m^2

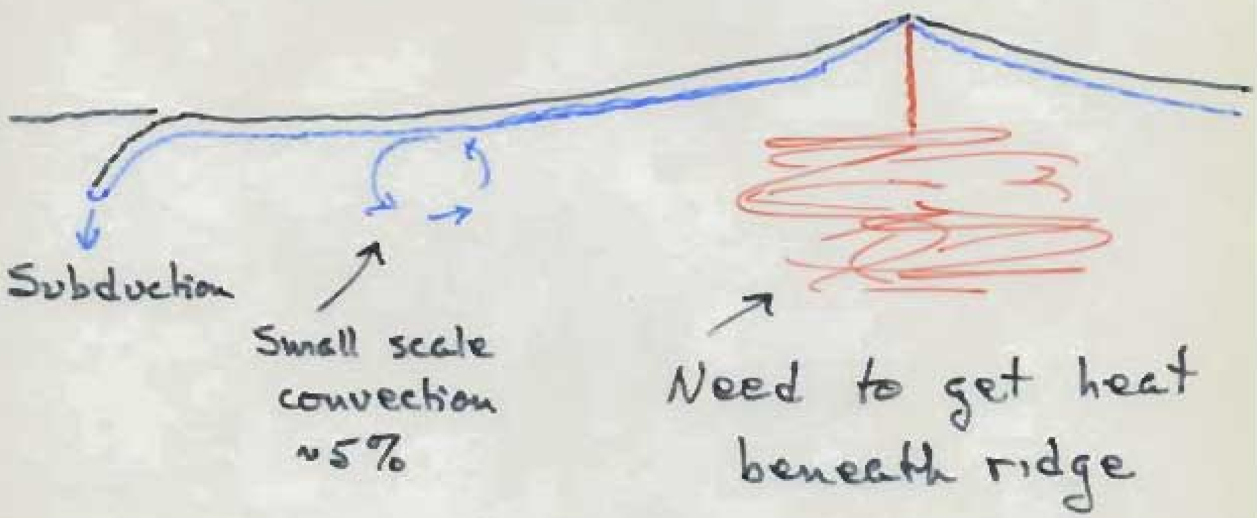
Oceanic

$J \sim \frac{500}{t^{1/2}(\text{my})}$

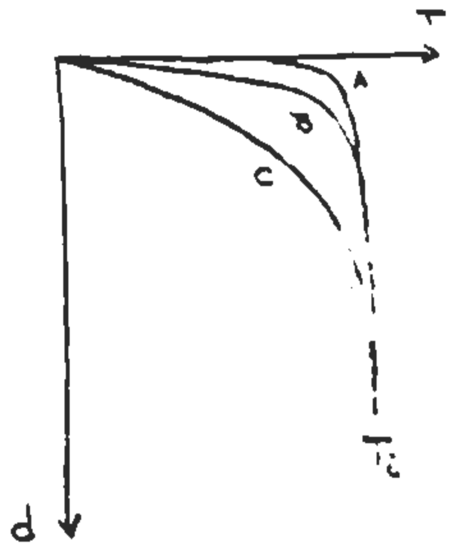
2 stages

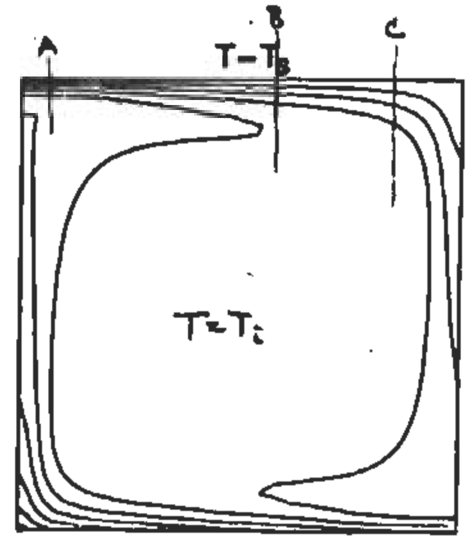
(1) Magma transports heat to ridge, heats lithosphere

(2) Lithosphere cools by conduction



Time or horizontal average boundary layer



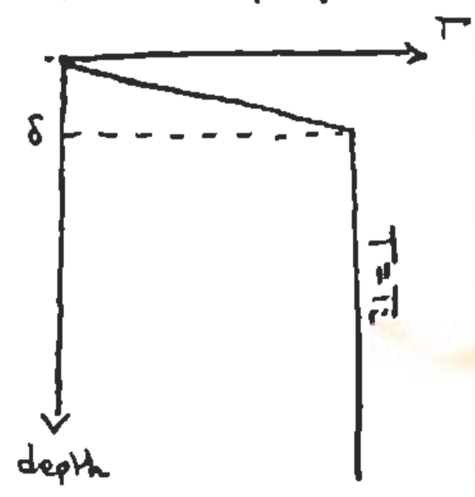


Thickness of boundary layer depends on position

Define average thickness such that average heat flux is

$$J = K \frac{T_i}{\delta}$$

or $\delta = \frac{KT_i}{J}$



Terrestrial heat flow

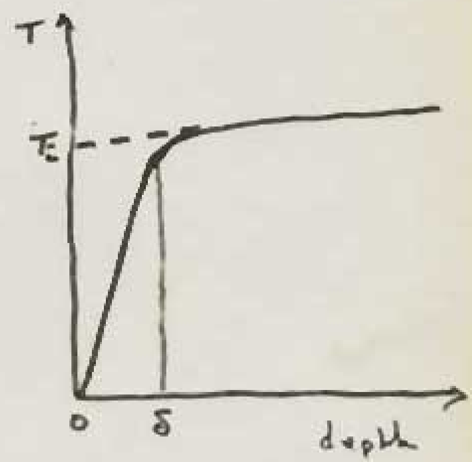
Oceans $J = 500/t^{1/2}$ mW/m^2 t (my)

Age distribution of oceans $\Rightarrow$ $J = 98$ mW/m^2

Continents $J = 53$ mW/m^2

Global average = 80 mW/m^2 (41 TW)

- 74% - cooling oceanic lithosphere
- 26% - continents



Equivalent boundary layer thickness

$$J = K \frac{T_c}{\delta} \sim 2.5 \frac{1250}{\delta}$$

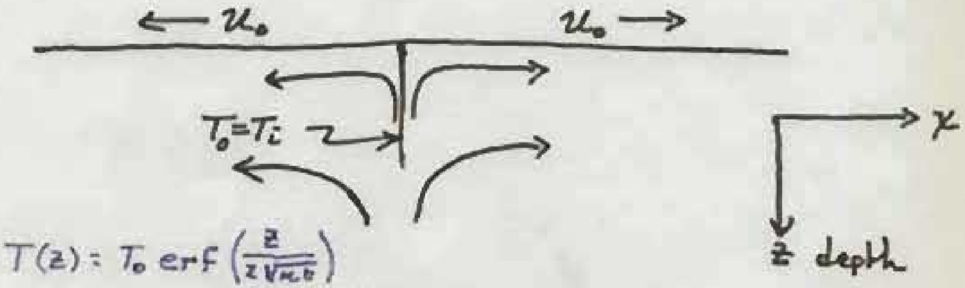
Oceans : $\delta \sim 32$ km

Continents : 59 km

Average : 39 km

neglects surface radioactivity

Surface cooling of boundary layer



$T(z) = T_0 \operatorname{erf}\left(\frac{z}{2\sqrt{\kappa t}}\right)$

Heat flux (age) $= KT_0 / \sqrt{\kappa t}$

Ave. heat flux $= \frac{1}{2} KT_0 / \sqrt{\kappa \tau}$

τ = maximum age

$u_0 \tau = \ell$ = horizontal size of plate

$$J = \frac{KT_0}{\delta} \Rightarrow \delta = 2\sqrt{\kappa \tau} = 2\left[\frac{\kappa \ell}{u_0}\right]^{1/2}$$

$\therefore$ relates velocity u_0, horiz length ℓ and boundary layer thickness δ

$$\boxed{u_0 \sim 16 \frac{\ell}{d} \frac{\kappa}{d} \left(\frac{Ra}{Ra_c}\right)^{1/2}}$$

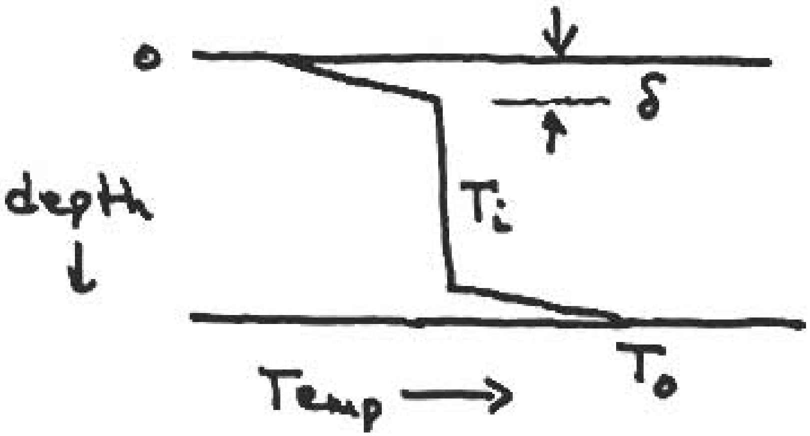
$\frac{2}{3}$ if heated beneath

$\sim 10^{-9} = 3\,\mathrm{cm/y}$

aspect ratio Δ

Convection - scaling at high Rayleigh number

Heated below, temp = T_0



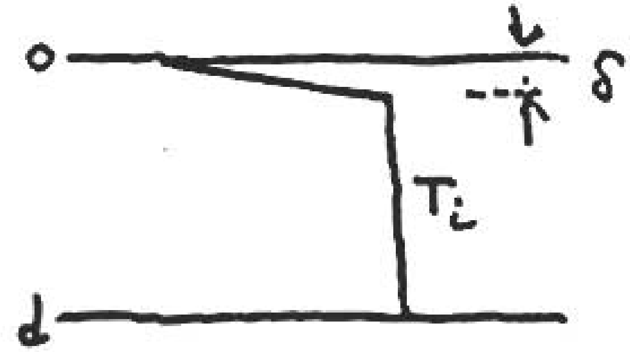
Temp $T_i = \frac{1}{2} T_0$ fixed

Heat flux $J = K\, T_i/\delta$ varies

$$Ra = \frac{\rho \alpha g d^3 T_0}{\kappa \eta}$$

$$Nu = \frac{J}{J_{cond}} = \frac{d}{2\delta}$$

Internal heat A/vol.



Flux $J = Ad$ fixed

Temp T_i varies

$$Ra = \frac{\rho \alpha g d^4 J/K}{\kappa \eta}$$

$$Nu = \frac{T_{cond}}{T_i} = \frac{d}{2\delta}$$

$$Nu = \frac{J}{J_{cond}} = \frac{d}{2\delta} \qquad Nu = \frac{T_{cond}}{T_i} = \frac{d}{2\delta}$$

Thermal boundary layer thickness $\delta = \frac{\kappa T_i}{J}$

① Convection strength $Nu = f(Ra)$

② δ independent of d -or- bound. layer marg. stable

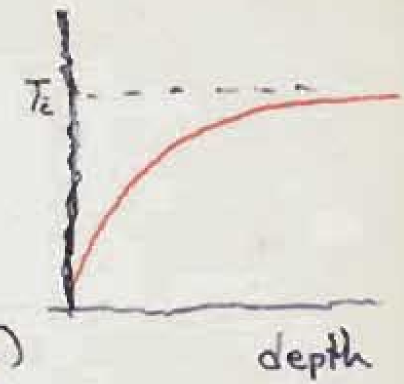
$$\Rightarrow \quad Nu \sim \left(\frac{Ra}{Ra_c}\right)^{1/3} \qquad Nu \sim \left(\frac{Ra}{Ra_c}\right)^{1/4}$$

$$\delta \sim \frac{d}{2}\left(\frac{Ra}{Ra_c}\right)^{-1/3} \qquad \delta \sim \frac{d}{2}\left(\frac{Ra}{Ra_c}\right)^{-1/4}$$

$$* \quad u_0 \sim 16\,\Delta\,\frac{\kappa}{d}\left(\frac{Ra}{Ra_c}\right)^{2/3} \qquad u_0 \sim 16\,\Delta\,\frac{\kappa}{d}\left(\frac{Ra}{Ra_c}\right)^{1/2}$$

* from boundary layer cooling, $\Delta = \frac{\ell}{d} = \frac{\text{width}}{[illegible]}$

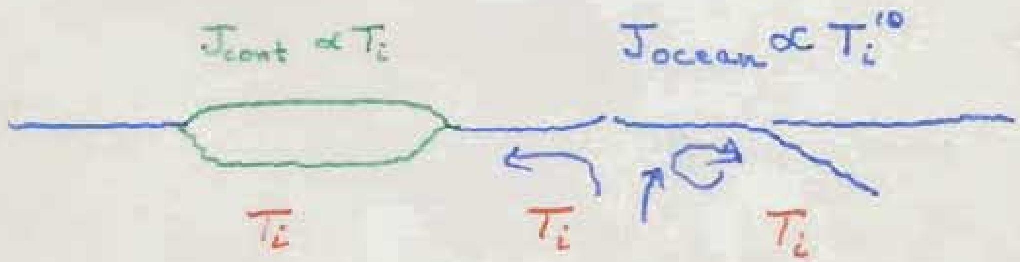
Heat flux $J = f(T_i)$



Conduction $J \propto T_i$

Convection $J^{1/3} \propto T_i$ (b.l. th)

$J^{1/10} \propto T_i$ (rheology $= f(T_i)$)



Oceans dominate global heat flow

$\Rightarrow T_i \propto J_{global}^{1/10}$

Double $J_g \Rightarrow$ 7% increase in T_i

Load line: T & J not independent