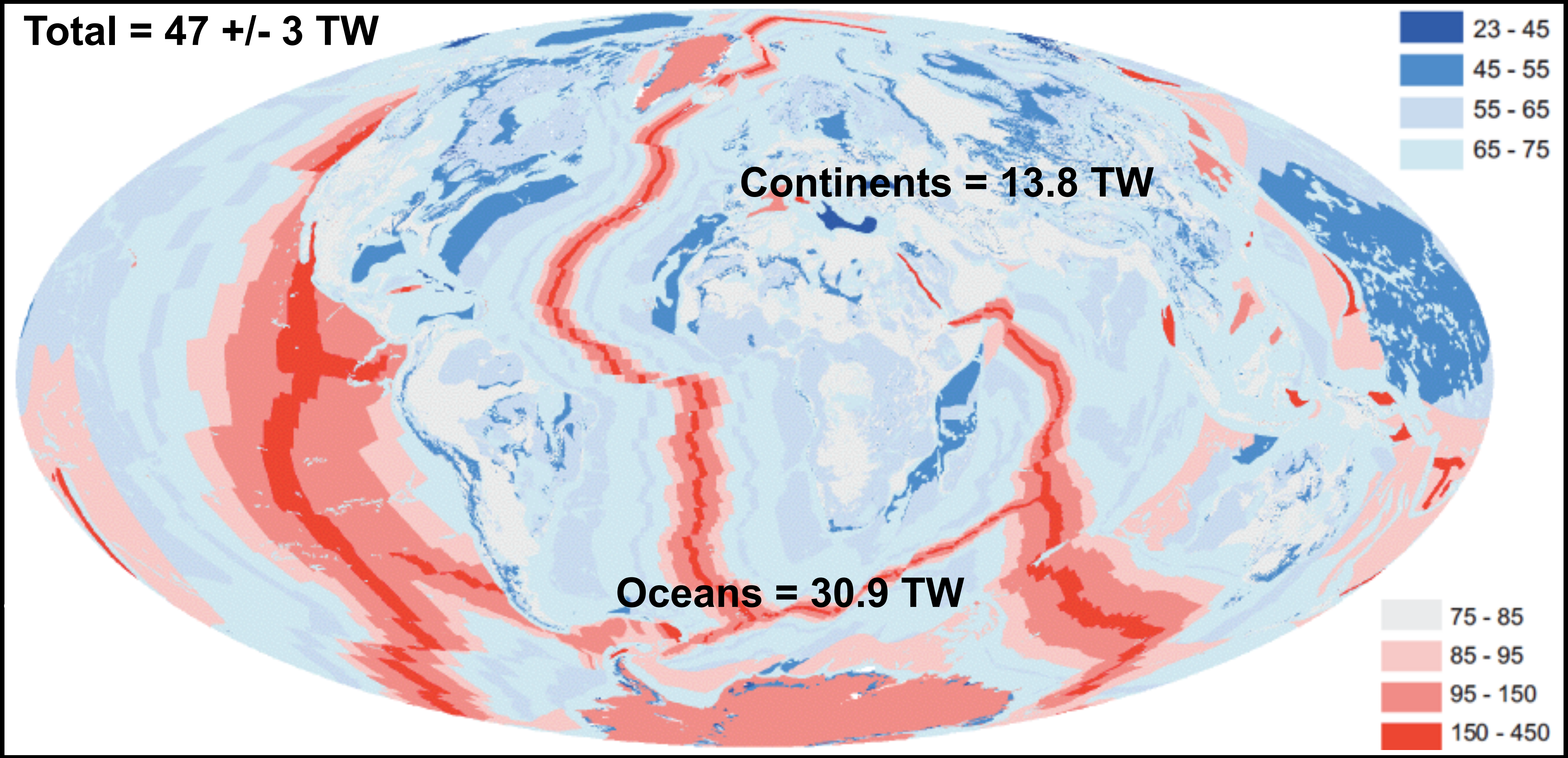
Earth’s Power Budget:

Significance of Radiogenic Heating

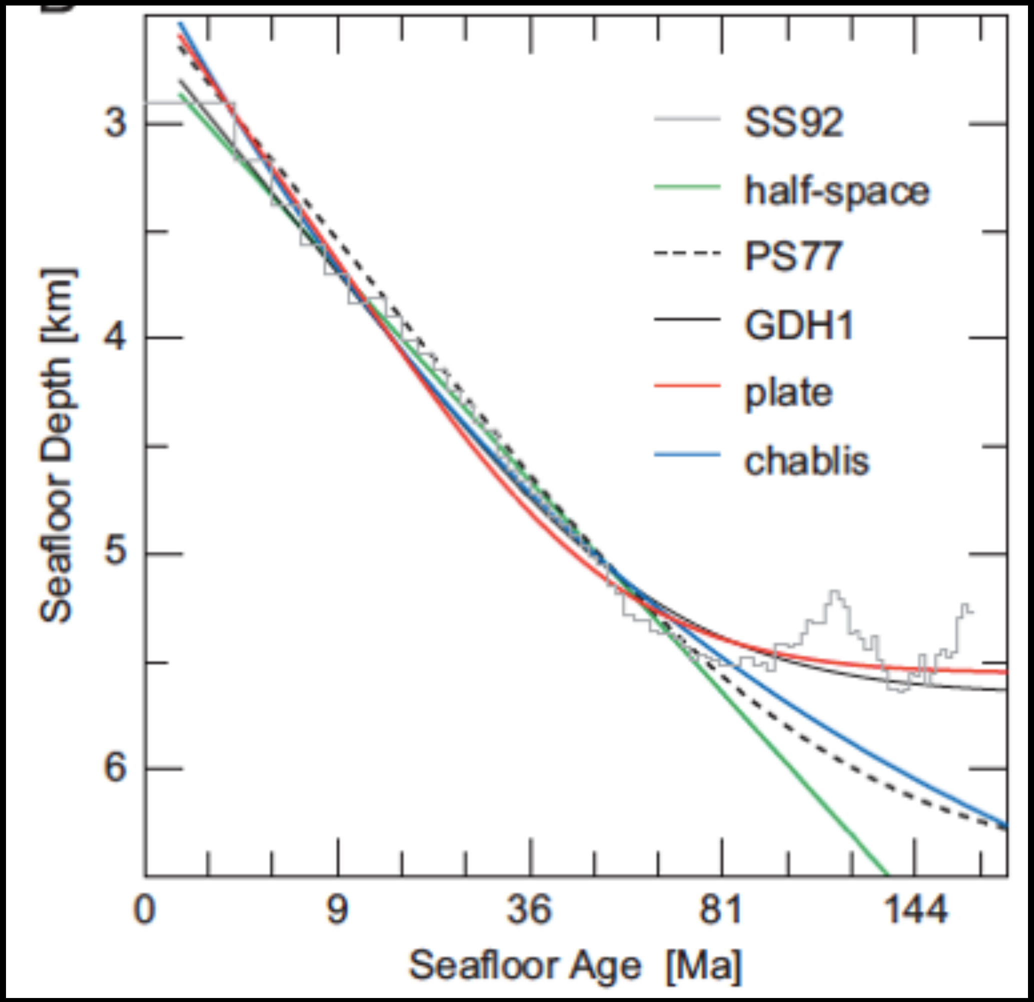
Global heat flux



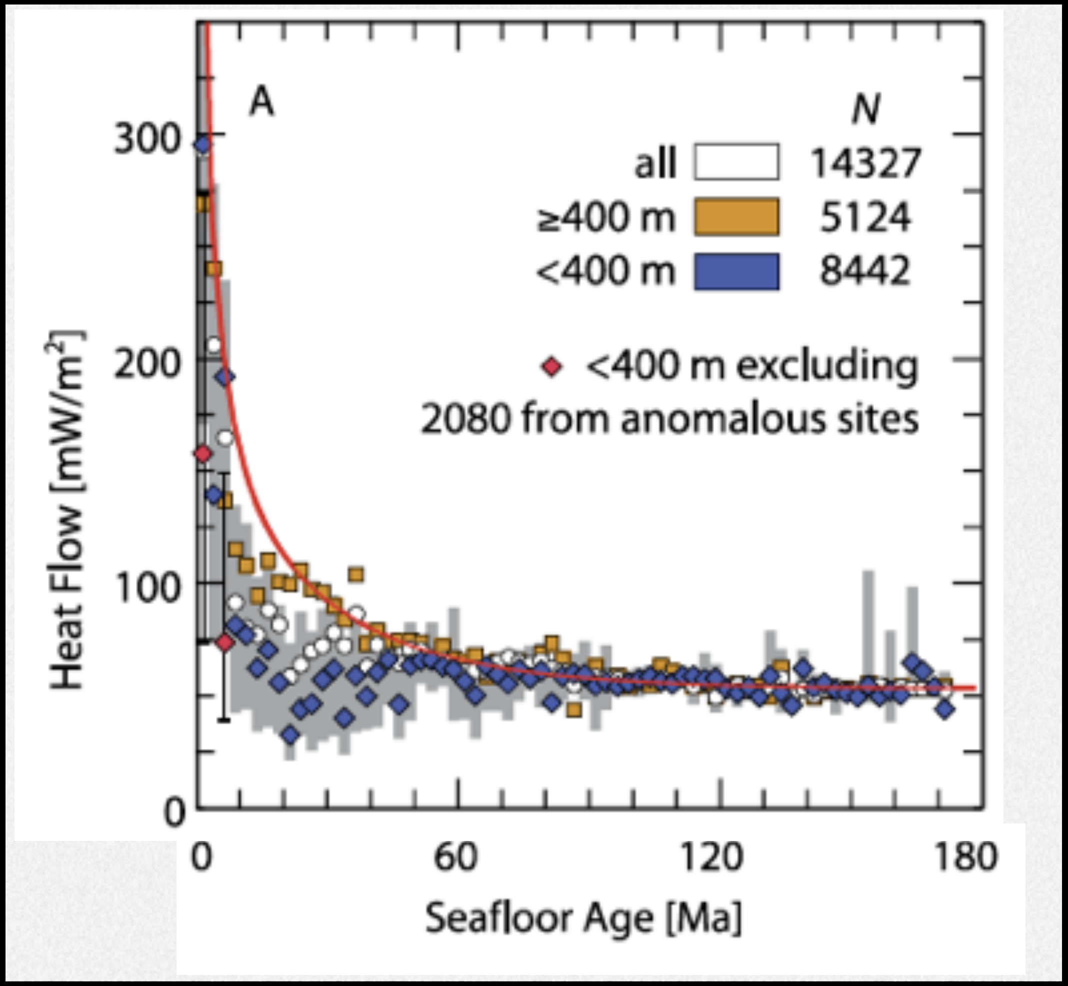
~38k data of various quality, Q correlated with geology, 1/2 space cooling model for young (<65Ma) seafloor

Davies and Davies, Solid Earth, 2010

Global heat flux



observed sea floor flattening in age-depth curve likely due to small scale convection and incomplete thermal contraction. Favors plate model.

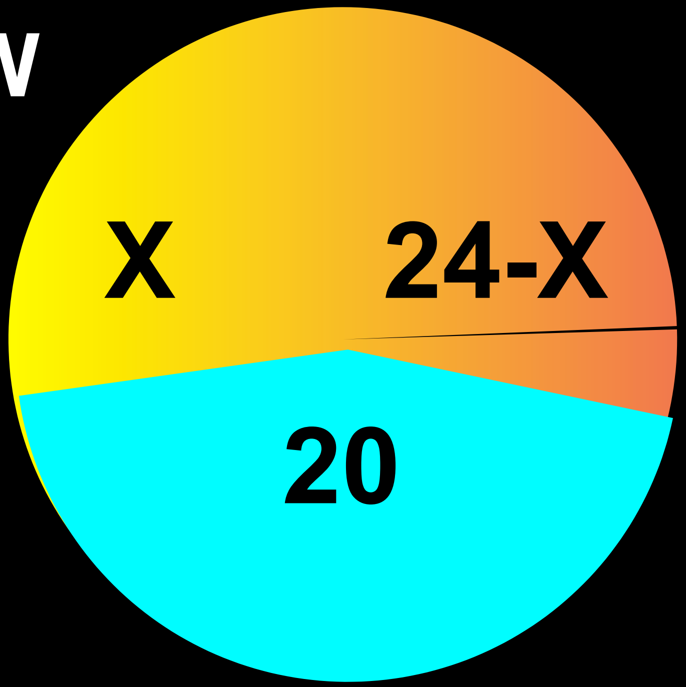


observed heatflow deficit in young ocean floor due to hydrothermal circulation. Estimated deficit = 8 TW

Hasterok, EPSL, 2013a,b

Earth’s budget crisis

in units of TW

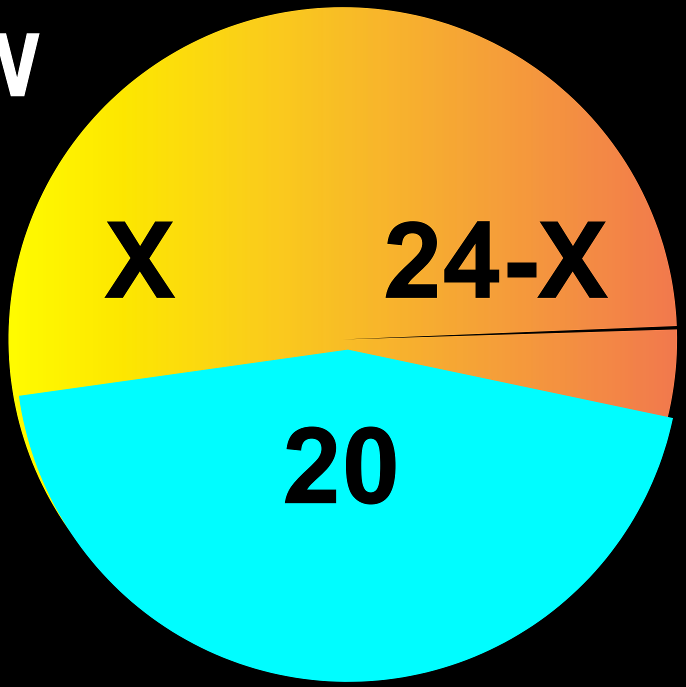


$$Q_{surface} = VH(t) + V\rho c_p dT/dt + Q_{cmb}$$

44 TW = radiogenic heat production + mantle secular cooling + core heat flux

Earth's budget crisis

in units of TW

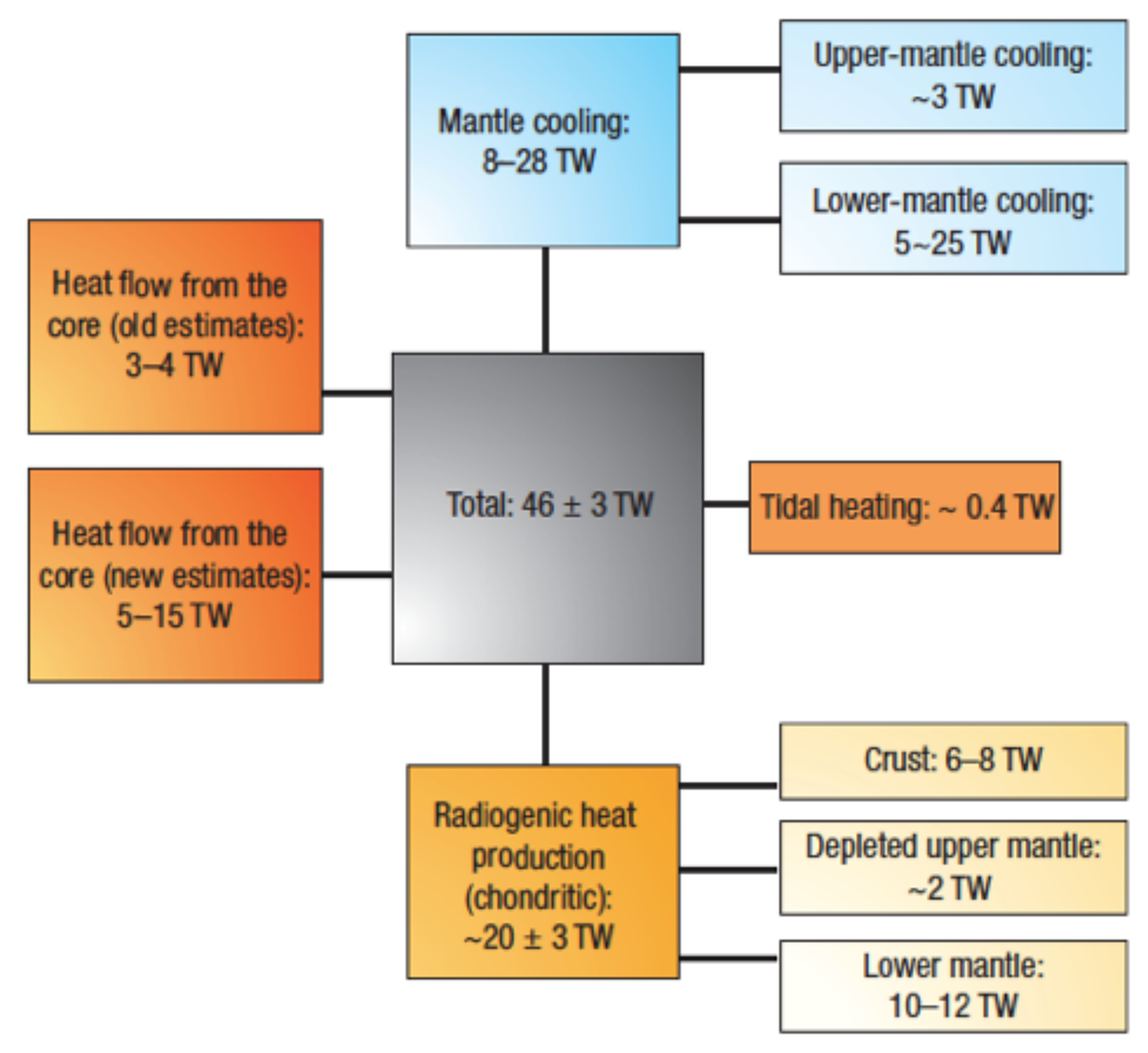


$Q_{surface}$ = $VH(t)$ + $V\rho c_p dT/dt$ + Q_{cmb}

44 TW = radiogenic heat production + mantle secular cooling + core heat flux

Observations Talks by Bill & Matt | This talk | Leah's talk

Sources of Heat



Mantle cooling: 8–28 TW

Upper-mantle cooling: ~3 TW

Lower-mantle cooling: 5–25 TW

Heat flow from the core (old estimates): 3–4 TW

Heat flow from the core (new estimates): 5–15 TW

Total: 46 ± 3 TW

Tidal heating: ~ 0.4 TW

Radiogenic heat production (chondritic): ~20 ± 3 TW

Crust: 6–8 TW

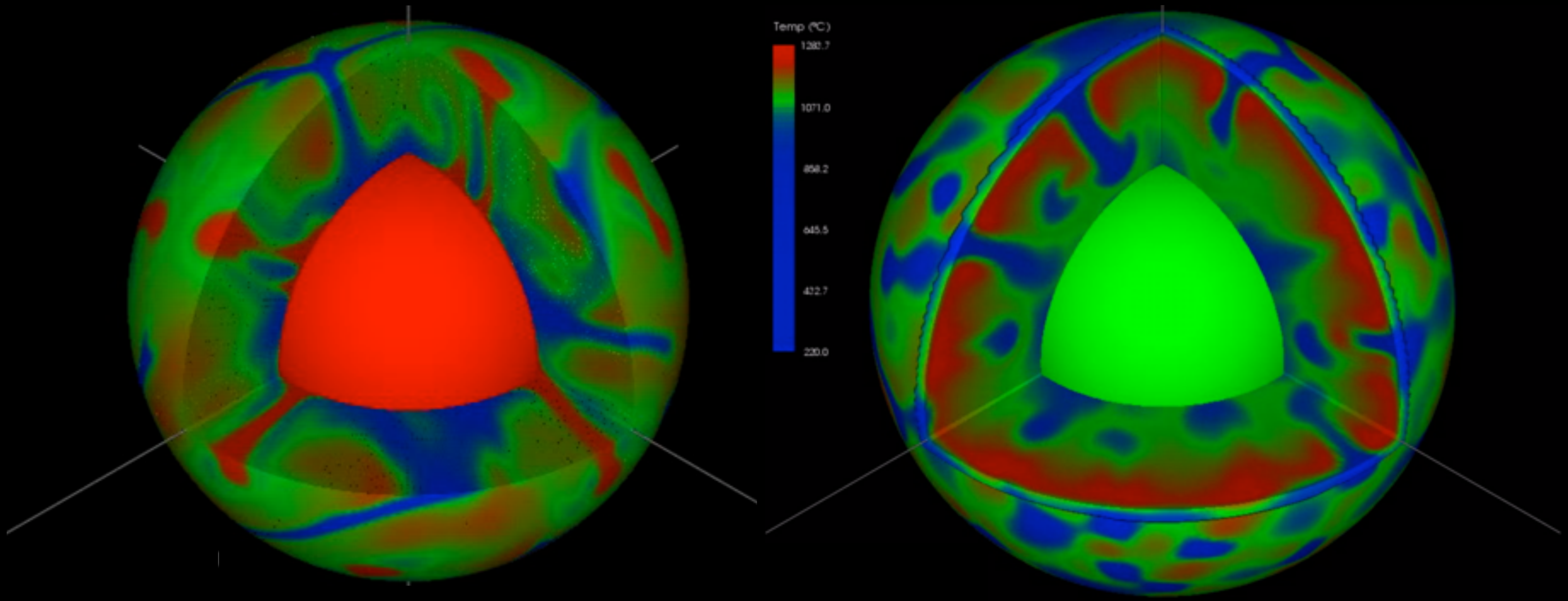
Depleted upper mantle: ~2 TW

Lower mantle: 10–12 TW

Lay, Hernlund, and Buffett, Nature Geoscience, 2008

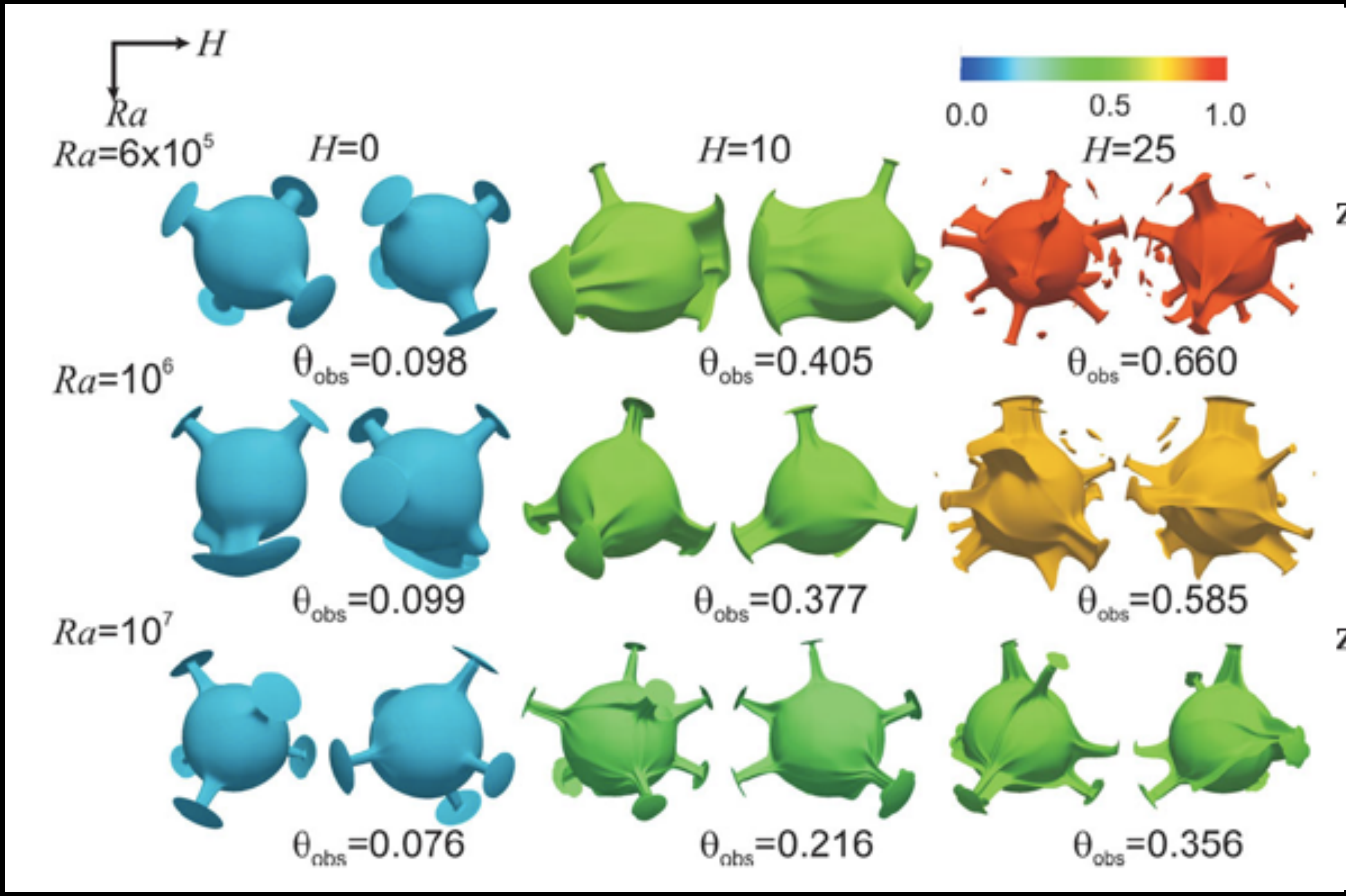
- **Few of these numbers have error bars**
- **Higher thermal conductivity values for the core now favor higher Qcmb**
- **Distribution and types of heat sources in the mantle strongly influence the dynamics and evolution and may change through time**

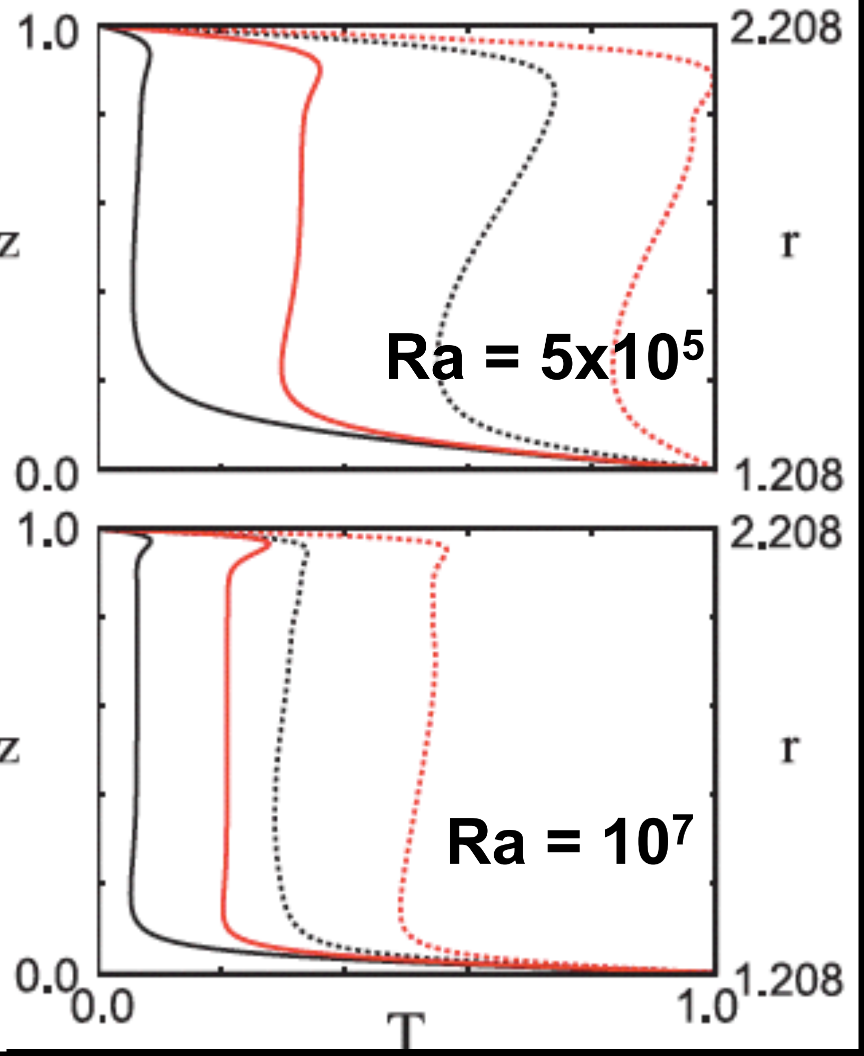
Bottom Heated vs Internal Heated



Stegman (unpublished)

Convection with mixed-mode heating





- **Viscously stratified convection models (black=spherical; dashed line H=20)**
  - **mean temperature more stratified and planform becomes time-dependent**

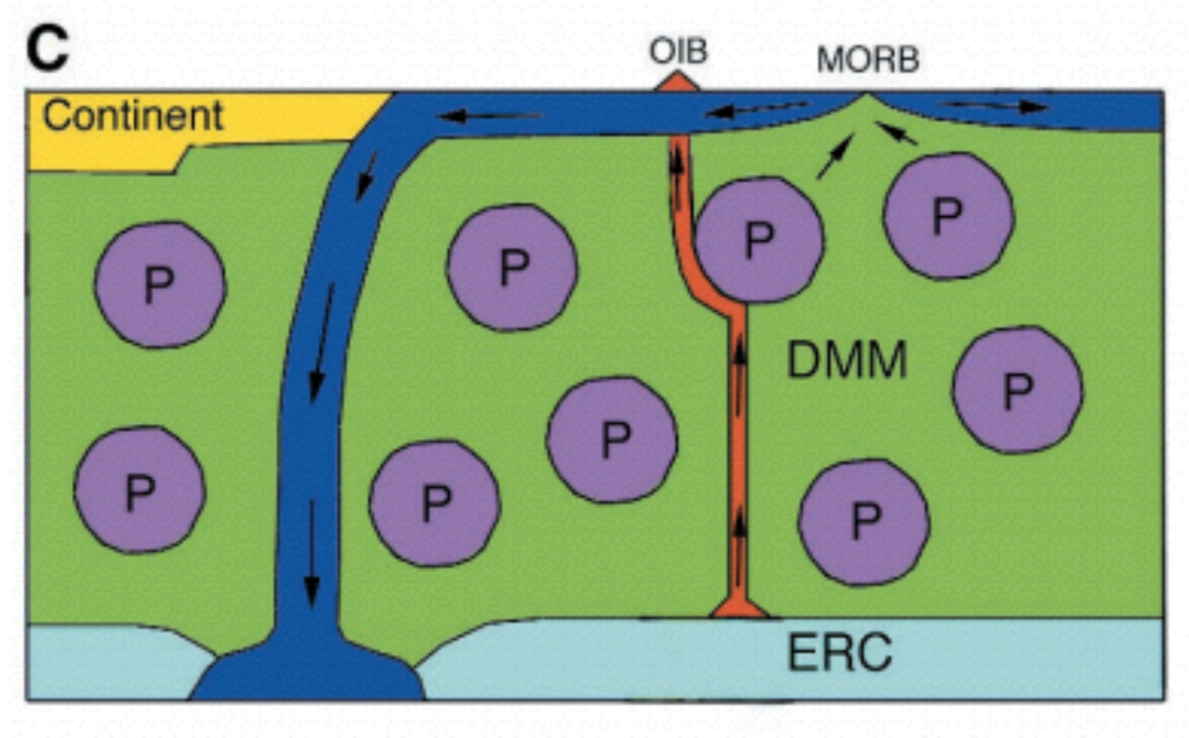
O'Farrell etal, GJI, 2013

Distribution of heat producing elements

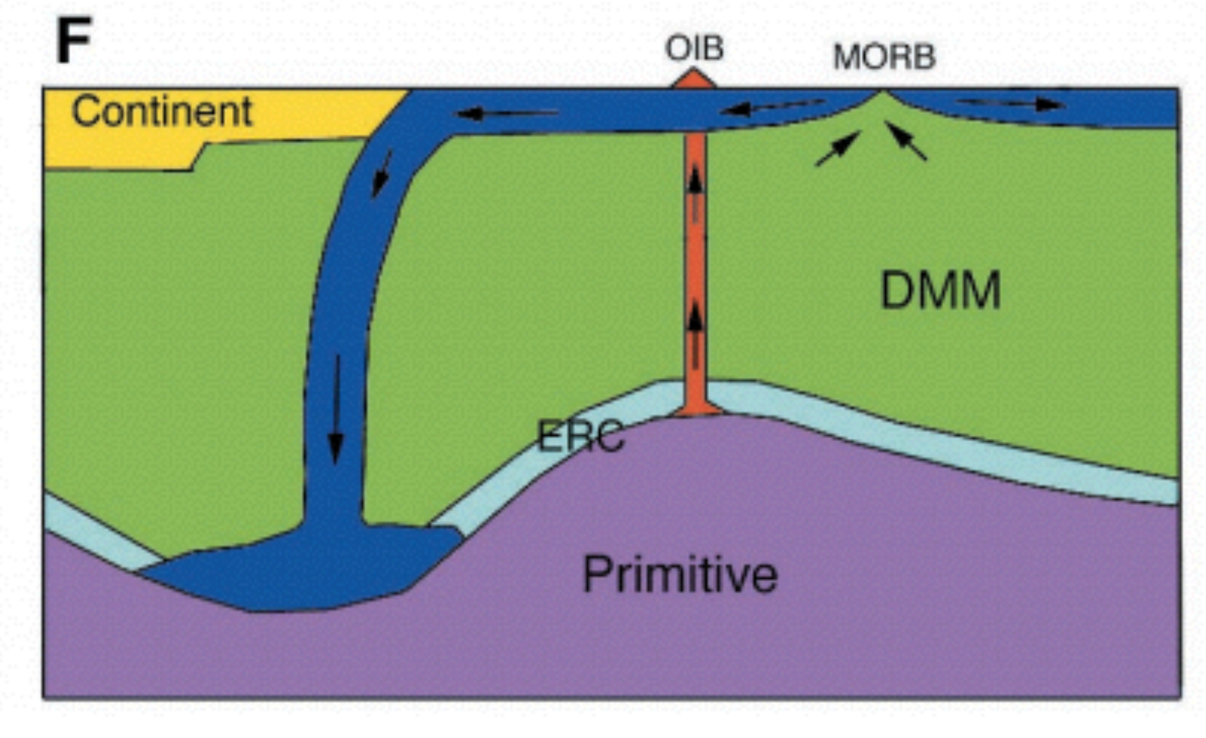
- [U] of 1 ppb ~ 1 TW (assuming Th/U and K/U ratios of 4 and 2×10^4)
- 20 ppb in $[U]_{BSE}$ which is concentration in a volume size of mantle
- Question: what is the distribution in the present day mantle?
  - 50% in continental crust, rest in mantle
  - $[U]_{CC}$ = 1.4 ppm (because volume of cont crust ~ 1% mantle)
  - $[U]_{DMM}$ = 2-7 ppb (based on [U] of fresh MORB and partitioning)
  - volume of DMM is unknown but large - upper mantle or most of mantle
- Conclusion: there must be a hidden reservoir that is highly enriched

Distribution of heat producing elements

- One idea is store radiogenic elements in primordial chemically dense material



Tackley, Science, 2000 (after Becker et al., EPSL, 1999)



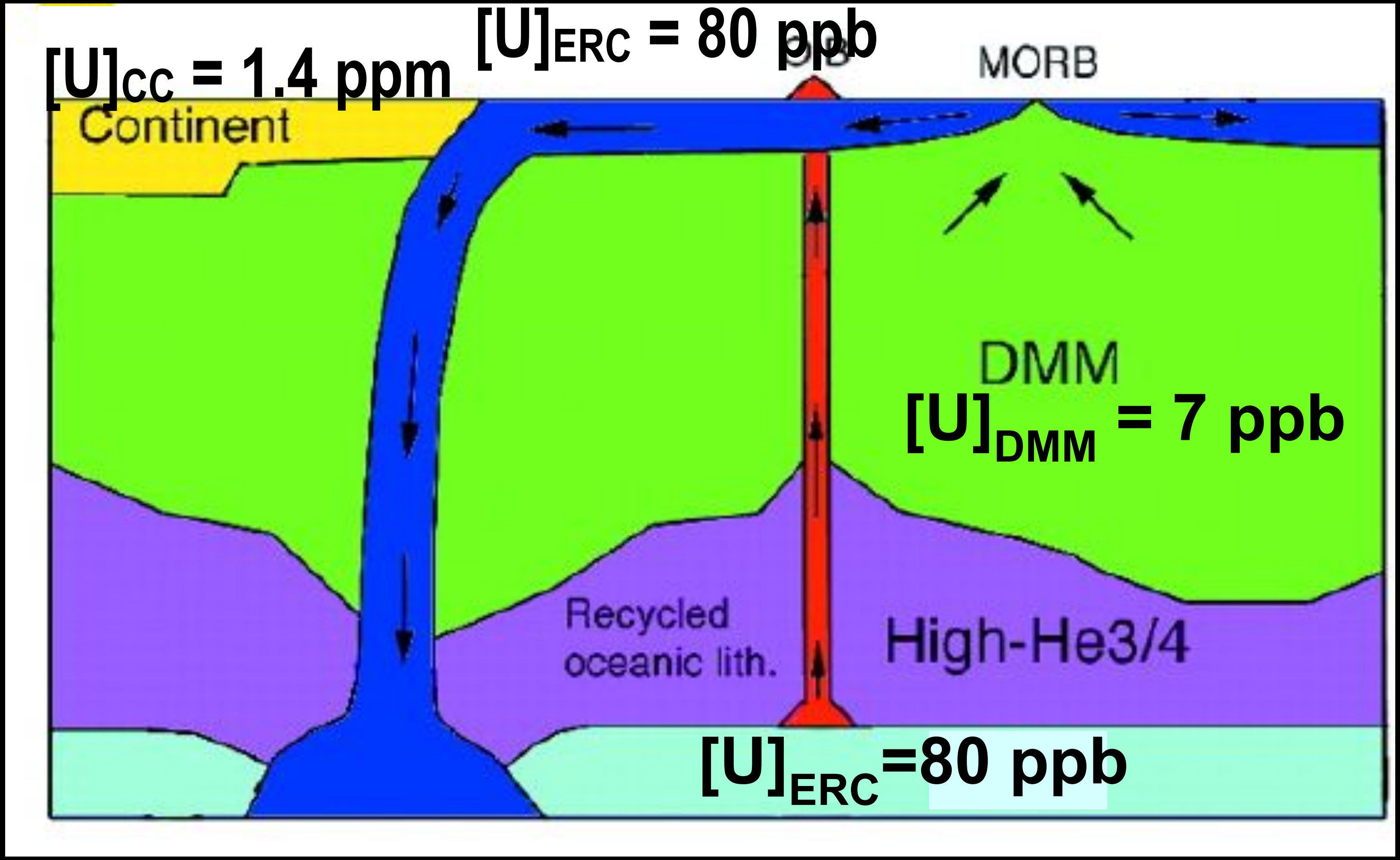
Tackley, Science, 2000 (after Kellogg et al., Science, 1999)

- neutrally buoyant blobs: compositional density is just large enough to offset temperature
- 'stealth' layer: compositional density is just large enough to offset excess temperature

- These only work for the present day since compositional density changes little over time, but radiogenic heating is exponentially decaying (x5 in 4.5 Gyr)

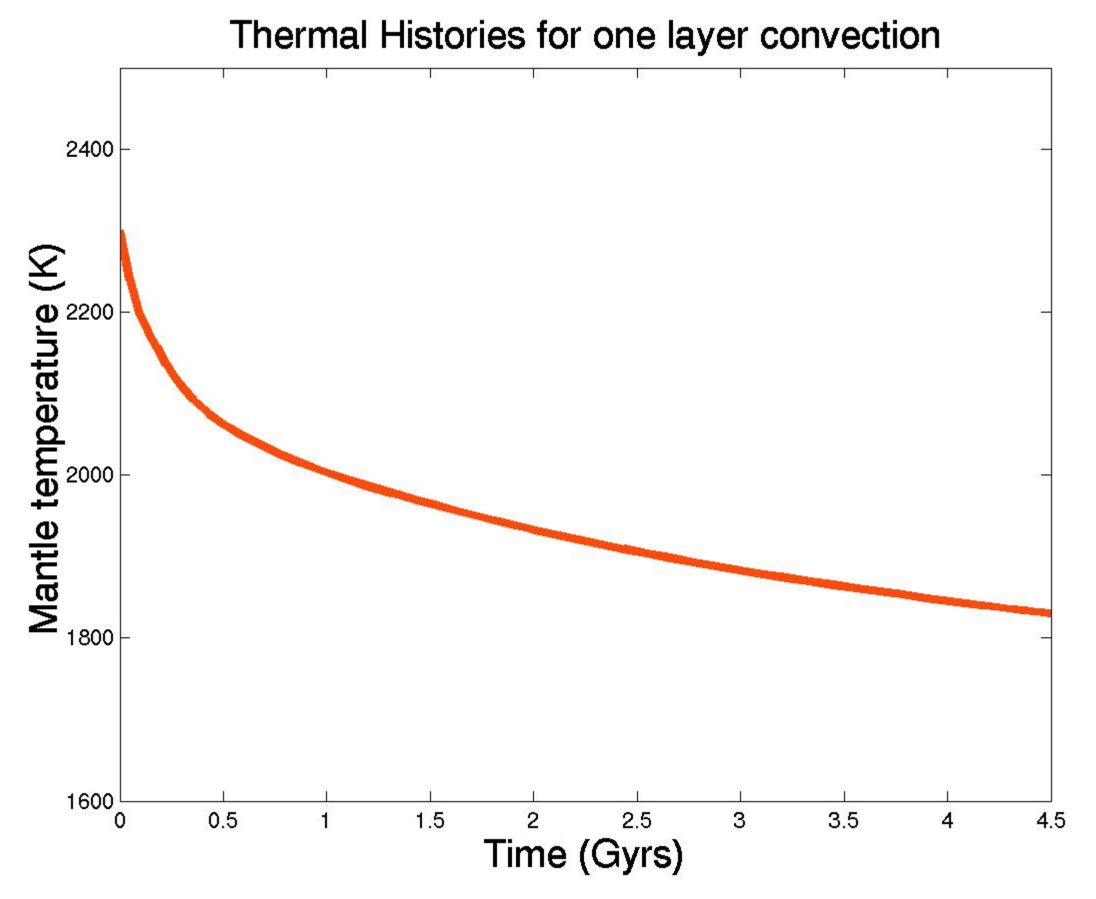
Distribution of heat producing elements

- **Estimate [U] for various geochemical reservoirs**
  - **differentiation has lead to enrichment and depletion of radiogenic elements**



Tackley, Science, 2000

Parameterized mantle convection

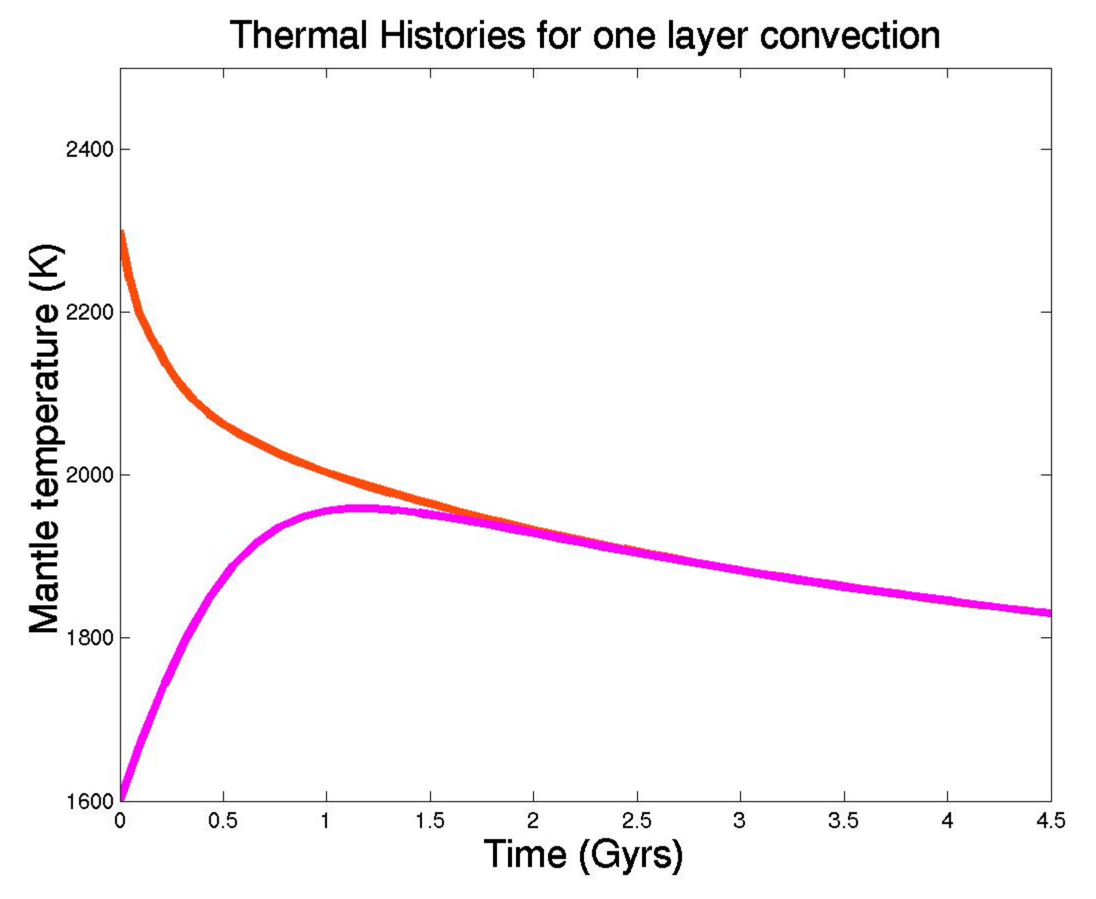


- nominal thermal history with constant viscosity (violates T-dep viscosity which allows the system to self-regulate)

- Method: use boundary layer theory to predict convective heat flow

- Constraints:
  - T_mantle present day = 1600K
  - Q_mantle present day = 36 TW
  - B-field for 3.5 Gyrs (Q_cmb)
  - T_mantle(t) < solidus for all t
  - BSE complement of HPE

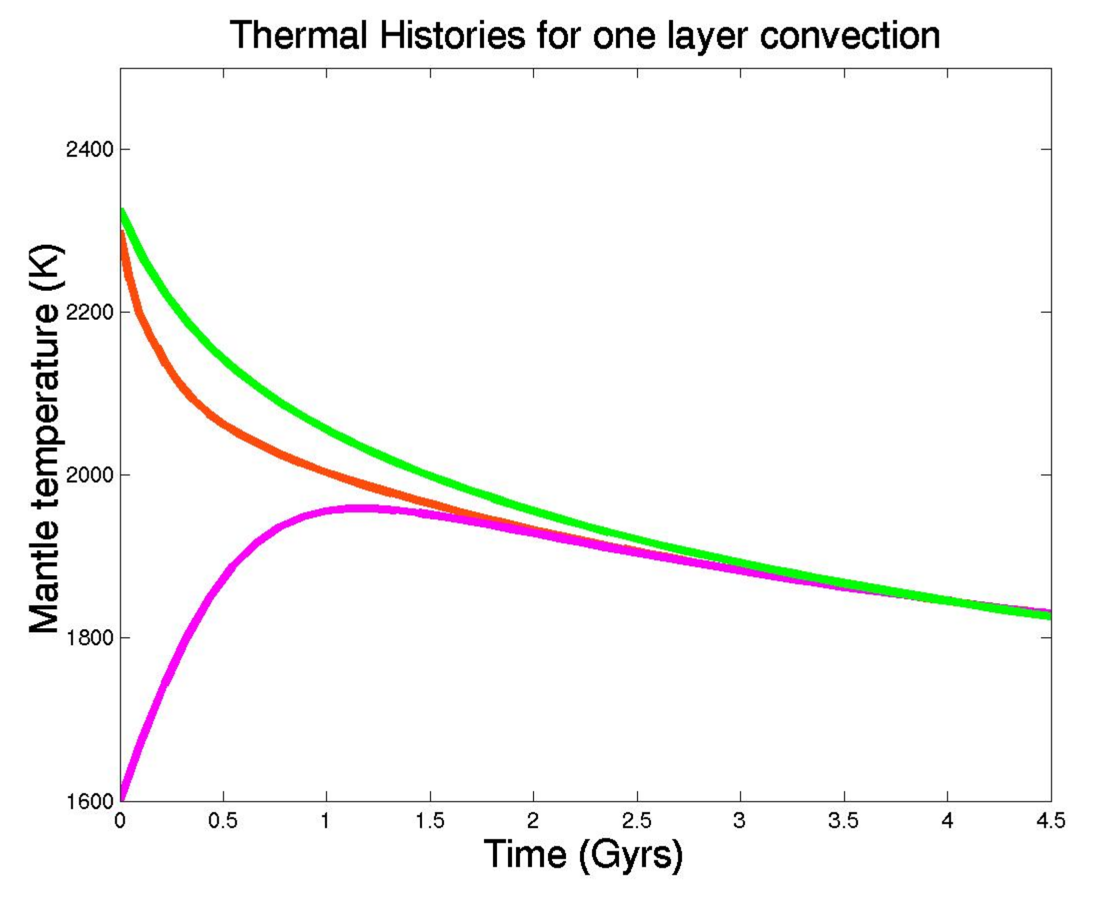
Parameterized mantle convection



- warming history (violates BSE model) initially cold start to offset very high heat production rates early on. High Q_rad delays secular cooling.

- **Method: use boundary layer theory to predict convective heat flow**
- **Constraints:**
  - **T_mantle present day = 1600K**
  - **Q_mantle present day = 36 TW**
  - **B-field for 3.5 Gyrs (Q_cmb)**
  - **T_mantle(t) < solidus for all t**
  - **BSE complement of HPE**

Parameterized mantle convection



- cooling history (violates Q_{mantle})
  Mantle cools quickly such that present day heat flow is ~30% observed value

- Method: use boundary layer theory to predict convective heat flow
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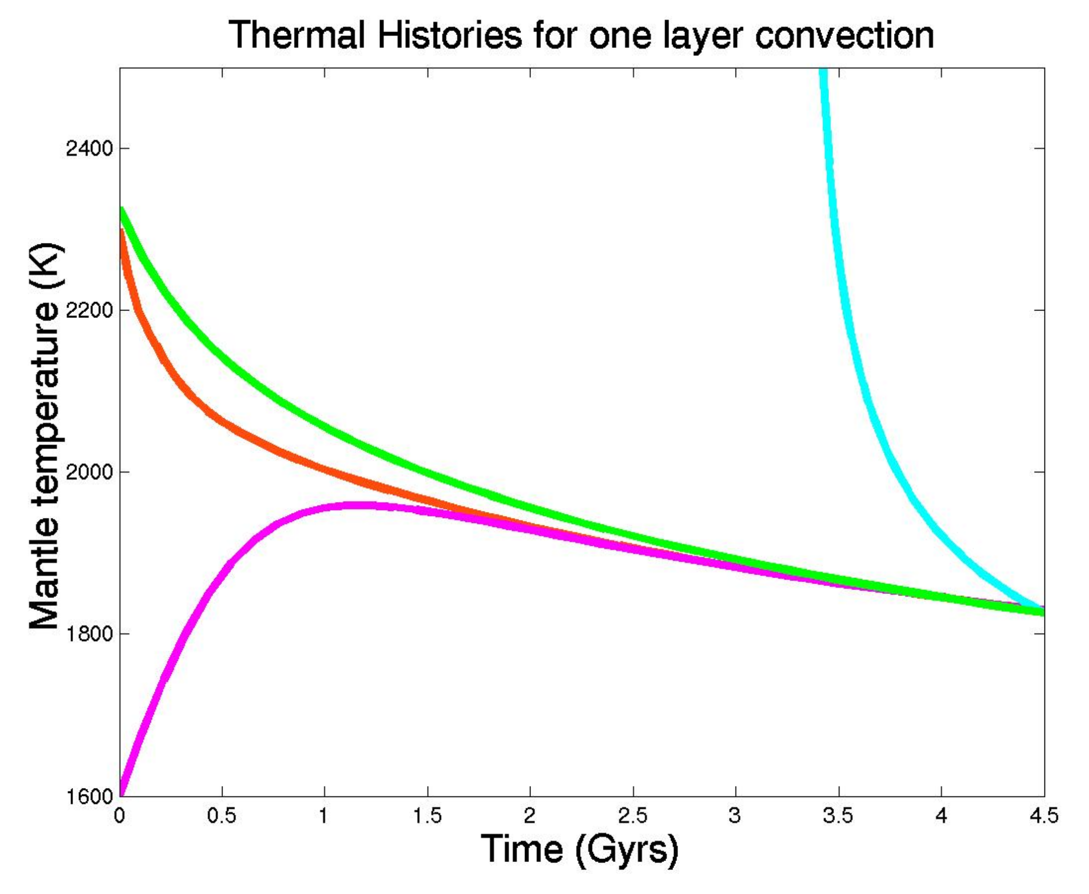
Parameterized mantle convection



- Early thermal catastrophy (violates $T_m(t)$)

with ~50% of present day Q being from secular cooling, rate of heat loss extrapolated back in time requires high mantle temps

- Method: use boundary layer theory to predict convective heat flow
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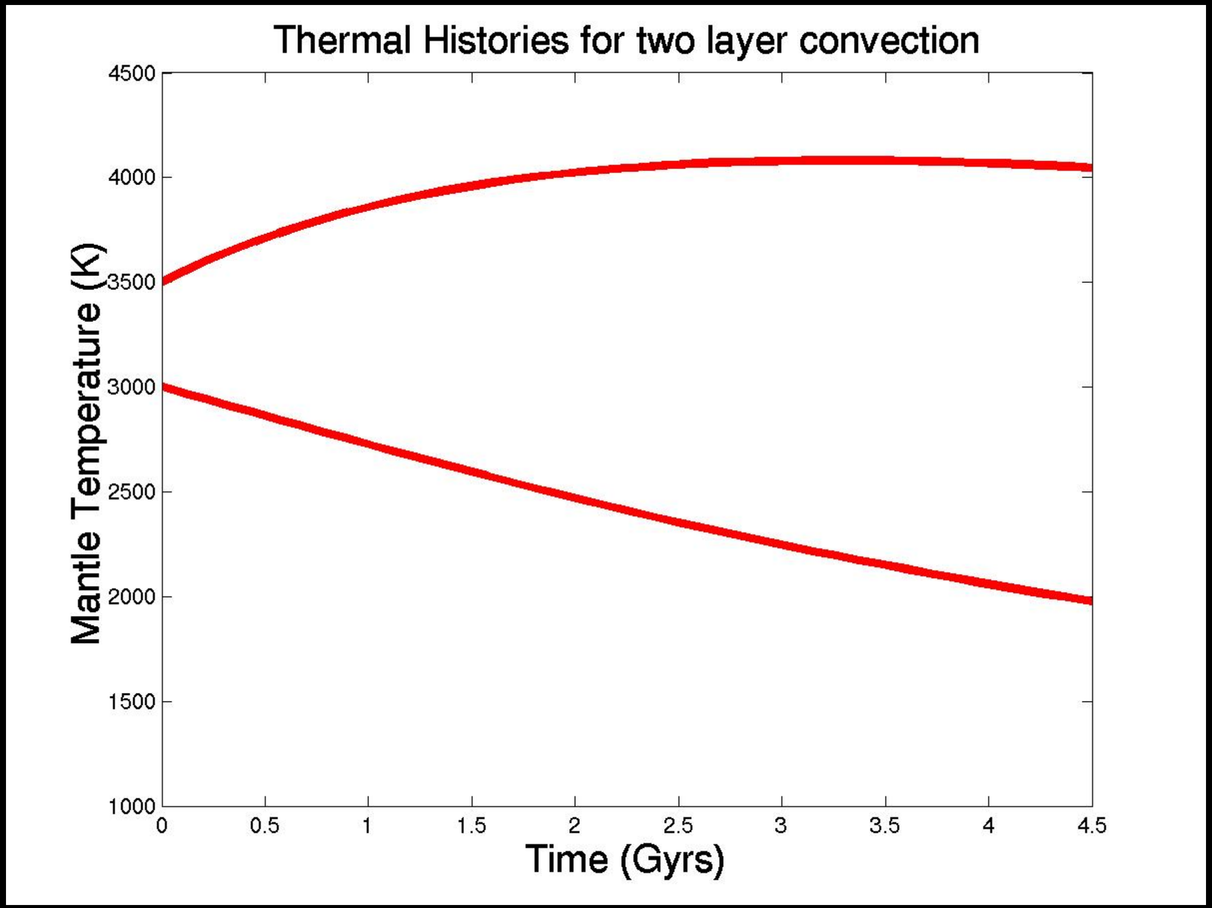

- upper mantle OK, lower mantle too hot
- large internal boundary layer would be seismically observable

- Method: use boundary layer theory to predict convective heat flow
- Constraints:
  - T_mantle present day = 1600K
  - Q_mantle present day = 36 TW
  - B-field for 3.5 Gyrs (Q_cmb)
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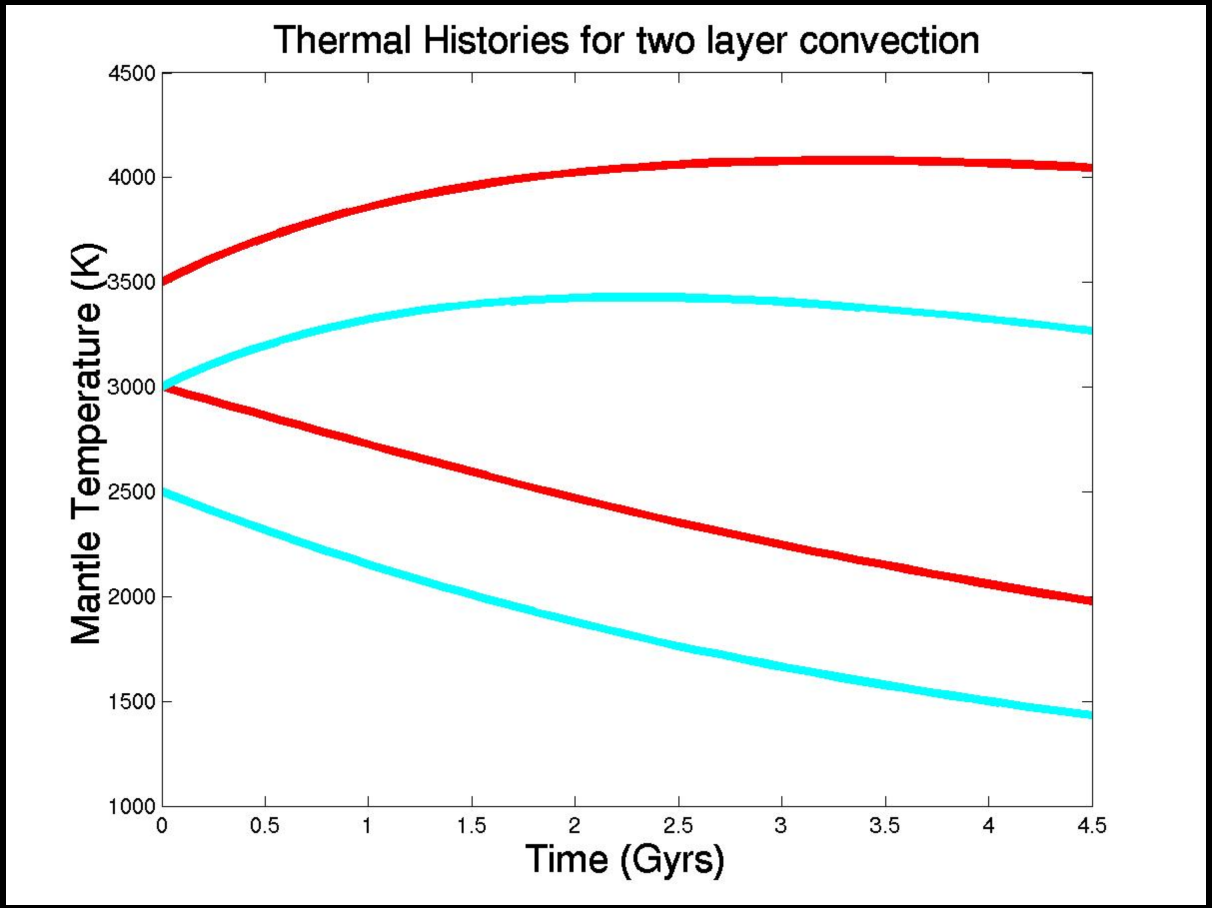
Parameterized mantle convection



- lower mantle OK, upper mantle too cold
- same problem with internal TBL

- Method: use boundary layer theory to predict convective heat flow
- Constraints:
    - T_mantle present day = 1600K
    - Q_mantle present day = 36 TW
    - B-field for 3.5 Gyrs (Q_cmb)
    - T_mantle(t) < solidus for all t
    - BSE complement of HPE

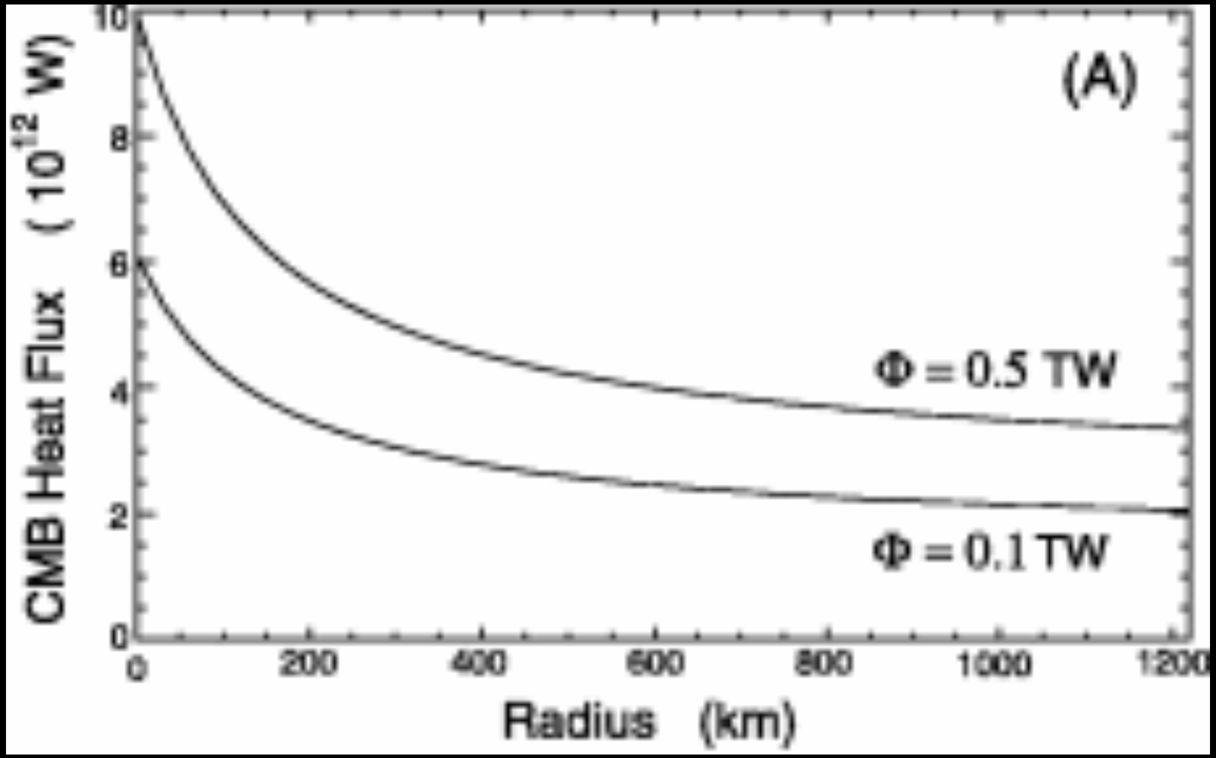
Age of the inner core

$$\rho_{ic} L V_{ic} = \int_{t_0}^{now} \left(Q_{cmb}(t) - \rho c_p V_c(t)\frac{dT}{dt} - V_c(t)H(t) - \Phi_{ohmic}\right)dt$$

- We want to find t_0, so just need to have a thermal history model of the core
- Adjust for secular cooling of core, radiogenic heating of core, and B-field
- Ohmic dissipation is about 0.1 TW and likely < 0.5 TW (Buffett, *GRL*, 2002)
- Conclusion: very difficult to reconcile IC older than 1 Gyr (pre-2010) and now 0.5 Gyr , i.e. “the New Core Paradox” (Olson, *Science*, 2013)

Age of the inner core

- **Observation: Earth's B-field is > 3 Gyr**
- **Problem: generating B-field is inefficient without IC XL-ization**
  - **leads to very high temperatures in early core**
  - **would imply partially molten lower mantle (maybe this is correct)**
  - **maybe needs to be revisited using updated values**



Buffett, GRL, 2002

Conclusions

- If BSE model is correct and high Qcmb are correct, “budget crisis” is solved
- New crisis arises for young inner core and generating B-field at least 3.5 Gyrs
- High (super-solidus?) temperatures in deep Earth are possible before 3 Gyrs
- Distribution of HPEs has a 1st order control on Earth’s thermochemical evolution and the style of mantle convection

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Thank you! Questions??