Earth’s fluctuating energy budget

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Main points

- Historical notes
- Heat flow in oceans and continents
- Total heat loss of Earth
- Energy Budget
- Short time scale fluctuations: climate

You must remember this …

- 3 mechanisms of heat transport
    - conduction (in a continuous medium)
    - convection
    - radiation (e.m waves)
- All 3 are important in the Earth

… and you must not forget this …

- Fourier's law $\vec{q} = -\lambda \nabla T$
  - heat flux q (W m^{-2})
  - thermal conductivity λ (W m^{-1} K^{-1})
- Heat conservation equation

$$\frac{d\rho CT}{dt} = -\nabla \cdot \vec{q} + H$$

H heat production rate (W m^{-3})

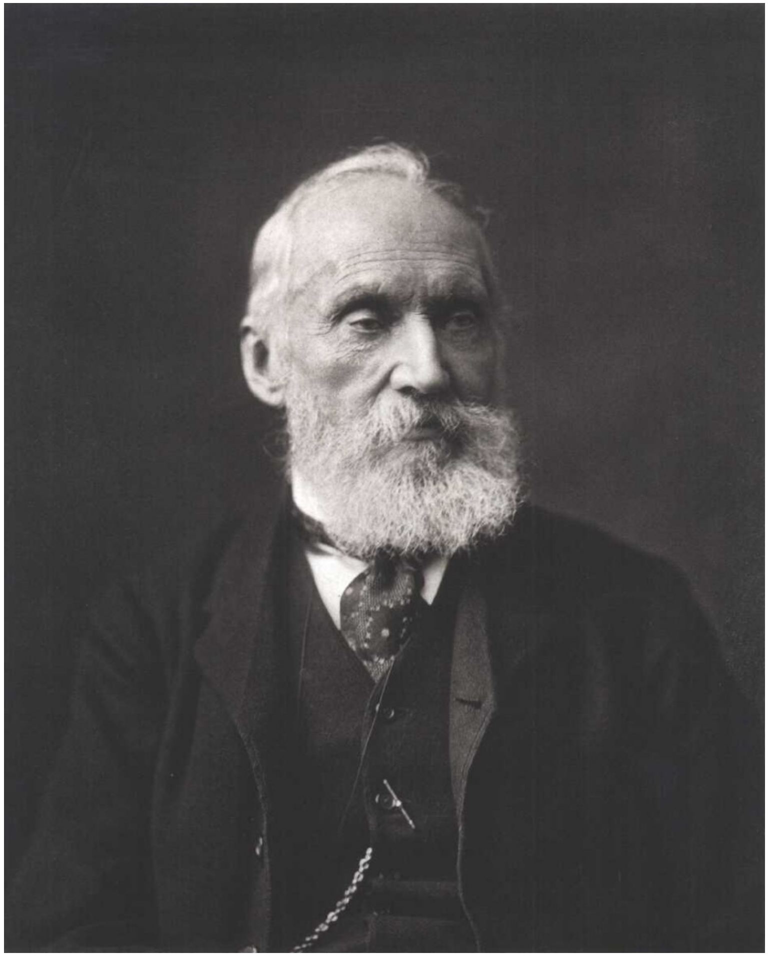
- $\frac{dT}{dt} = \kappa \nabla^2 T + \frac{H}{\rho C}$
  - C specific heat (W kg^{-1} K^{-1})
  - κ thermal diffusivity (m^2 s^{-1})

- Order of magnitude for Earth
  - dT/dz ≈20 mK/m
  - λ ≈ 3 W/m/K
  - q ≈ 60 mWm^{-2}
- For comparison, solar constant 1360 Wm^{-2}
- κ ≈10^{-6} m^2s^{-1} ≈30m^2/y
- Scaling time (τ) distance (l): $\tau = l^2/\kappa$

Baron Jean-Baptiste Joseph Fourier (1768-1830)

- Theorie analytique de la chaleur (1822)
- Downward increase in temperature
- Fourier inferred that Earth is cooling
- Discussed effect of surface boundary condition (exchange of heat between solid Earth and its atmosphere)

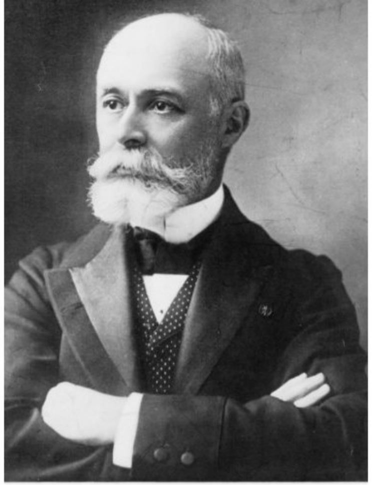
Kelvin and the age of the Earth
Cooling of Earth by conduction (1862)



Sir William Thomson, Lord Kelvin (1824-1907)

- Temperature gradient 15K/km
- Initial condition T≈2000°C
- No heat sources
- Time required for conductive cooling of half space (Earth)
- <100 My
- This number coincided with estimated time the sun would run out of energy

Discovery of radioactivity (Becquerel, 1896)



Henri Becquerel (1852-1908)

- Kelvin assumed that there were no heat sources inside the Earth
- Radioactivity within the Earth provides source of energy
  - one of the assumptions of Kelvin was wrong.
  - (the other key assumption was wrong too!)
  - Is the Earth really cooling or could it be heating?
  - Compare total heat production with total heat loss (Urey number): $Ur > 1$ Earth is heating; $Ur < 1$ Earth is cooling

Continental crust is rich in radioactive elements
3 importants elements: U, Th, K

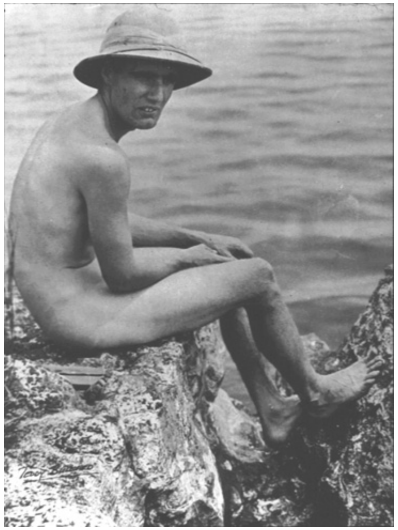
- 1907, Baron Robert Strutt, 4th Lord Rayleigh (1890-1947), compares heat production in crustal rocks with heat flux
- concludes that radioactive crust can not be thicker than 60 km (This was 4 years before Mohorovicic discovered discontinuity)
- Let us measure systematically the heat flux!

- Crustal heat production constrains thickness and composition.
- <H> for granitic rocks $\approx 3 \mu W\ m^{-3}$ => continental crust can not made up of granite (Jeffries, 1940)

Arthur Holmes (1890-1965)

- Developed geochronometry => Earth is older than 2.5 Gy
  - (1925, This came as a shock to astrophysicists. Hubble's initial value for his constant gave an age <2Gy)
- Differences in heat production => differences in temperature at depth
- Could the Earth be cooling by convection?

Systematic heat flow measurements



Sir Edward Crisp Bullard
(1907-1980)

- First continental heat flow measurements (1939)
    - Temperature gradient in drillholes
    - Thermal conductivity
    - Fourier's law
- Marine heat flow measurements (1952)
    - Long probe dropped from ship

Surprise!
Oceanic heat flux ≈ Continental heat flux (1960)

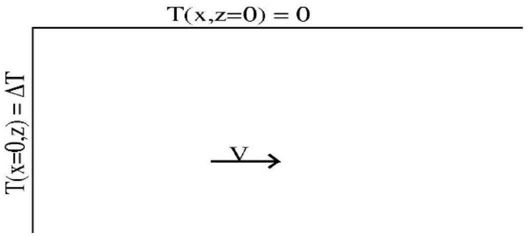
- Continental heat flow can be accounted for by crustal heat production
- Not the oceanic heat flow (crust is thin and depleted)
- Is continental mantle depleted relative to oceanic to make up for difference?
- BUT transporting heat from deep mantle to surface by conduction requires too long a time.
- Do we need convection in the mantle?

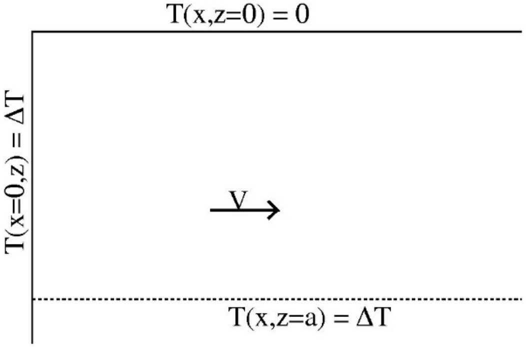
Energy budget (1960)

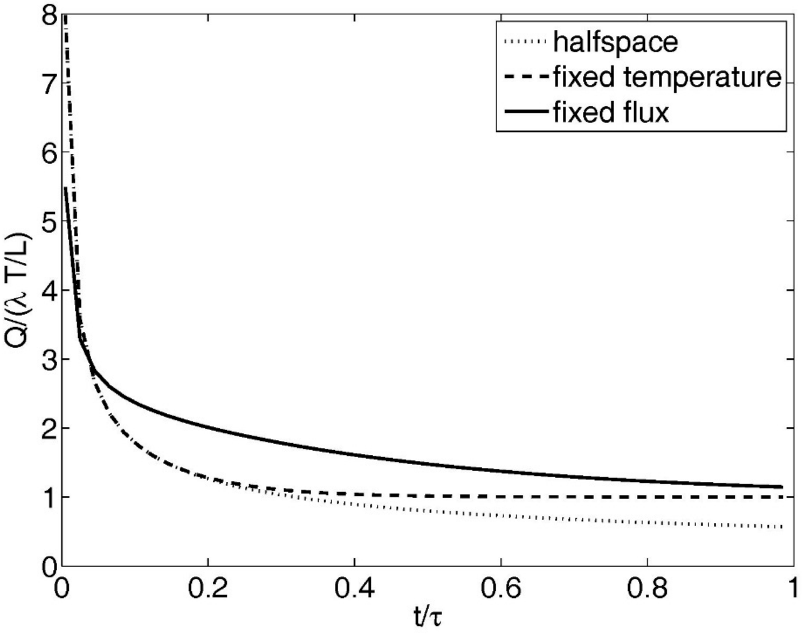
- Birch estimated total heat loss (then) ≈30TW
- Mass of mantle times heat production of chondritic meteorites ≈30TW
- Urey # =1???
- Equilibrium ???

- But ….
- K/U 4 times smaller in Earth than in meteorites
- Correcting for loss of K, heat production = 20TW

Sea floor spreading (1963) => Oceanic lithosphere is cooling







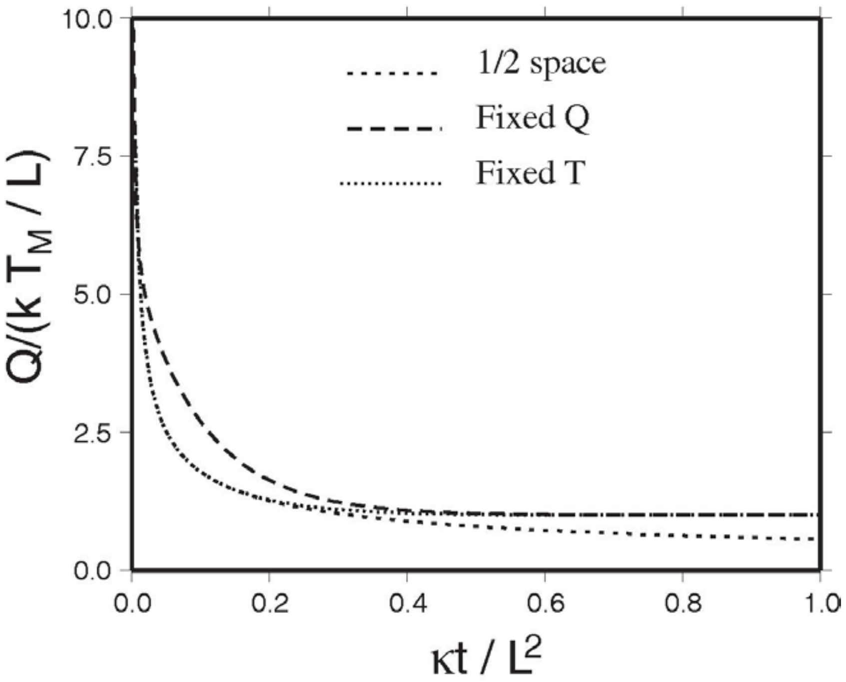
Cooling half space or plate

Heat flow cooling half space

$$Q = \lambda \frac{\Delta T}{\sqrt{\pi \kappa \tau}} = C_Q \tau^{-1/2} \qquad (1)$$

where $C_Q = \lambda \Delta T / \sqrt{\pi \kappa}$ is a constant.
λ thermal conductivity, κ thermal diffusivity, $\Delta T =$ $1350 \pm 50\text{K}$ from petrology.

$C_Q = 490 \pm 20$ $\text{mWm}^{-2}\ \text{My}^{1/2}$ based on petrology and physical properties

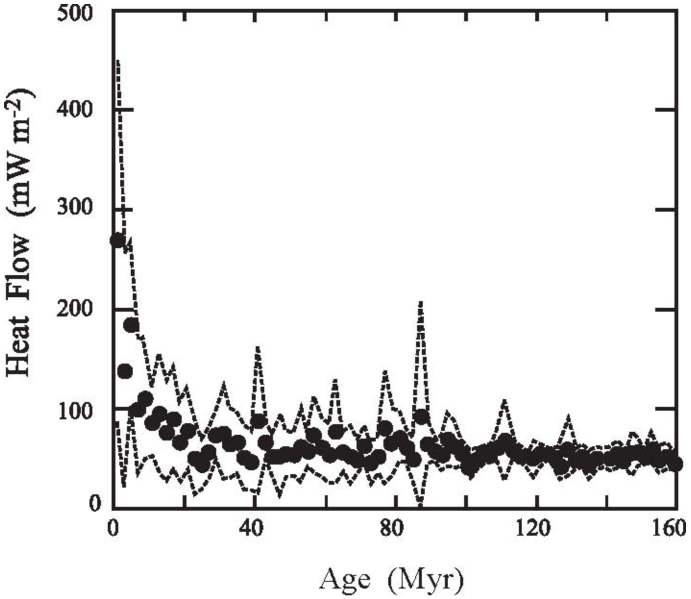


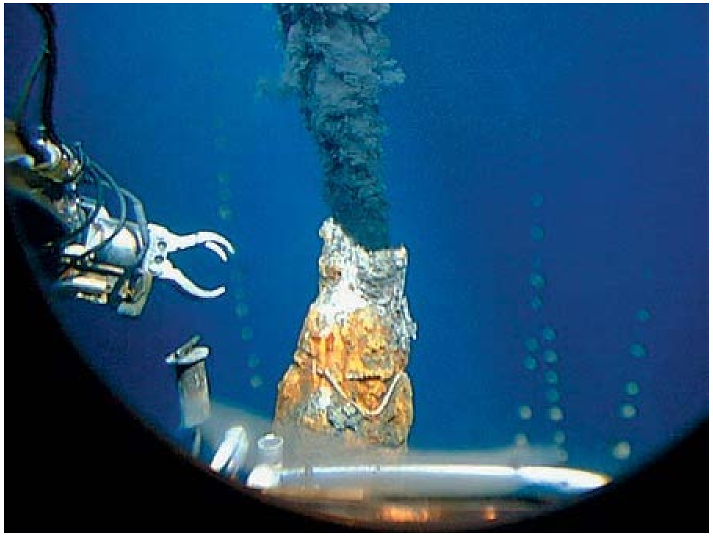
2 predictions

- Sea floor cools as it moves away from spreading centers
- Heat flux
- $Q(\tau) = C_Q \tau^{-1/2}$ Does not fit data well
- Lithosphere becomes colder and denser, subsides, sea floor depth increases $\propto$ total cooling
- $h(\tau) = h_0 + C_h \tau^{1/2}$ Fits data very well

Oceanic heat flow

- Raw average of all oceanic heat flux data 80 mWm^{-2}
- Noisy data at young ages because of hydrothermal circulation
- Better to rely on models and test with “noise free” data

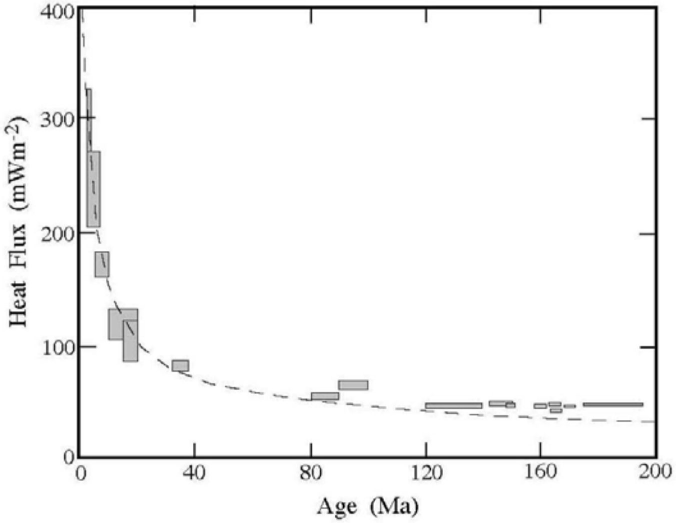


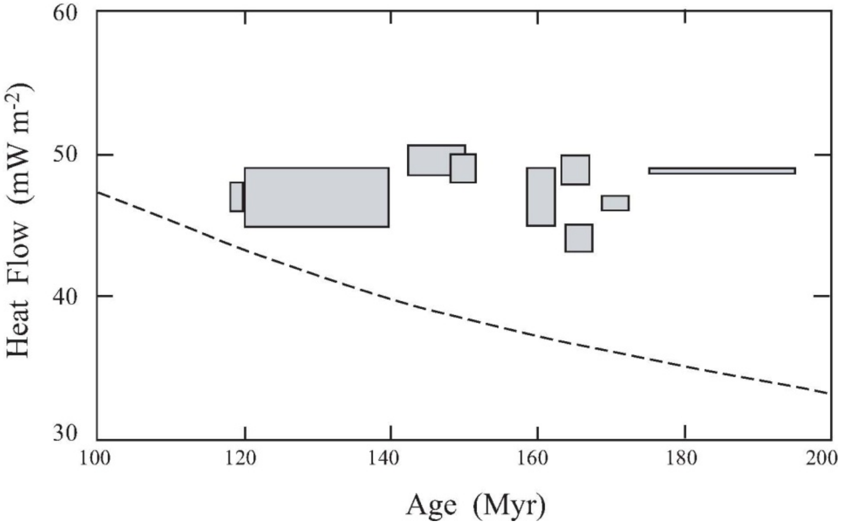


Noise free heat flux data fit cooling model

All ages

Ages > 100My





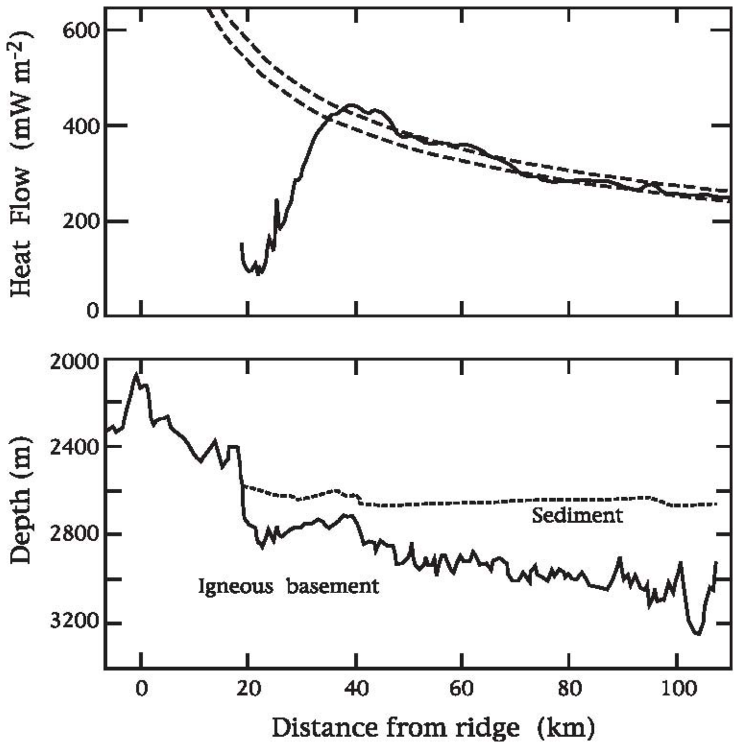
For ages > 80My, heat flux is ≈ constant ≈ 48 $\mathrm{mWm^{-2}}$

Very young sea floor

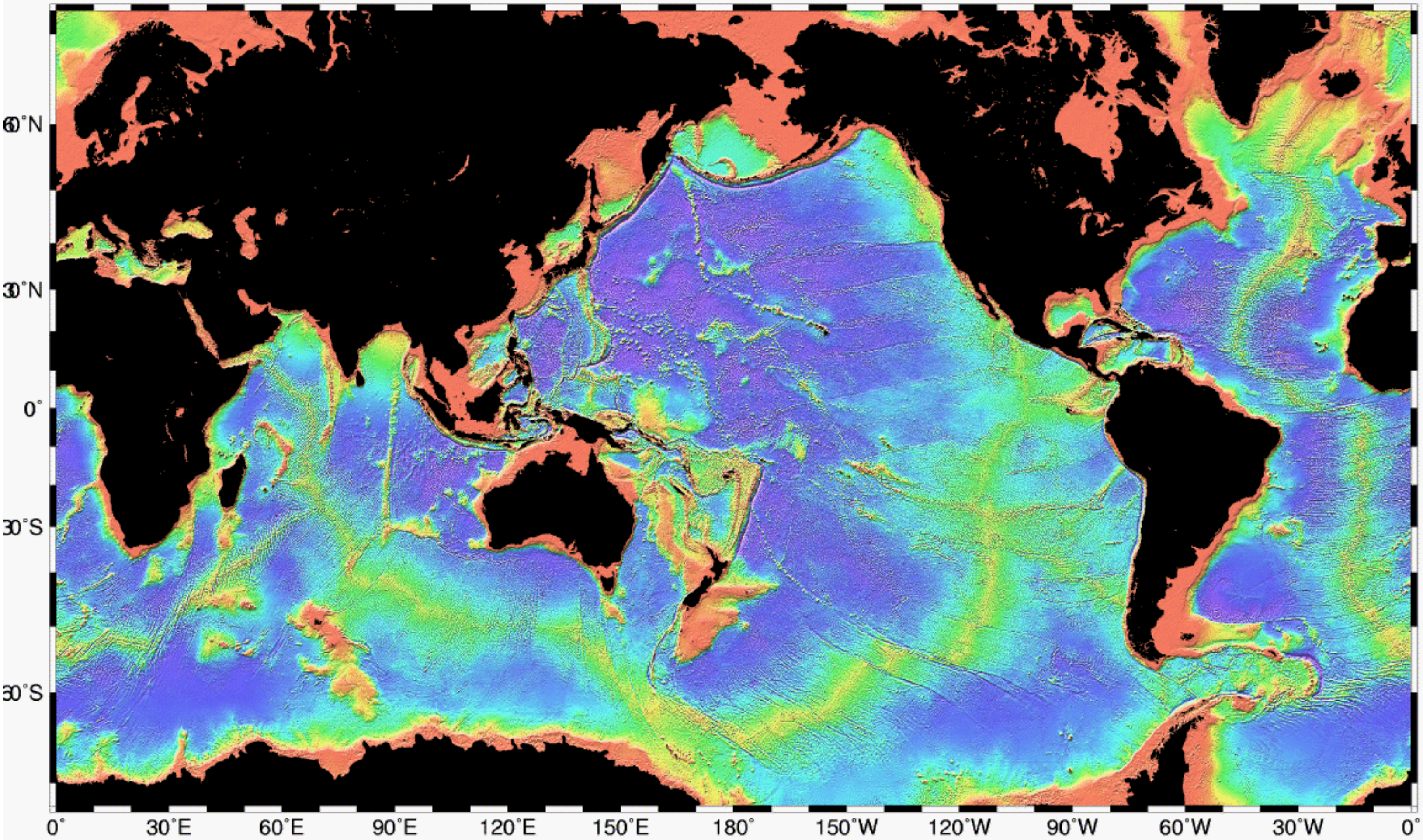
On sediment covered sea floor, convection shuts off, heat flux follows the cooling model predictions

$Q(t) = C_Q t^{-1/2}$ with

$C_Q = 490\ \mathrm{mWm^{-2}\ My^{1/2}}$

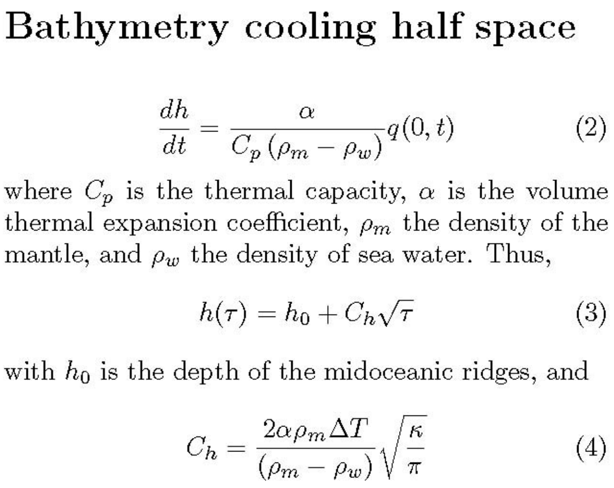


Confirmation from sea floor bathymetry



Walter H. F. Smith and David T. Sandwell, Seafloor Topography Version 4.0, SIO, September 26, 1996

Bathymetry also provides direct estimate of total heat loss



Bathymetry cooling half space

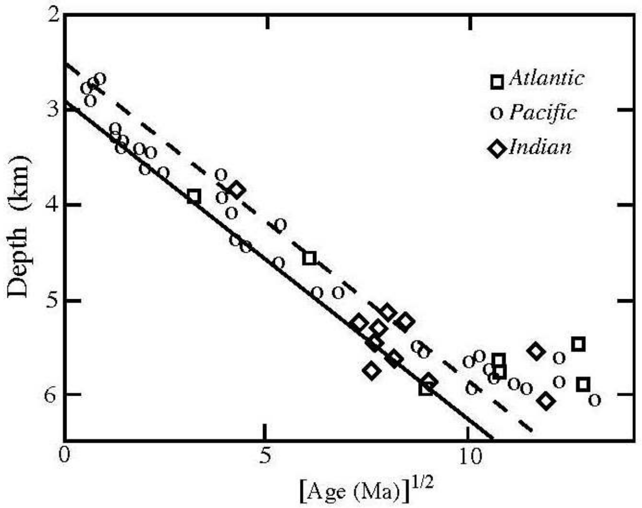
$$\frac{dh}{dt} = \frac{\alpha}{C_p\,(\rho_m - \rho_w)} q(0,t) \qquad (2)$$

where C_p is the thermal capacity, α is the volume thermal expansion coefficient, ρ_m the density of the mantle, and ρ_w the density of sea water. Thus,

$$h(\tau) = h_0 + C_h\sqrt{\tau} \qquad (3)$$

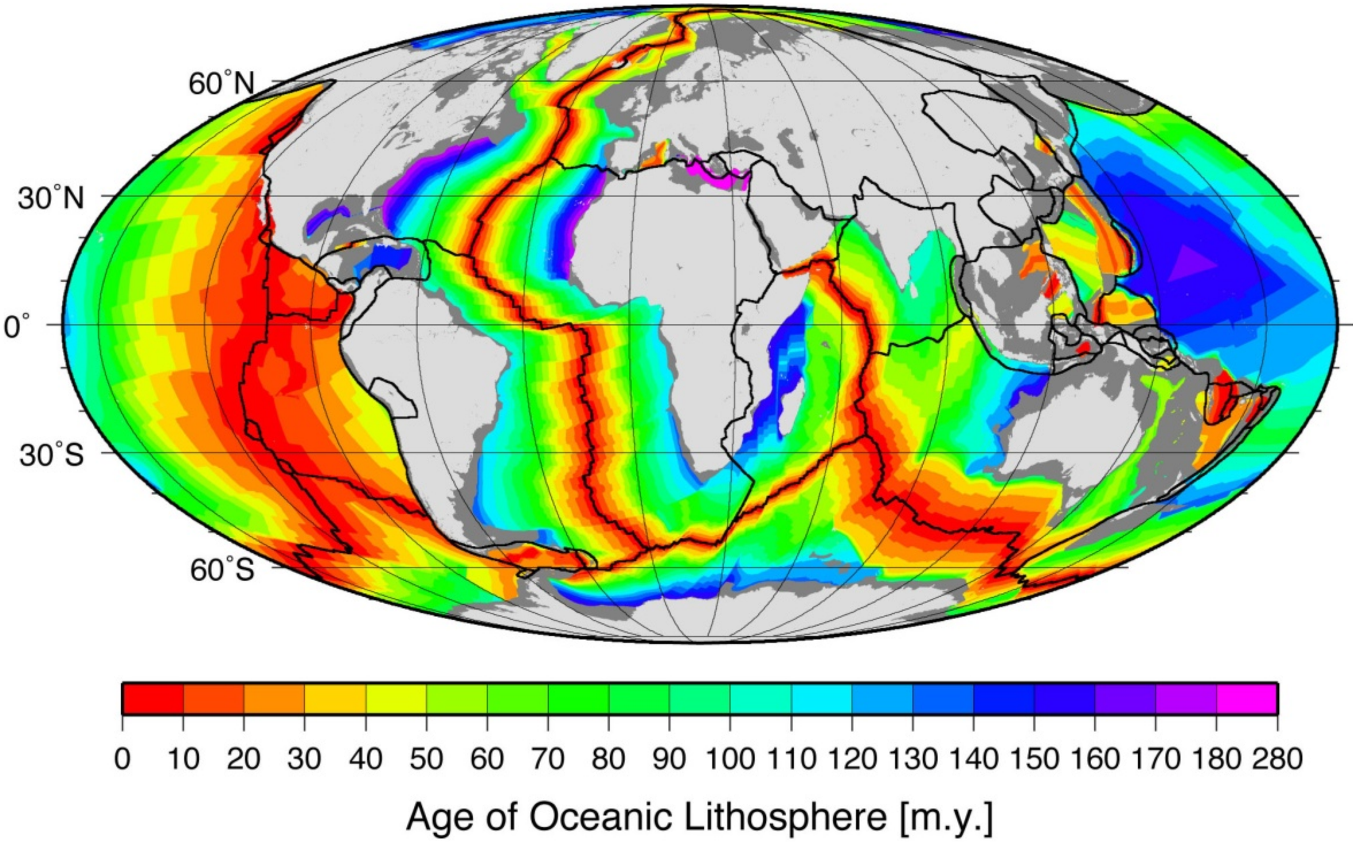
with h_0 is the depth of the midoceanic ridges, and

$$C_h = \frac{2\alpha\rho_m\Delta T}{(\rho_m - \rho_w)}\sqrt{\frac{\kappa}{\pi}} \qquad (4)$$

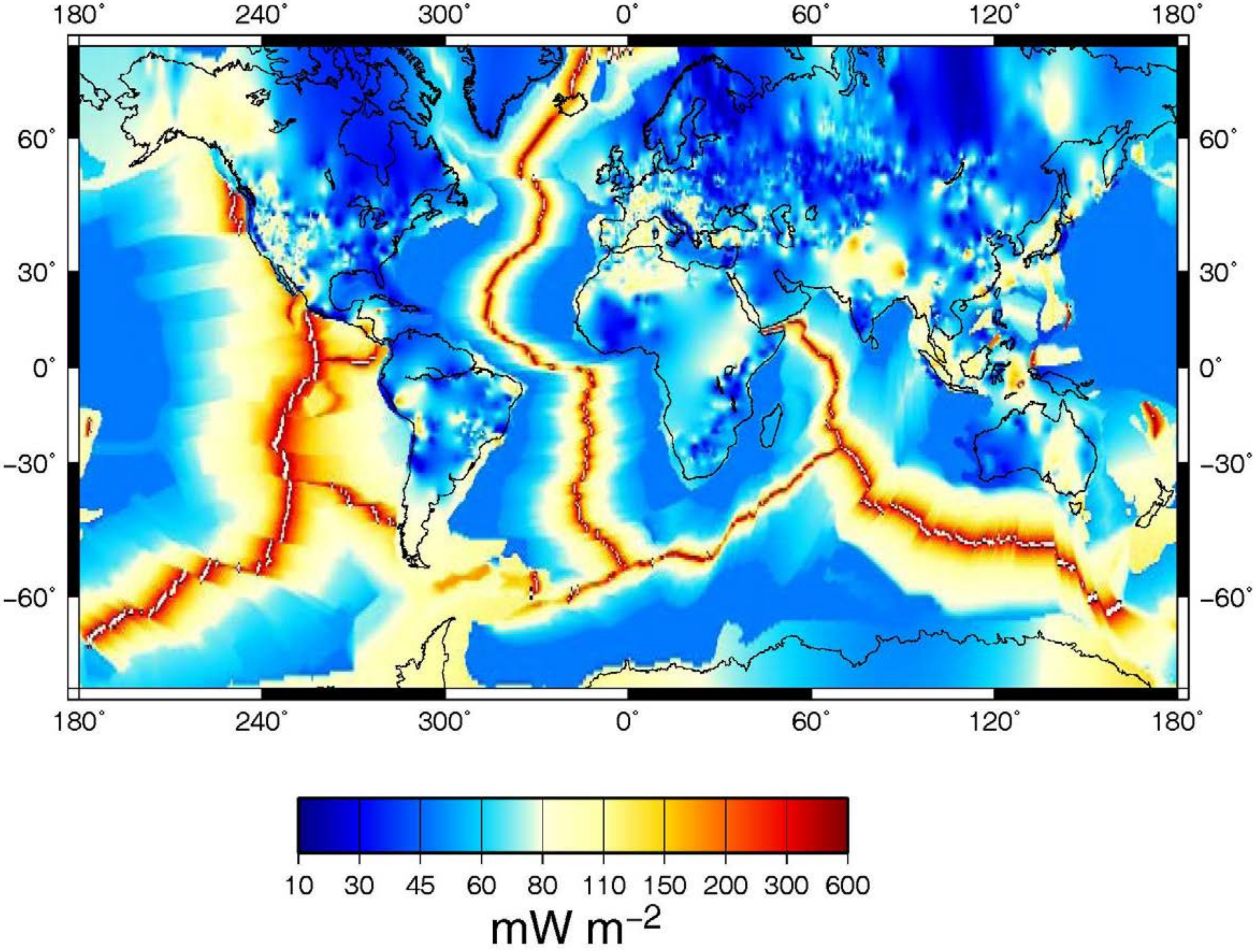


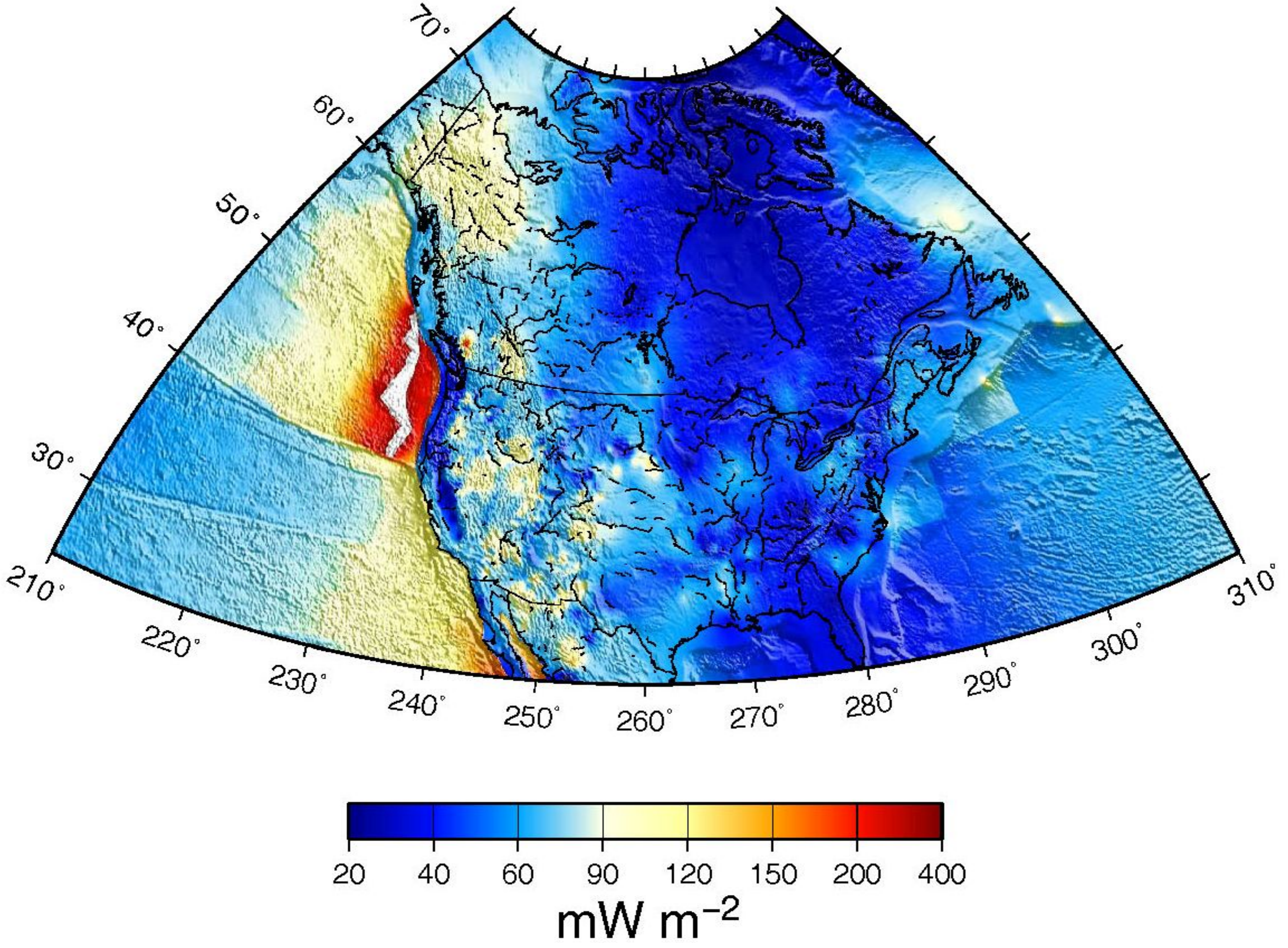
Geoid provides another test of cooling model

We can predict oceanic heat flux from sea floor age map



World heat flux map



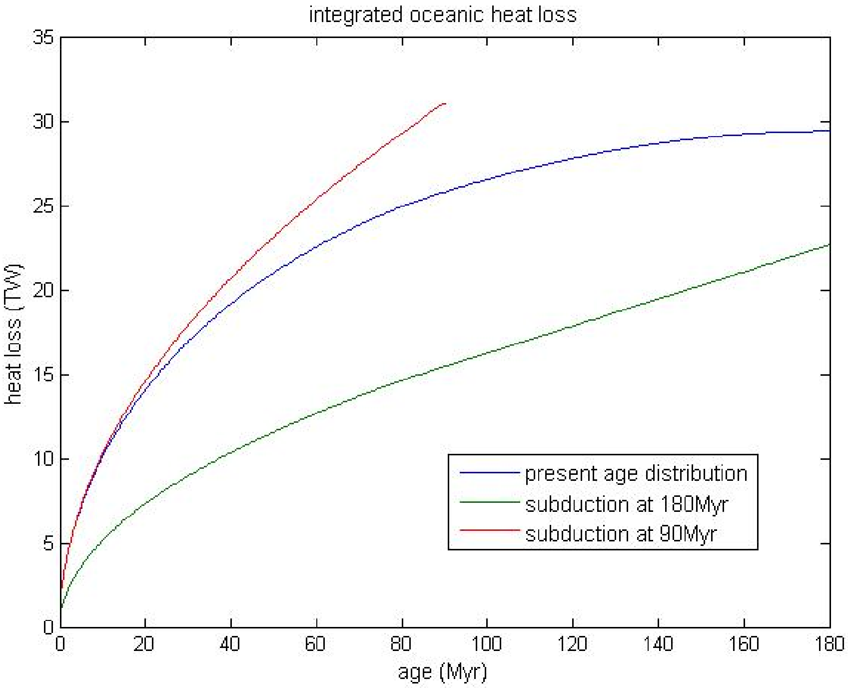

70°
60°
50°
40°
30°
210°
220°
230°
240°
250°
260°
270°
280°
290°
300°
310°
20
40
60
90
120
150
200
400
mW m^{-2}

Calculating heat loss

- For oceans, age of seafloor + cooling model
  - Heat loss from mantle
- For continents, heat flux measurements
  - Accounting for crustal heat production
  - Heat loss from mantle
- Small input from hotspots

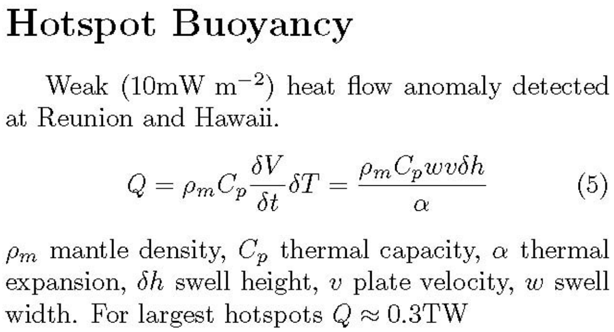
Total energy loss of cooling oceanic lithosphere

- Age < 80My, use half space cooling and age distribution ≈24 TW
- Age > 80 My, use constant flux 48 mWm^{-2} ≈5TW
- Total 29 TW
- Depends very much on age distribution of sea floor.



Hot spots

- Weak heat flow anomaly on hot spots
- Use sea floor bathymetry to estimate heat input from buoyancy of swells
- ~2-4TW
- Upper bound because plate may be subducted before heat flows out



Hotspot Buoyancy

Weak (10mW m^{-2}) heat flow anomaly detected at Reunion and Hawaii.

$$Q = \rho_m C_p \frac{\delta V}{\delta t} \delta T = \frac{\rho_m C_p w v \delta h}{\alpha} \tag{5}$$

ρ_m mantle density, C_p thermal capacity, α thermal expansion, δh swell height, v plate velocity, w swell width. For largest hotspots $Q \approx 0.3$TW

Energy loss through continents: eliminating the bias in the data

- Method 1: Determine average heat flux for each geological age and weight according to areal distribution 65mWm^{-2}
- Method 2: Determine area weighted averages 63 mWm^{-2}
- Total continents (210×10^6 km^2 = 14TW)

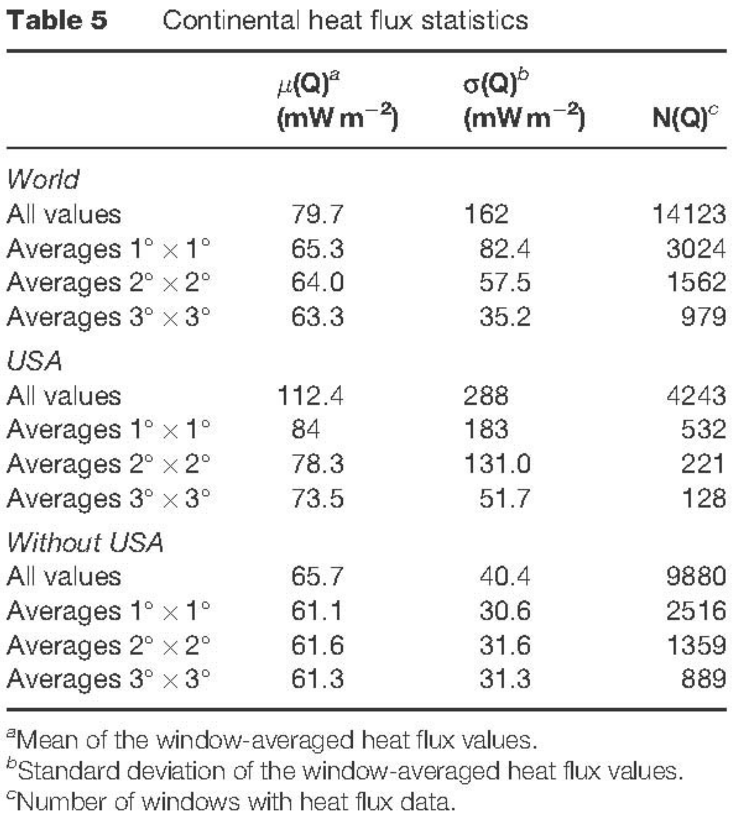


Table 5 Continental heat flux statistics

	$\mu(Q)^a$ (mW m^{-2})	$\sigma(Q)^b$ (mW m^{-2})	N(Q)^c
World			
All values	79.7	162	14123
Averages 1° × 1°	65.3	82.4	3024
Averages 2° × 2°	64.0	57.5	1562
Averages 3° × 3°	63.3	35.2	979
USA			
All values	112.4	288	4243
Averages 1° × 1°	84	183	532
Averages 2° × 2°	78.3	131.0	221
Averages 3° × 3°	73.5	51.7	128
Without USA			
All values	65.7	40.4	9880
Averages 1° × 1°	61.1	30.6	2516
Averages 2° × 2°	61.6	31.6	1359
Averages 3° × 3°	61.3	31.3	889

[a] Mean of the window-averaged heat flux values.
[b] Standard deviation of the window-averaged heat flux values.
[c] Number of windows with heat flux data.

Crustal vs Mantle components?
Moho heat flux in Shields and stable continents
15 ± 3 mWm^{-2}

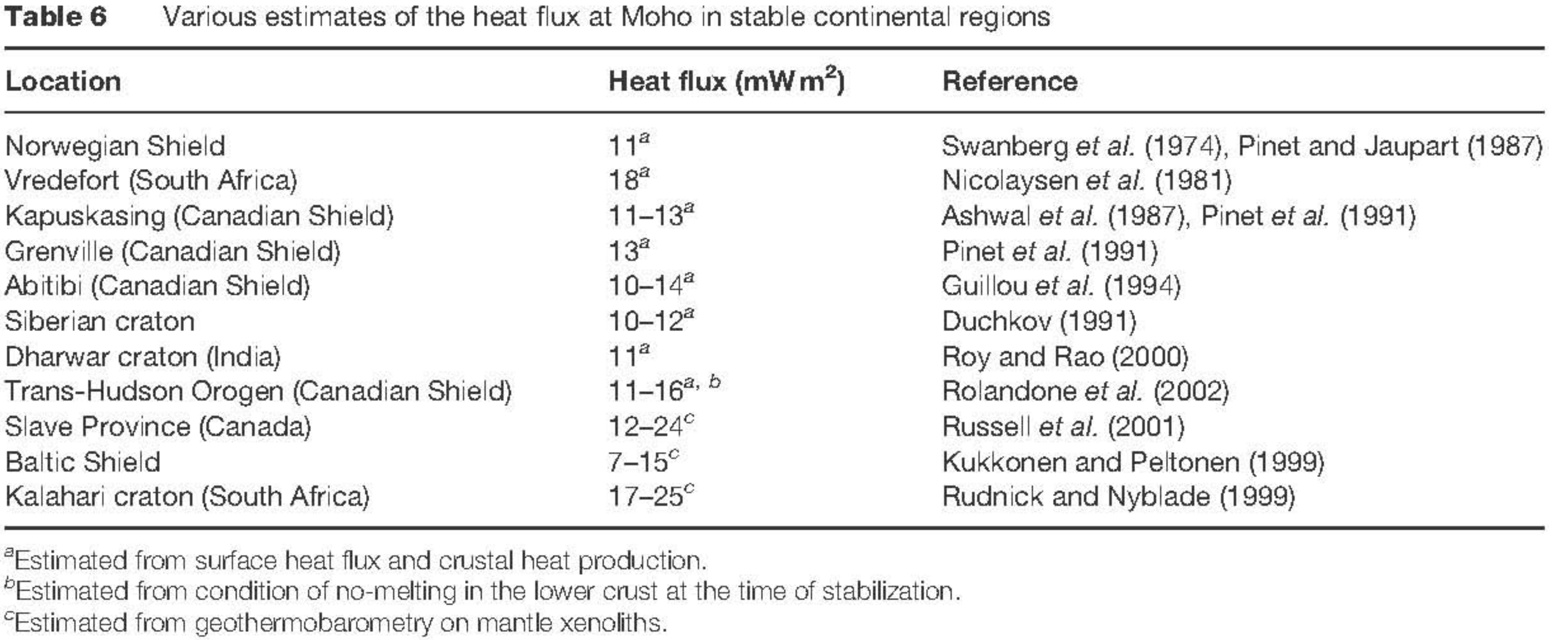


Table 6 Various estimates of the heat flux at Moho in stable continental regions

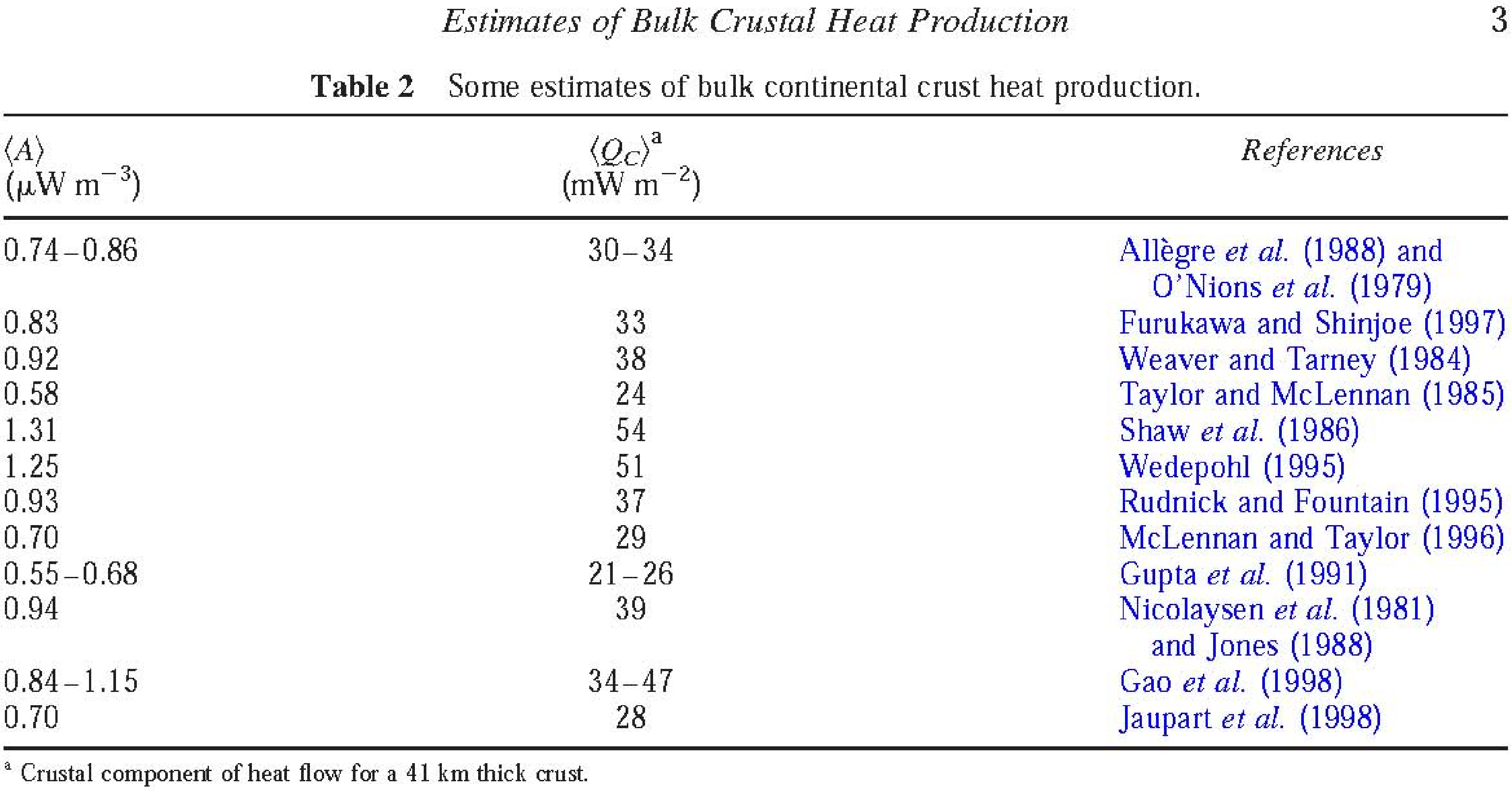
Location	Heat flux (mW m^2)	Reference
Norwegian Shield	11[a]	Swanberg *et al.* (1974), Pinet and Jaupart (1987)
Vredefort (South Africa)	18[a]	Nicolaysen *et al.* (1981)
Kapuskasing (Canadian Shield)	11–13[a]	Ashwal *et al.* (1987), Pinet *et al.* (1991)
Grenville (Canadian Shield)	13[a]	Pinet *et al.* (1991)
Abitibi (Canadian Shield)	10–14[a]	Guillou *et al.* (1994)
Siberian craton	10–12[a]	Duchkov (1991)
Dharwar craton (India)	11[a]	Roy and Rao (2000)
Trans-Hudson Orogen (Canadian Shield)	11–16[a, b]	Rolandone *et al.* (2002)
Slave Province (Canada)	12–24[c]	Russell *et al.* (2001)
Baltic Shield	7–15[c]	Kukkonen and Peltonen (1999)
Kalahari craton (South Africa)	17–25[c]	Rudnick and Nyblade (1999)

[a] Estimated from surface heat flux and crustal heat production.

[b] Estimated from condition of no-melting in the lower crust at the time of stabilization.

[c] Estimated from geothermobarometry on mantle xenoliths.

Crustal heat production in stable continental regions



Estimates of Bulk Crustal Heat Production 3

Table 2 Some estimates of bulk continental crust heat production.

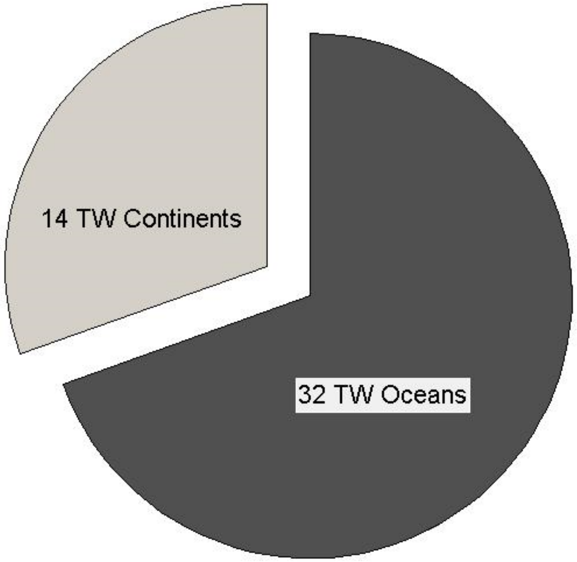
$\langle A \rangle$ (μW m^{-3})	$\langle Q_C \rangle$[a] (mW m^{-2})	*References*
0.74–0.86	30–34	Allègre *et al.* (1988) and O'Nions *et al.* (1979)
0.83	33	Furukawa and Shinjoe (1997)
0.92	38	Weaver and Tarney (1984)
0.58	24	Taylor and McLennan (1985)
1.31	54	Shaw *et al.* (1986)
1.25	51	Wedepohl (1995)
0.93	37	Rudnick and Fountain (1995)
0.70	29	McLennan and Taylor (1996)
0.55–0.68	21–26	Gupta *et al.* (1991)
0.94	39	Nicolaysen *et al.* (1981) and Jones (1988)
0.84–1.15	34–47	Gao *et al.* (1998)
0.70	28	Jaupart *et al.* (1998)

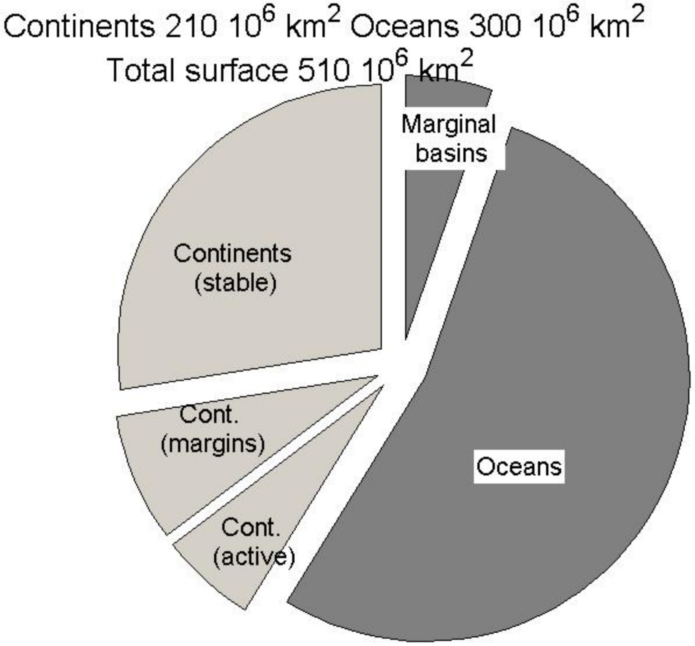
[a] Crustal component of heat flow for a 41 km thick crust.

Bulk continental crust 0.85 ± 0.15 μWm^{-3}

Total heat production = 7 ± 1 TW

Global energy loss of Earth 46±3TW





For comparison, world power consumption ~ 16 TW (in 2008)

Mantle budget

- Total power from convecting mantle = 46-7=39TW
- $\delta M C_p T = -Q + H$
- $Q_{out} = Q_{in} + H_{rad} - \mathrm{MC_p \Delta T}$
- $Q_{in} =$ Heat flow from core
- $H_{rad} =$ Radiogenic heat production in mantle
- $MC_p\Delta T$ = secular cooling of mantle
- Other sources (tidal dissipation, crustal differentiation, etc.) negligible (<1TW)

Mantle radiogenic power H_{rad}

- Radioactive elements in crust and mantle
- Crust + Mantle = Bulk silicate Earth
- Composition of BSE from geochemical or cosmochemical models

Heat production of BSE

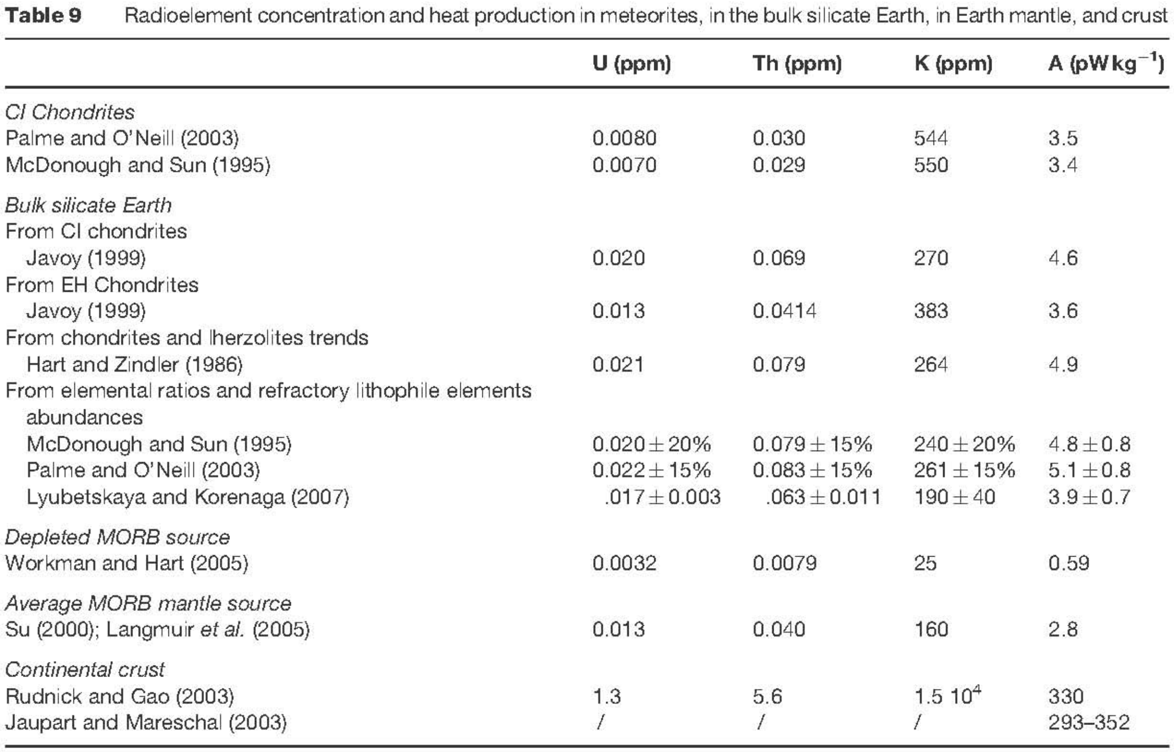


Table 9 Radioelement concentration and heat production in meteorites, in the bulk silicate Earth, in Earth mantle, and crust

	U (ppm)	Th (ppm)	K (ppm)	A (pW kg^{-1})
CI Chondrites				
Palme and O'Neill (2003)	0.0080	0.030	544	3.5
McDonough and Sun (1995)	0.0070	0.029	550	3.4
Bulk silicate Earth				
From CI chondrites				
Javoy (1999)	0.020	0.069	270	4.6
From EH Chondrites				
Javoy (1999)	0.013	0.0414	383	3.6
From chondrites and lherzolites trends				
Hart and Zindler (1986)	0.021	0.079	264	4.9
From elemental ratios and refractory lithophile elements abundances				
McDonough and Sun (1995)	0.020 ± 20%	0.079 ± 15%	240 ± 20%	4.8 ± 0.8
Palme and O'Neill (2003)	0.022 ± 15%	0.083 ± 15%	261 ± 15%	5.1 ± 0.8
Lyubetskaya and Korenaga (2007)	.017 ± 0.003	.063 ± 0.011	190 ± 40	3.9 ± 0.7
Depleted MORB source				
Workman and Hart (2005)	0.0032	0.0079	25	0.59
Average MORB mantle source				
Su (2000); Langmuir *et al.* (2005)	0.013	0.040	160	2.8
Continental crust				
Rudnick and Gao (2003)	1.3	5.6	1.5 10^4	330
Jaupart and Mareschal (2003)	/	/	/	293–352

18TW

15TW

20TW

16TW

Total BSE (including crust)≈ 18 TW (12-21)

Mantle heat production ~ 11 TW

Heat flux from core (Q_{in})

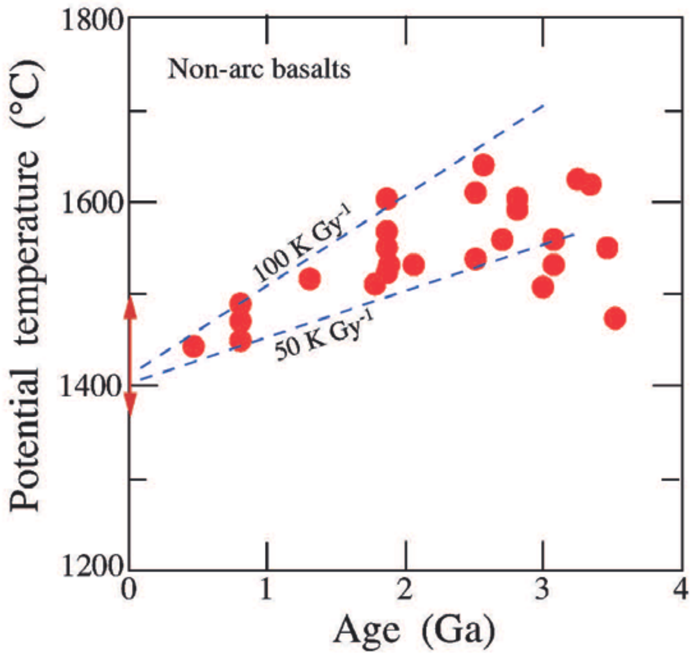
- Assume same secular cooling rate than the mantle. Accounting for latent heat release and gravitational potential energy change due to crystallization and settling of inner core Q_{in} = 4-6TW
- Ohmic dissipation of dynamo (0.1 -> 1 TW)
- Thermodynamic efficiency of dynamo ≈10%
- Lower bound from heat conducted along the core isentropic gradient: $Q = \lambda \Gamma_{ad}$
- New laboratory measurements show high thermal conductivity in core $85 < \lambda < 125$ W/m/K => Q_{in} >10-15 TW
- Dynamo efficiency and whole core convection Q_{in}= > 11TW

Core energy sources

- Latent heat due to freezing of inner core
- Gravitational settling of inner core
- Core secular cooling

- Problem: with heat flow of 9TW, the inner core must be young (<1 Gy)
- To have a geodynamo, core must have cooled even faster before the inner core started to grow
- 1ppm K = 0.02TW
- Or a nuclear reactor? (Herndon, 1994)

Mantle cooling



- Past mantle temperature from basalt composition (% of MgO in basalt)
- Cooling rate <100K/Gy
- 1TW ≈7K/Gy

We have a deficit in the budget?

- Mantle heat generation 11TW
- Heat flux from core 11TW
- Mantle secular cooling 7TW
- Total = 29 TW

- Total mantle energy loss = 39 TW

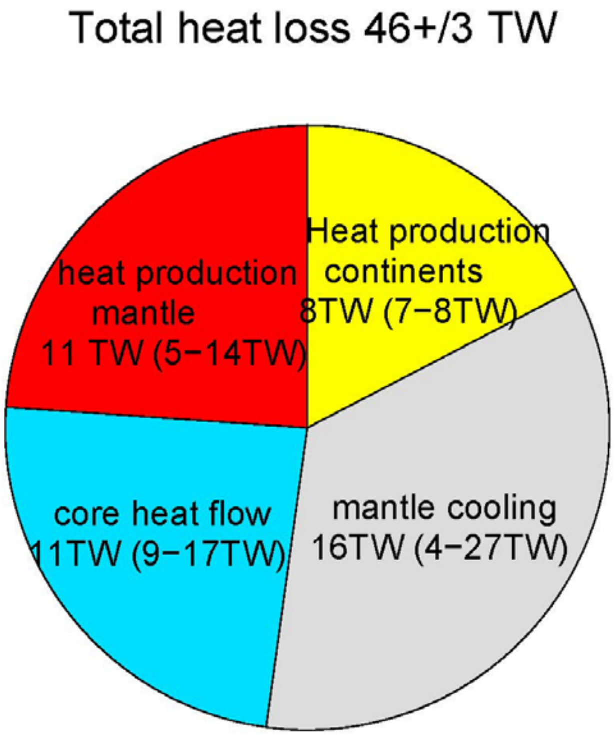
- 10 TW not accounted for!!!

How can we balance the budget? Adjust the mantle cooling rate?

- Heat loss 39TW
- Core flux 11 TW
- Mantle radioactivity 11 TW
- Cooling must provide 17 TW (52 x 10^{19} J/y)
- Rate ~ 110 K/Gy
- Present cooling rate may be higher than long term cooling rate

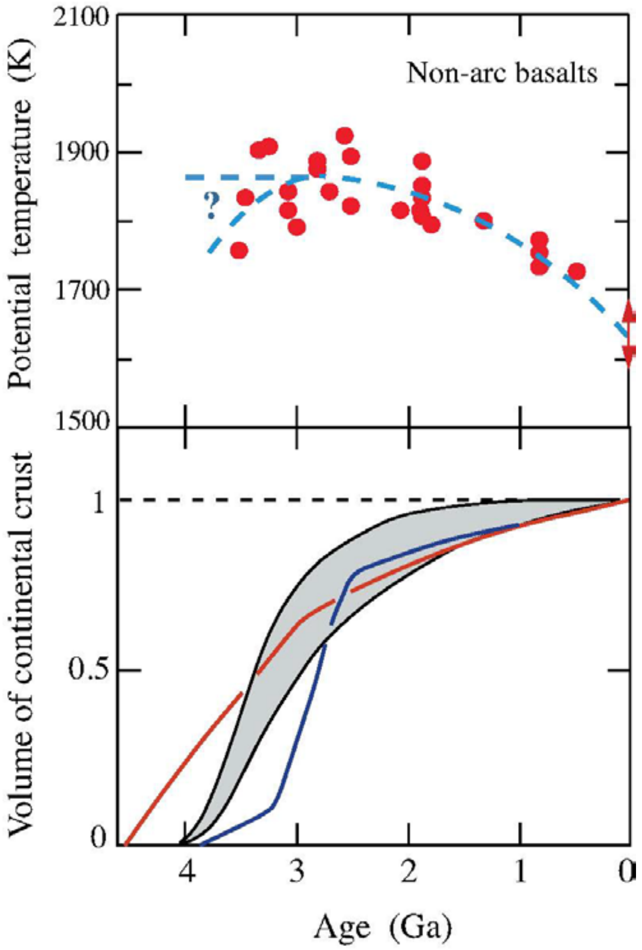
Mantle energy budget

- Heat loss 39TW
- Radio-activity BSE= 18TW- crust = 11 TW
- Core heat flux = 11 TW
- Secular cooling (16 TW => 110K/Gy
- Mantle Urey # ≈ 0.28 (0.13-0.44)



Same questions for 200 years
No final answer yet!

- Is Earth cooling?
    - Yes
- Rate of cooling?
    - We do not know yet
- Will geoneutrinos help?
- Empirical thermal history of mantle?

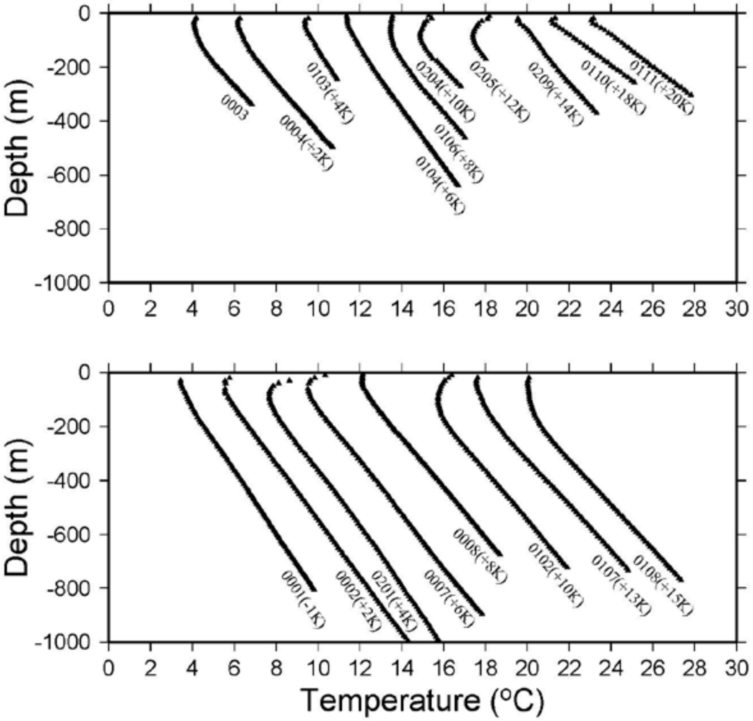


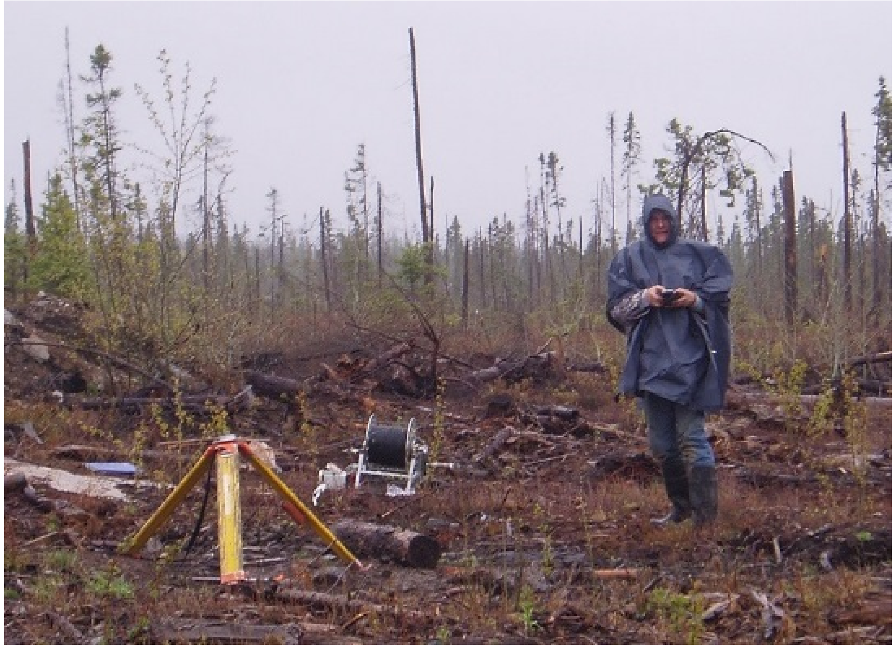
SHORT TIME FLUCTUATIONS

What do we know about recent climate?

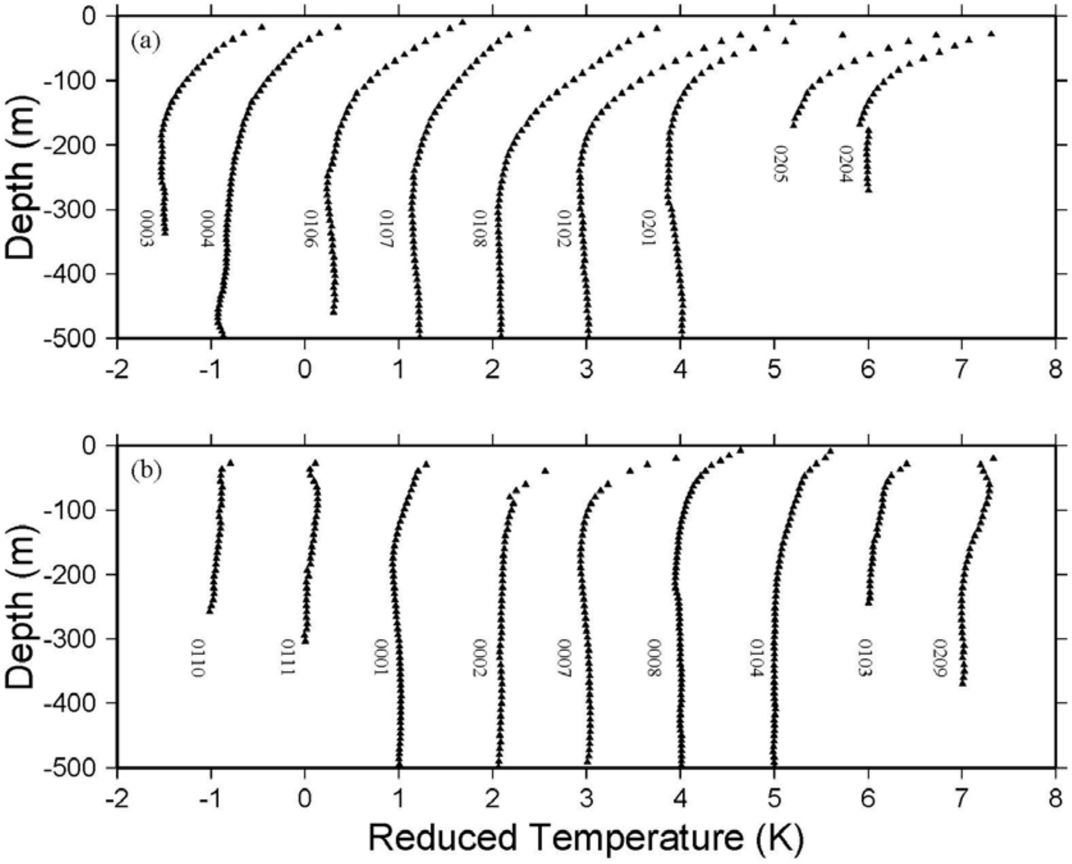
- Oldest weather stations 300 years
- Until recently very sparse geographic coverage
- Almost no continuous record
- We must rely on proxy data
- Proxies must be calibrated
- Direct measure of temperature?

Measuring heat flow
Vertical temperature profiles!

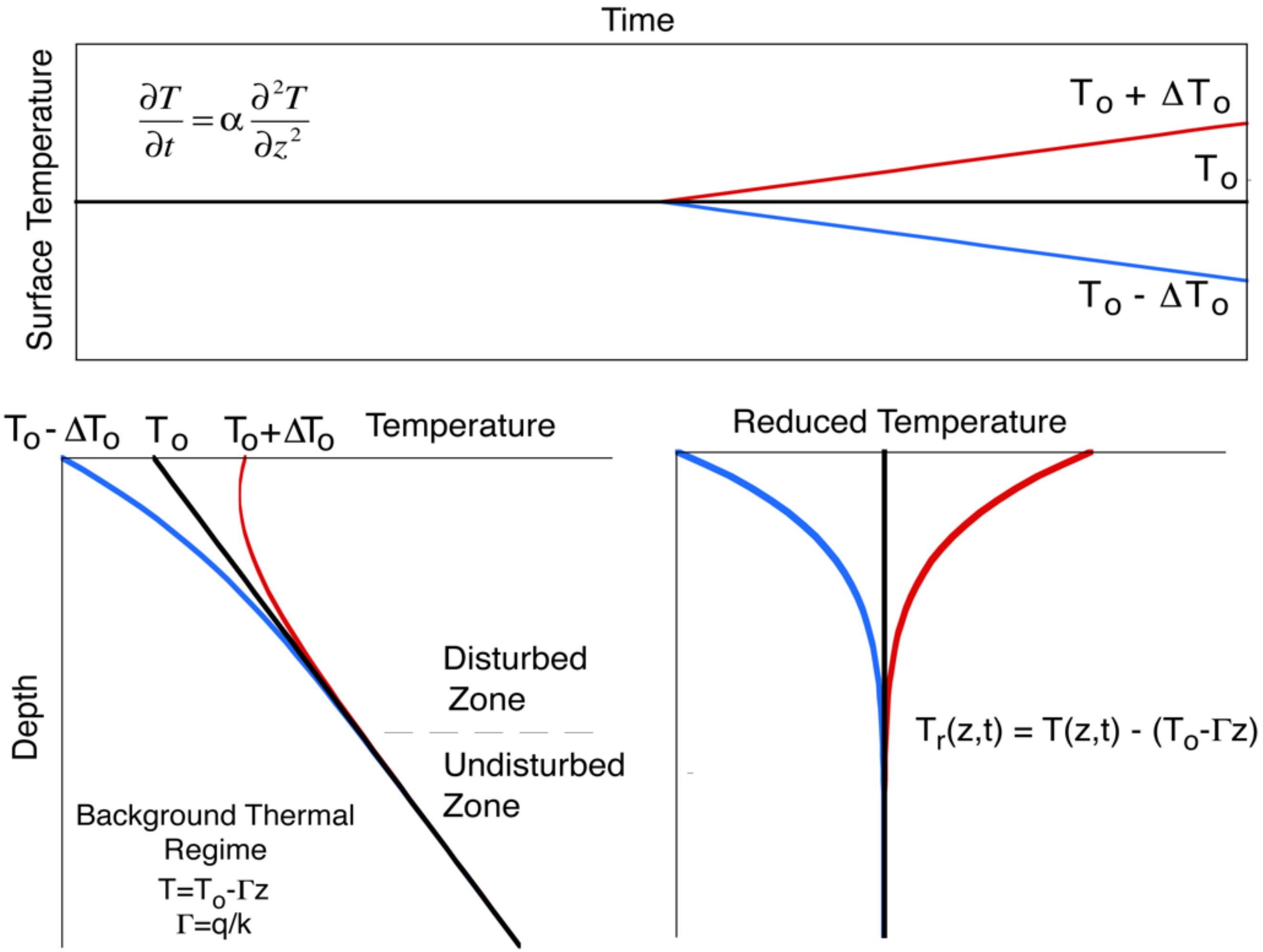




Remove the linear part
=> temperature perturbation



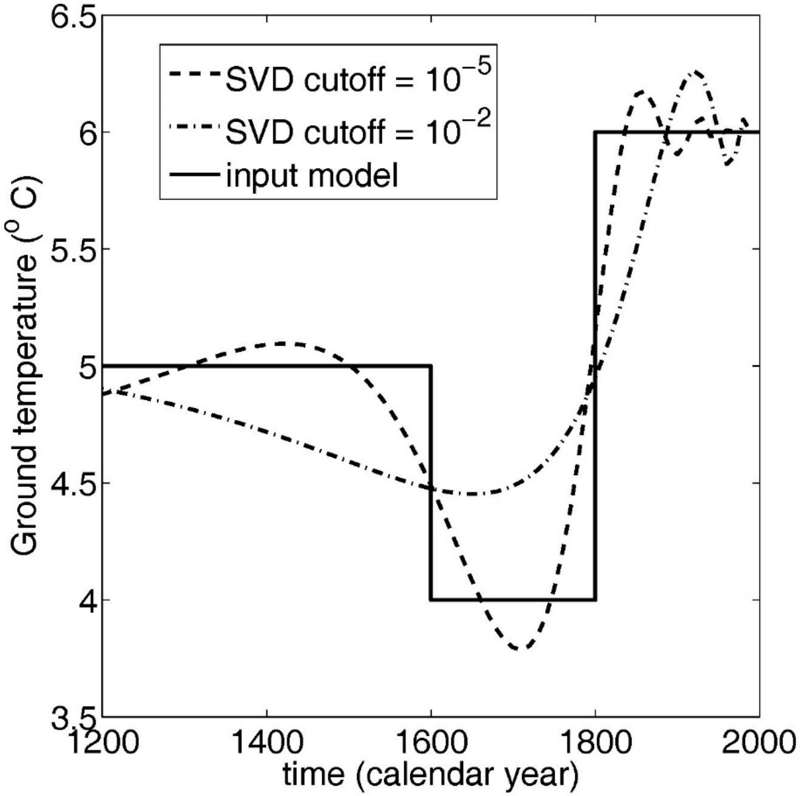
$$\tau = \frac{z^2}{\kappa} \approx 200y$$


Time
Surface Temperature
$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2}$
$T_o + \Delta T_o$
T_o
$T_o - \Delta T_o$
$T_o - \Delta T_o$
T_o
$T_o + \Delta T_o$
Temperature
Depth
Disturbed Zone
Undisturbed Zone
Background Thermal Regime
$T = T_o - \Gamma z$
$\Gamma = q/k$
Reduced Temperature
$T_r(z,t) = T(z,t) - (T_o - \Gamma z)$

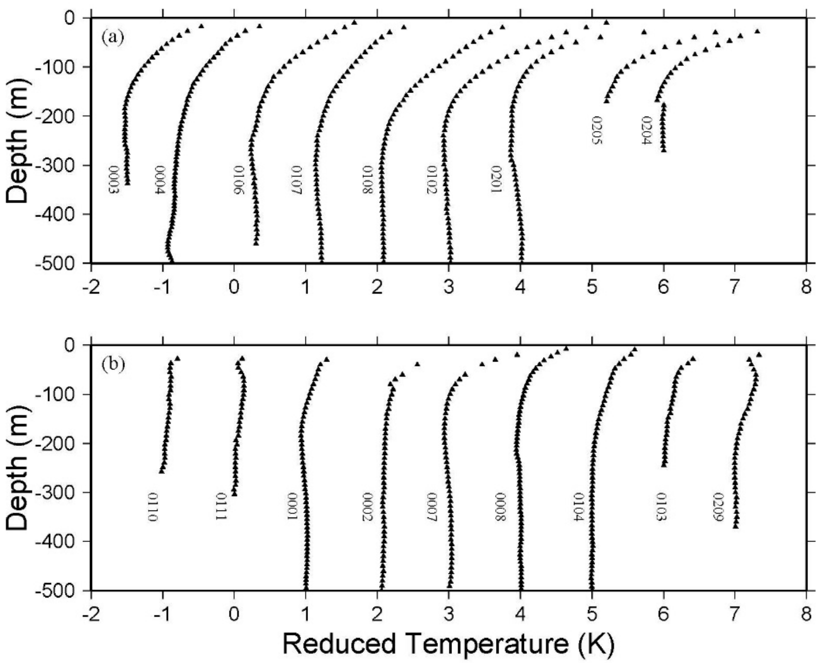
Inverting the temperature profile?

$$T_t(z,t) = \frac{z}{2\sqrt{\pi\kappa}} \int_0^t \frac{T_0(t')}{(t-t')^{3/2}} \times \exp\left(\frac{-z^2}{4\kappa(t-t')}\right) dt'$$

- Direct problem straightforward
- Inverse problem very tricky (very sensitive to noise)
- Solution is to decrease resolution
- Retains only low frequency variations

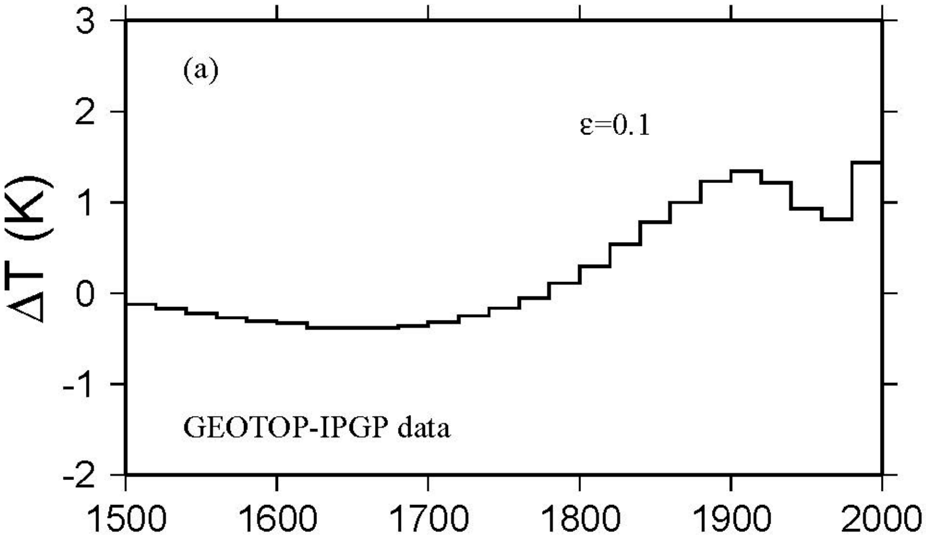


All the temperature perturbations from one region are not identical



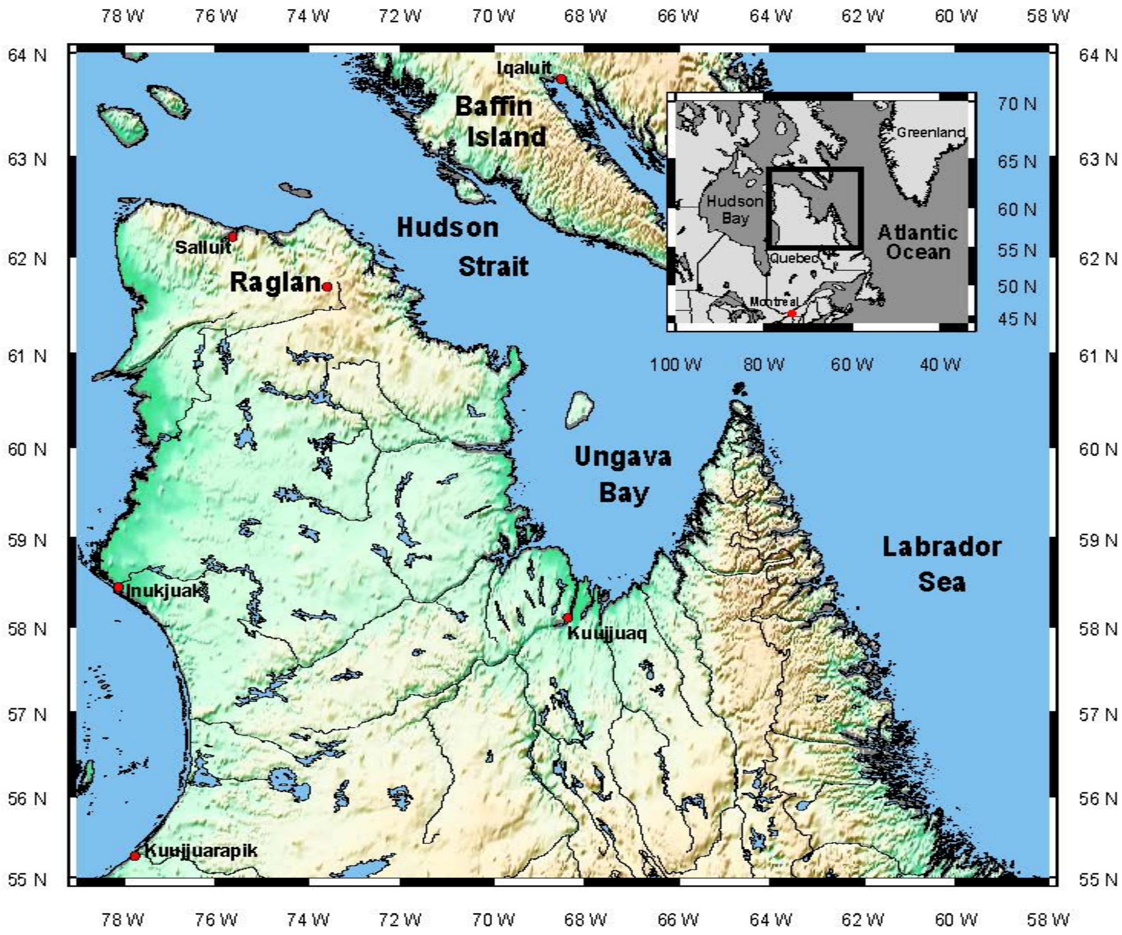
- Same region and very similar temperature changes
- Local differences
- Noise in the data
- On strategy is to find common GSTH for all sites

Western Ontario
Ground surface temperature history

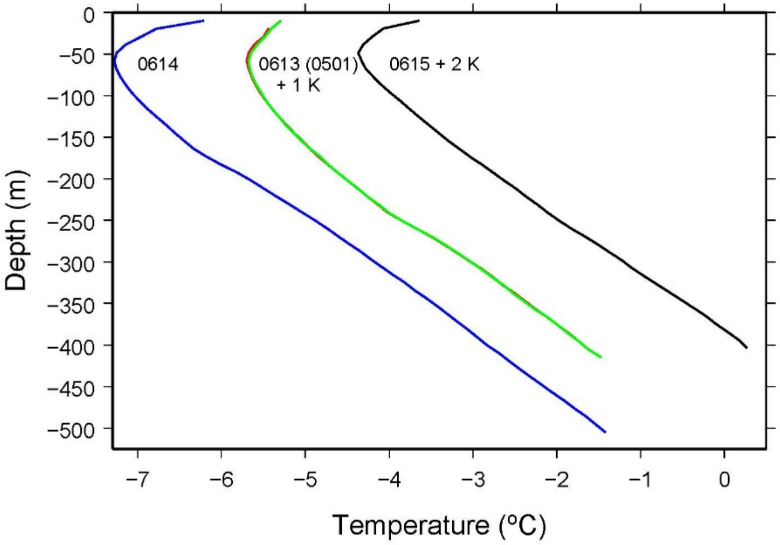


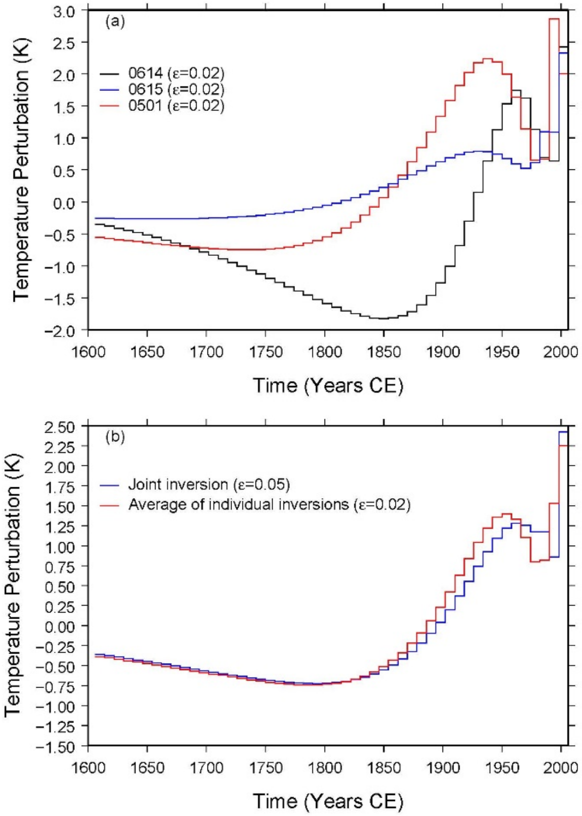
1500-1800 Cooling (LIA?)
Warming since 1800

Oldest meteorological station in Northern Quebec (1940)



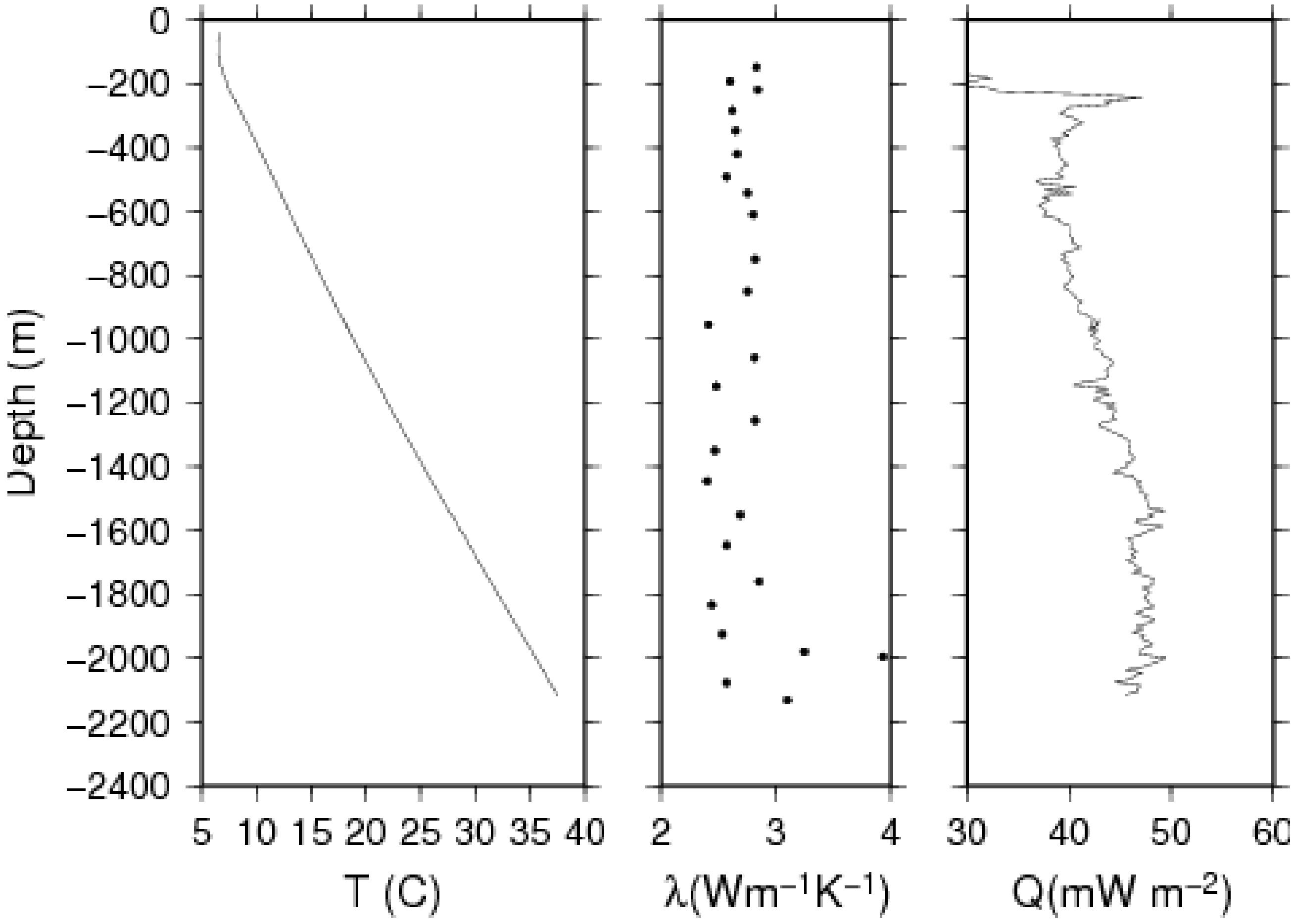
But there are boreholes around the Raglan mine





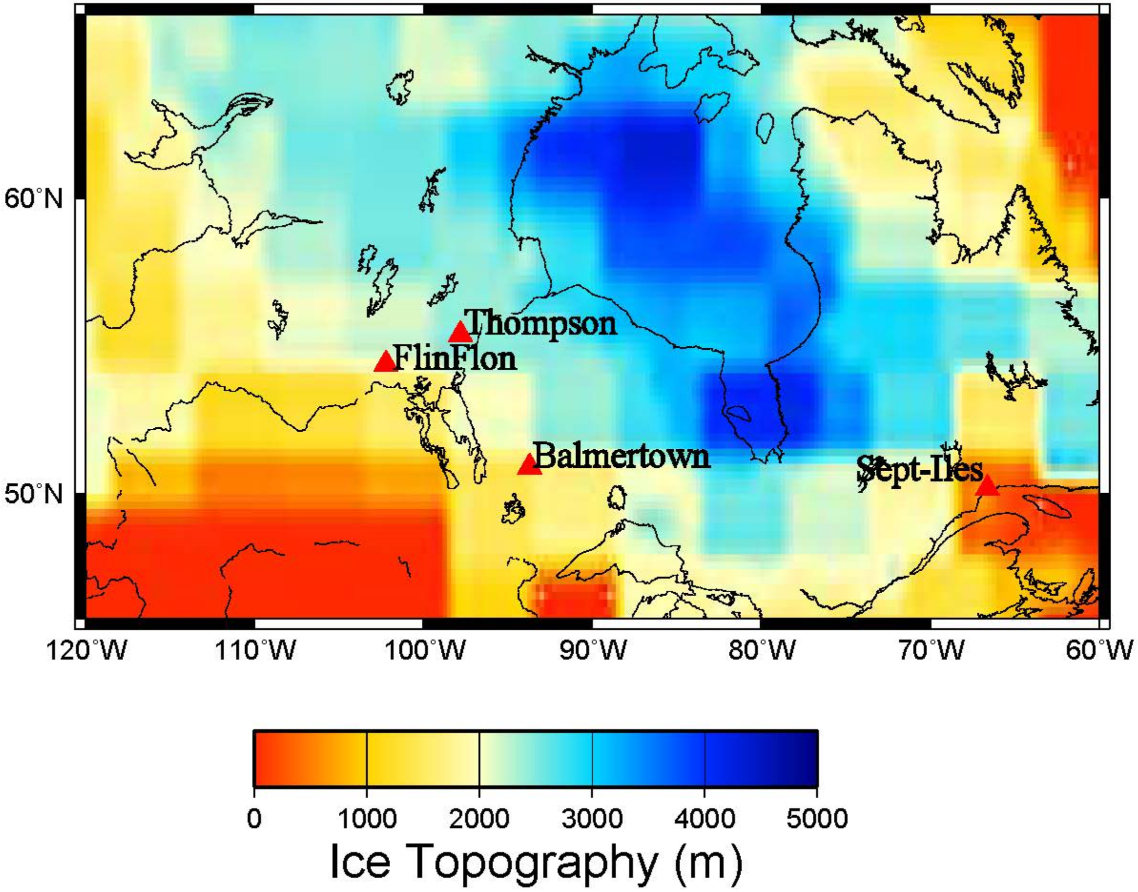
LIA cooling
Warming since 1800
Accelerated in past 50 years?

Variations at greater depth =>2000m (Lockerby mine, Sudbury, ON)

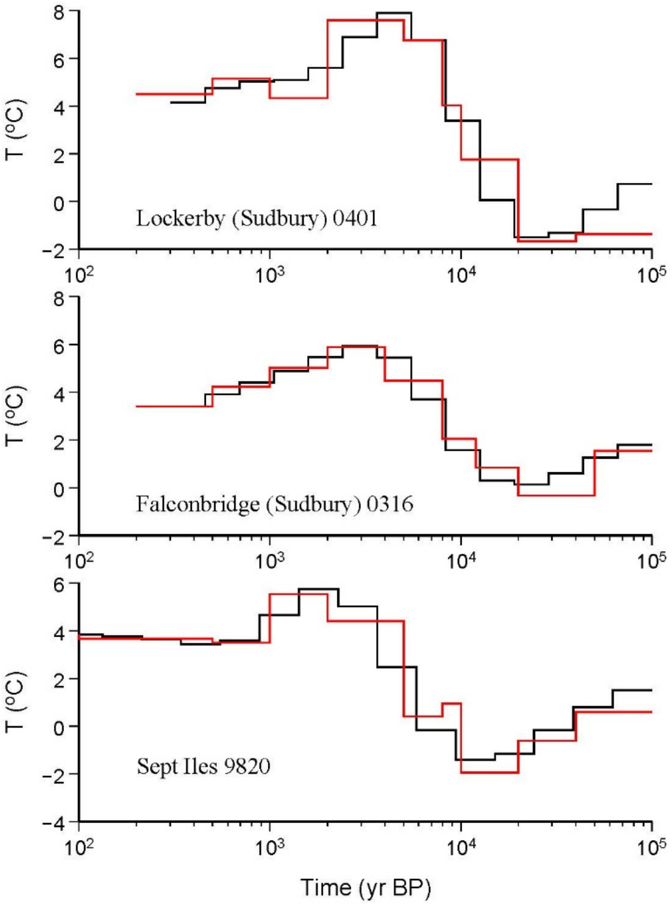


Time scale 20,000 years

Retreat of the Laurentide ice sheet 10,000 years ago



Ground temperature history for some sites



- Temperature near 0°C at the base of the ice sheet
- Not much colder than ground temperature today
- (Blanket of ice)

Heat flow and climate

- Past ground surface temperature variations are recorded in ground below
- Vertical temperature profiles can be used to retrace recent climate variations
- In some regions, only information available

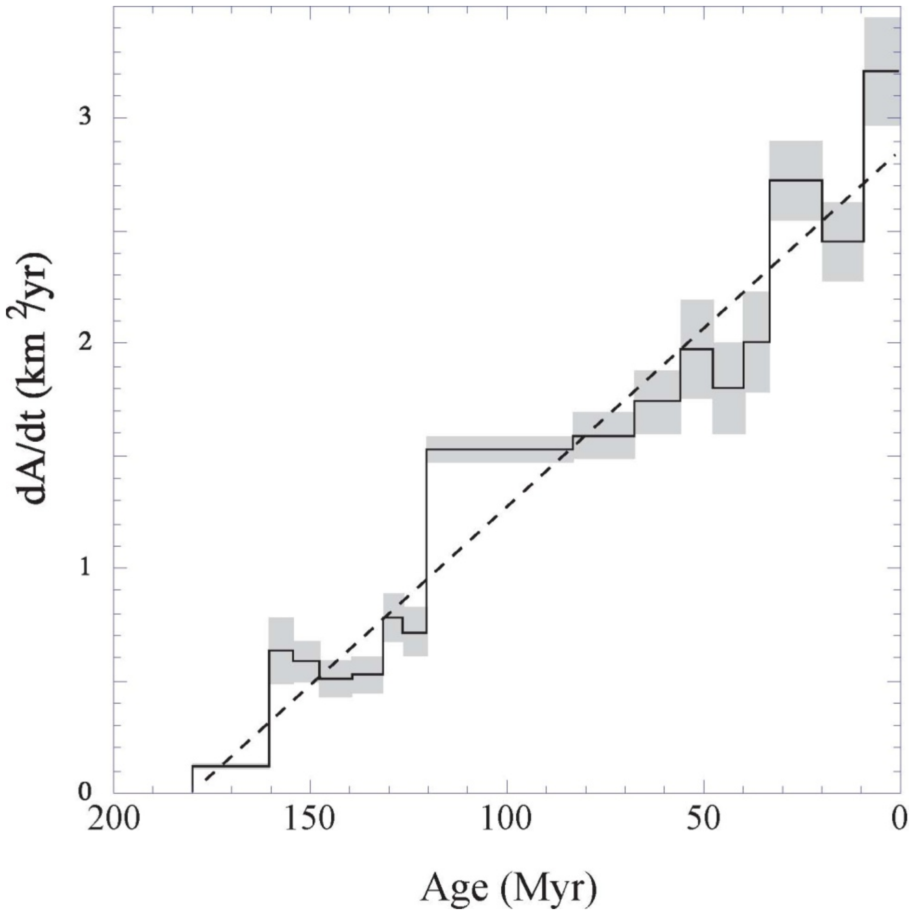
- Heat flux negative or reduced at the surface
- In the uppermost 200m, Earth is not cooling but warming
- Energy absorbed by the ground in continents during past 200 years $\approx 15 \times 10^{21}$J (100 times less than oceans)

Good place to stop!

- Total energy loss from Earth
  - Continents
  - Oceans
- Where does it come from?
  - Crust
  - Mantle
  - Core
- Outstanding questions?
- Some answers from geo-neutrino studies?
- Challenges for geo-neutrino studies.
  - Example of SNO

Age distribution of sea floor

- Age distribution shows that sea floor is subducted regardless of age
- Integrate age distribution times heat flux => heat loss



Mantle cooling from petrology of MORB-like lavas

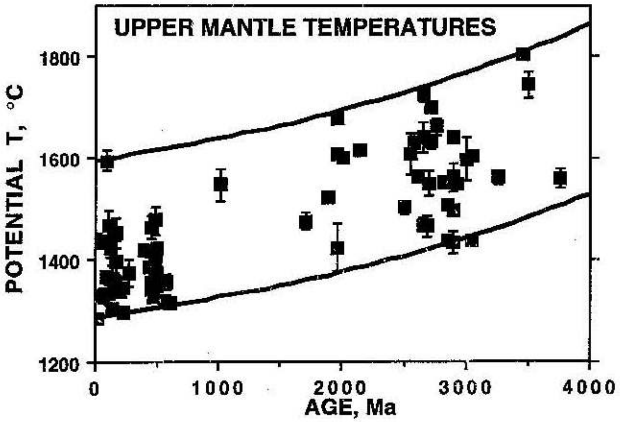


Figure 5. The potential temperatures for each rock suite versus their ages, for all MORBlike suites used in this study. Exponential curves which approximate the shape of the radiogenic heat production curve of *Wasserburg et al.*, [1964] mark the upper and lower boundaries of the data set.

- Temperature of sources of lavas
- Mantle cooling < 200K/3.5 Gy
- 50K/Gy = 7-8 TW

You must remember this …

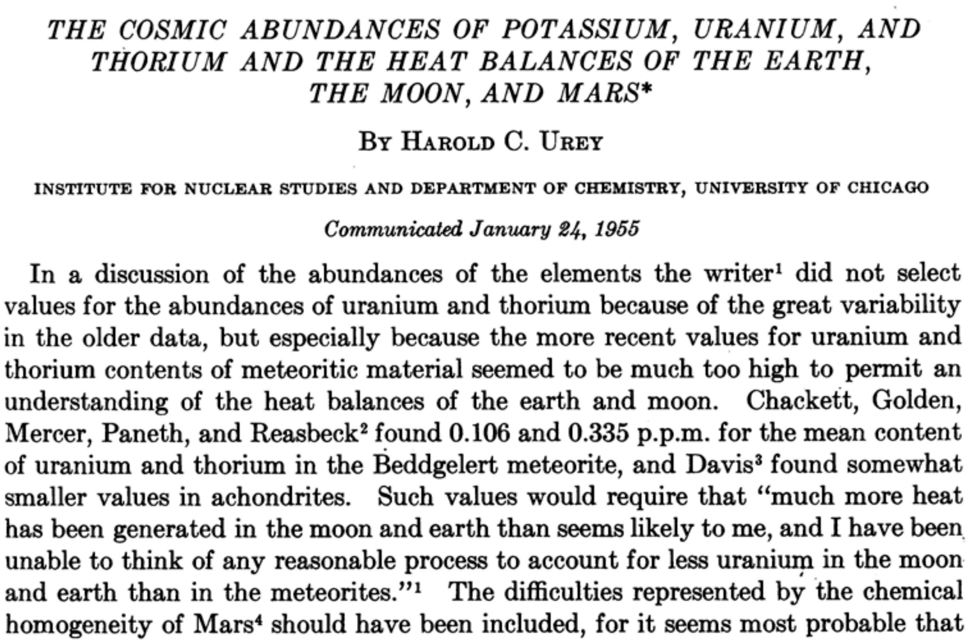
- Heat or energy flux measured in J m^{-2} s^{-1} or W m^{-2}
- Continents 60 mW m^{-2}
- Oceans 100 mW m^{-2}

- Heat generation W kg^{-1}
- (from decay of U, Th, and K)
- In crust W m^{-3}
- Continental crust 1 µ W m^{-3}
- Mantle 3-4 pW kg^{-1}

Moho heat flux in the Canadian Shield

- Lowest values $Q_s = 22$ mW m^{-2} => $Q_m < 18$ mW m^{-2}
- $Q_s = Q_m + \int A\, dz$
  with A(z) estimated from exposures of different crustal levels (i.e. Kapuskasing area)
- Exposed crustal section Kapuskasing Q_s=33 mW m^{-2} => Q_m =13 mW m^{-2}
- Grenville $\langle Q_s \rangle = 41$ mW m^{-2} $\langle A \rangle$ =0.75 µW m^{-3} Q_m = 13 mW m^{-2}

Heat generation in the mantle?



*THE COSMIC ABUNDANCES OF POTASSIUM, URANIUM, AND THORIUM AND THE HEAT BALANCES OF THE EARTH, THE MOON, AND MARS**

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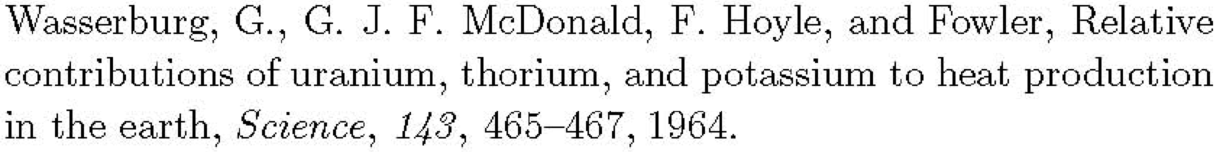
Communicated January 24, 1955

In a discussion of the abundances of the elements the writer[1] did not select values for the abundances of uranium and thorium because of the great variability in the older data, but especially because the more recent values for uranium and thorium contents of meteoritic material seemed to be much too high to permit an understanding of the heat balances of the earth and moon. Chackett, Golden, Mercer, Paneth, and Reasbeck[2] found 0.106 and 0.335 p.p.m. for the mean content of uranium and thorium in the Beddgelert meteorite, and Davis[3] found somewhat smaller values in achondrites. Such values would require that "much more heat has been generated in the moon and earth than seems likely to me, and I have been unable to think of any reasonable process to account for less uranium in the moon and earth than in the meteorites."[1] The difficulties represented by the chemical homogeneity of Mars[4] should have been included, for it seems most probable that



Wasserburg, G., G. J. F. McDonald, F. Hoyle, and Fowler, Relative contributions of uranium, thorium, and potassium to heat production in the earth, *Science*, *143*, 465–467, 1964.

BSE 1 (Hart and Zindler)

- U is calculated from trends in elemental ratios in meteorites and lherzolites.
- Th/U = 3.8
- K/U = 12000

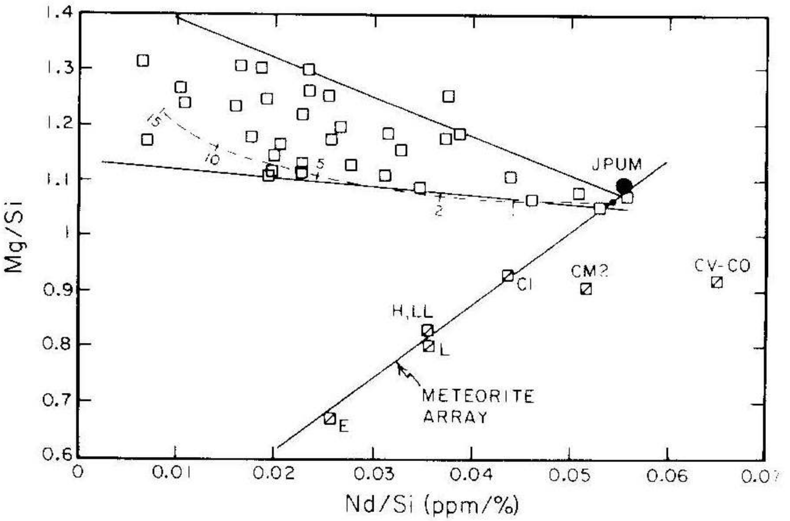


Fig. 2. Mg/Si--Nd/Si relationships of meteorites and lherzolites (cpx corrected). Nd/Si ratios given as ppm/wt.% metal. *Large solid circle* (*JPUM*) is upper-mantle estimate of Jagoutz et al. (1979); *small closed circle* is our estimate for PUM derived from subsequent figures. *Dashed line* is trajectory of residual compositions following melt extraction, with % melt extracted shown at *tic marks*.

BSE 2 (McDonough and Sun)

- Pyrolite from CI chondrites
- Refractory elements ratios pyrolitic BSE same as CI chondrites
- Non refractory elements: Compare ratios in crust and mantle to see if partitioning, and compare ratios to refractory elements in CI and crust samples.
- Results similar to BSE 1

Table 5 Enrichment of elements in the bulk continental crust over the PM (abundances in ppb, except when otherwise noted, refractory lithophile elements are in bold face).

	Element	*Mantle* (PM)	*Crust*	*Crust/Mantle*		*Element*	*Mantle* (PM)	*Crust*	*Crust/Mantle*
1	Tl	3	360	120.0	**31**	**Dy**	**711**	**3,700**	**5.20**
2	W	16	1,000	62.5	**32**	**Ho**	**159**	**780**	**4.91**
3	Cs	18	1,000	55.6	**33**	**Yb**	**462**	**2,200**	**4.76**
4	Rb (ppm)	0.605	32	52.9	**34**	**Er**	**465**	**2,200**	**4.73**
5	Pb	185	8,000	43.2	**35**	**Y**	**4.37**	**20**	**4.58**
6	**Th**	**83.4**	**3,500**	**42.0**	**36**	**Tm**	**72**	**320**	**4.44**
7	**U**	**21.8**	**910**	**41.7**	**37**	**Lu**	**71.7**	**300**	**4.18**
8	**Ba** (ppm)	**6.75**	**250**	**37.1**	**38**	**Ti** (ppm)	**1,282**	**5,400**	**4.21**
9	K (ppm)	260	9,100	35.0	39	Ga (ppm)	4.4	18	4.09
10	Mo (ppm)	39	1,000	25.6	40	In	13	50	3.85
11	**Ta**	**40**	**1,000**	**25.0**	41	Cu (ppm)	20	75	3.75
12	**La**	**686**	**16,000**	23.3	**42**	**Al (%)**	**2.37**	**8.41**	**3.55**
13	**Be** (ppm)	**0.07**	**1.5**	**21.4**	43	Au	0.88	3	3.41
14	Ag	4	80	20.0	**44**	**V (ppm)**	**86**	**230**	**2.67**
15	**Ce**	1,785	33,000	18.5	**45**	**Ca (%)**	**2.61**	**5.29**	**2.03**
16	**Nb** (ppm)	**0.6**	**11**	**18.3**	**46**	**Sc (ppm)**	**16.5**	**30**	**1.82**
17	Sn	138	2,500	18.1	47	Re	0.32	0.5	1.56
18	Sb	12	200	16.7	48	Cd	64	98	1.53
19	As	66	1,000	15.2	49	Zn (ppm)	53.5	80	1.50
20	**Pr**	**270**	**3,900**	**14.4**	50	Ge (ppm)	1.2	1.6	1.33
21	**Sr** (ppm)	**20.3**	**260**	**12.8**	51	Mn (ppm)	1,050	1,400	1.33
22	**Nd**	**1,327**	**16,000**	**12.1**	52	Si (%)	21.22	26.77	1.26
24	**Hf**	**300**	**3,000**	**10.0**	53	Fe (%)	6.3	7.07	1.12
25	**Zr** (ppm)	**10.8**	**100**	**9.26**	54	Se	79	50	0.63
26	Na (ppm)	2,590	23,000	8.88	55	Li (ppm)	2.2	1.3	0.59
25	**Sm**	**431**	**3,500**	**8.12**	56	Co (ppm)	102	29	0.28
27	**Eu**	**162**	**1,100**	**6.79**	57	Mg (%)	22.17	3.2	0.14
28	**Gd**	**571**	**3,300**	**5.78**	58	Cr (ppm)	2,520	185	0.073
29	B (ppm)	0.26	1.5	5.77	59	Ni (ppm)	1,860	105	0.056
30	**Tb**	**105**	**600**	**5.71**	60	Ir	3.2	0.1	0.031

Sources of data: mantle—Table 4; continental crust—Chapter 3.01.

Core energy loss?

- > 4 TW (hot spots)
- Conductive heat flux on adiabat -> 4 TW
- Ohmic dissipation of dynamo (0.1 -> 1 TW)
- Thermodynamic efficiency of dynamo ~10%

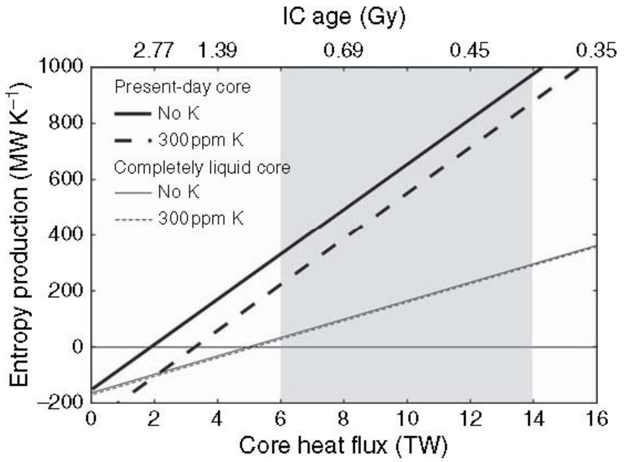


Figure 3 Rate of entropy production as a function of CMB heat flow. Calculations carried out using the expressions given in Section 8.02.3.4 and the parameter values given in **Table 2**. The IC ages given are only relevant to the case of a present-day IC containing no potassium, and are calculated assuming a constant heat flow. Shaded area denotes estimated present-day CMB heat flow (see text).

Table 5
Recommended chemical composition of the Silicate Earth–"Pyrolite"

Element	CI	Pyrolite	Pyrolite (normalized to Mg and CI)	±	Element	CI	Pyrolite	Pyrolite (normalized to Mg and CI)	±
Li (ppm)	1.5	1.6	0.45	30	Pd	550	3.9	0.003	80
Be	0.025	0.068	1.16	20	Ag	200	8	0.017	*F*3
B	0.9	0.30	0.14	*F*2	Cd	710	40	0.024	30
C	35,000	120	0.0015	*F*2	In	80	11	0.058	40
N	3,180	2	0.0003	*F*2	Sn	1,650	130	0.033	30
F	60	25	0.17	*F*2	Sb	140	5.5	0.017	50
Na	5,100	2,670	0.22	15	Te	2,330	12	0.002	*F*2
Mg (%)	9.65	22.8	1.00	10	I	450	10	0.009	*F*3
Al (%)	0.860	2.35	1.16	10	Cs	190	21	0.047	40
Si (%)	10.65	21.0	0.83	10	Ba	2,410	6600	1.16	10
P (ppm)	1,080	90	0.035	15	La	237	648	1.16	10
S	54,000	250	0.002	20	Ce	613	1,675	1.16	10
Cl	680	17	0.011	*F*2	Pr	92.8	254	1.16	10
K	550	240	0.18	20	Nd	457	1,250	1.16	10
Ca (%)	0.925	2.53	1.16	10	Sm	148	406	1.16	10
Sc	5.92	16.2	1.16	10	Eu	56.3	154	1.16	10
Ti	440	1,205	1.16	10	Gd	199	544	1.16	10
V	56	82	0.62	15	Tb	36.1	99	1.16	10
Cr	2,650	2,625	0.42	15	Dy	246	674	1.16	10
Mn	1,920	1,045	0.23	10	Ho	54.6	149	1.16	10
Fe (%)	18.1	6.26	0.15	10	Er	160	438	1.16	10
Co	500	105	0.089	10	Tm	24.7	68	1.16	10
Ni	10,500	1,960	0.079	10	Yb	161	441	1.16	10
Cu	120	30	0.11	15	Lu	24.6	67.5	1.16	10
Zn	310	55	0.075	15	Hf	103	283	1.16	10
Ga	9.2	4.0	0.18	10	Ta	13.6	37	1.16	15
Ge	31	1.1	0.015	15	W	93	29	0.13	*F*2
As	1.85	0.05	0.011	*F*2	Re	40	0.28	0.003	30
Se	21	0.075	0.002	70	Os	490	3.4	0.003	30
Br	3.57	0.050	0.006	*F*2	Ir	455	3.2	0.003	30
Rb	2.30	0.600	0.11	30	Pt	1,010	7.1	0.003	30
Sr	7.25	19.9	1.16	10	Au	140	1.0	0.003	*F*2
Y	1.57	4.30	1.16	10	Hg	300	10	0.014	*F*4
Zr	3.82	10.5	1.16	10	Tl	140	3.5	0.011	40
Nb (ppb)	240	658	1.16	15	Pb	2,470	150	0.026	20
Mo	900	50	0.024	40	Bi	110	2.5	0.010	30
Ru	710	5.0	0.003	30	Th	29	79.5	1.16	15
Rh	130	0.9	0.003	40	U	7.4	20.3	1.16	20

From Li to Zr element concentrations are given in ppm; Nb to U are given in ppb; and Mg, Al, Si, Ca and Fe are in wt%. The ± column is a subjective judgement of the uncertainty of this estimate. Uncertainties are expressed in %, unless otherwise stated; *F*=factor (*F*2=we know this estimate to within a factor of 2). Most of the major and minor elements and a number of the refractory lithophile elements are known to within ±10% or better.