SECULAR COOLING OF THE EARTH

Claude Jaupart
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The cooling of the Earth : a bit of history

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Mistakes: ignores convection, radiogenic heat production, presence of continents.

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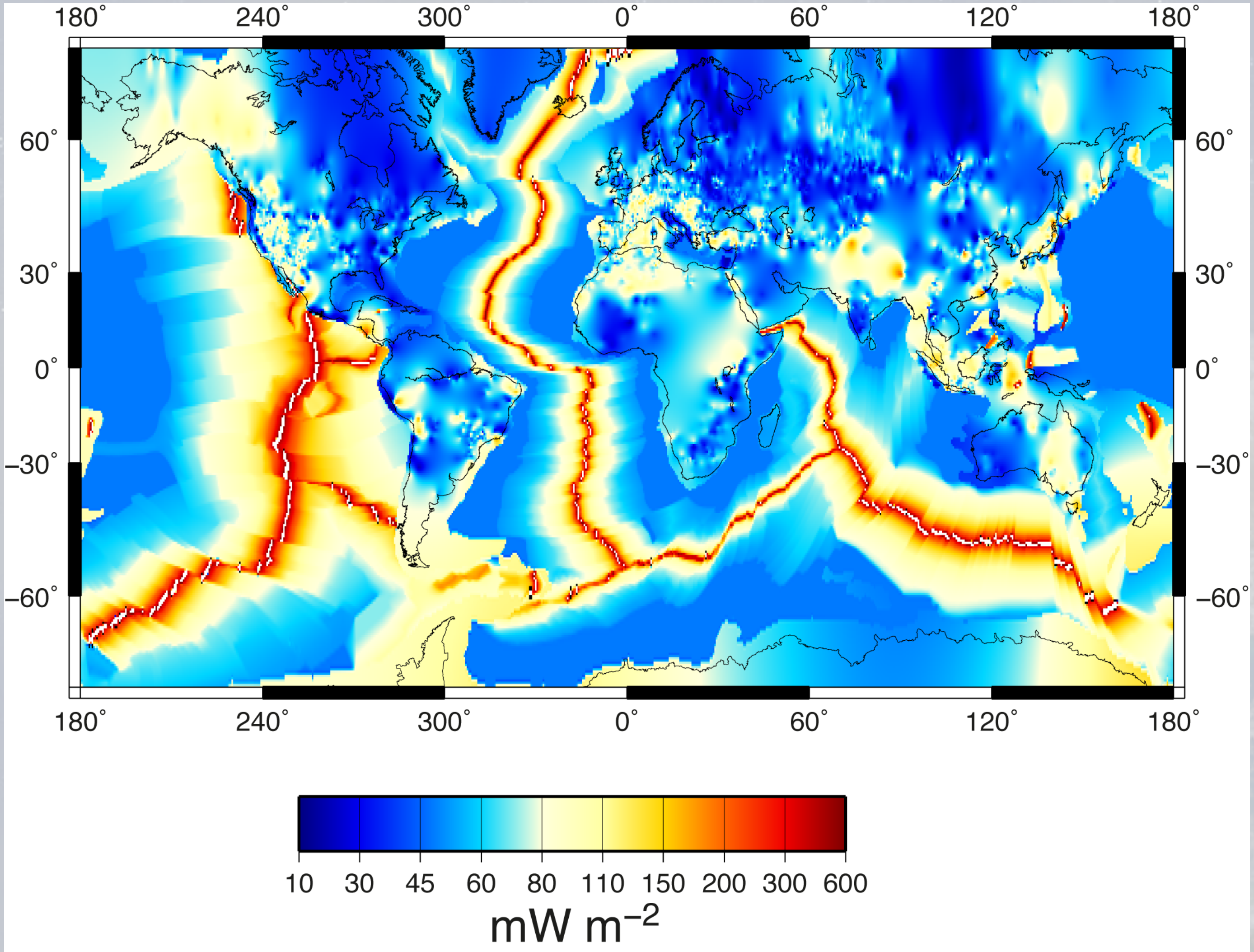
1975-today: "parameterized" convection models relating heat loss to interior temperature.

Mistake: **continents are ignored or imposed (*i.e.* are not part of solution).**

Earth's surface heat flow field



SECULAR COOLING EQUATION

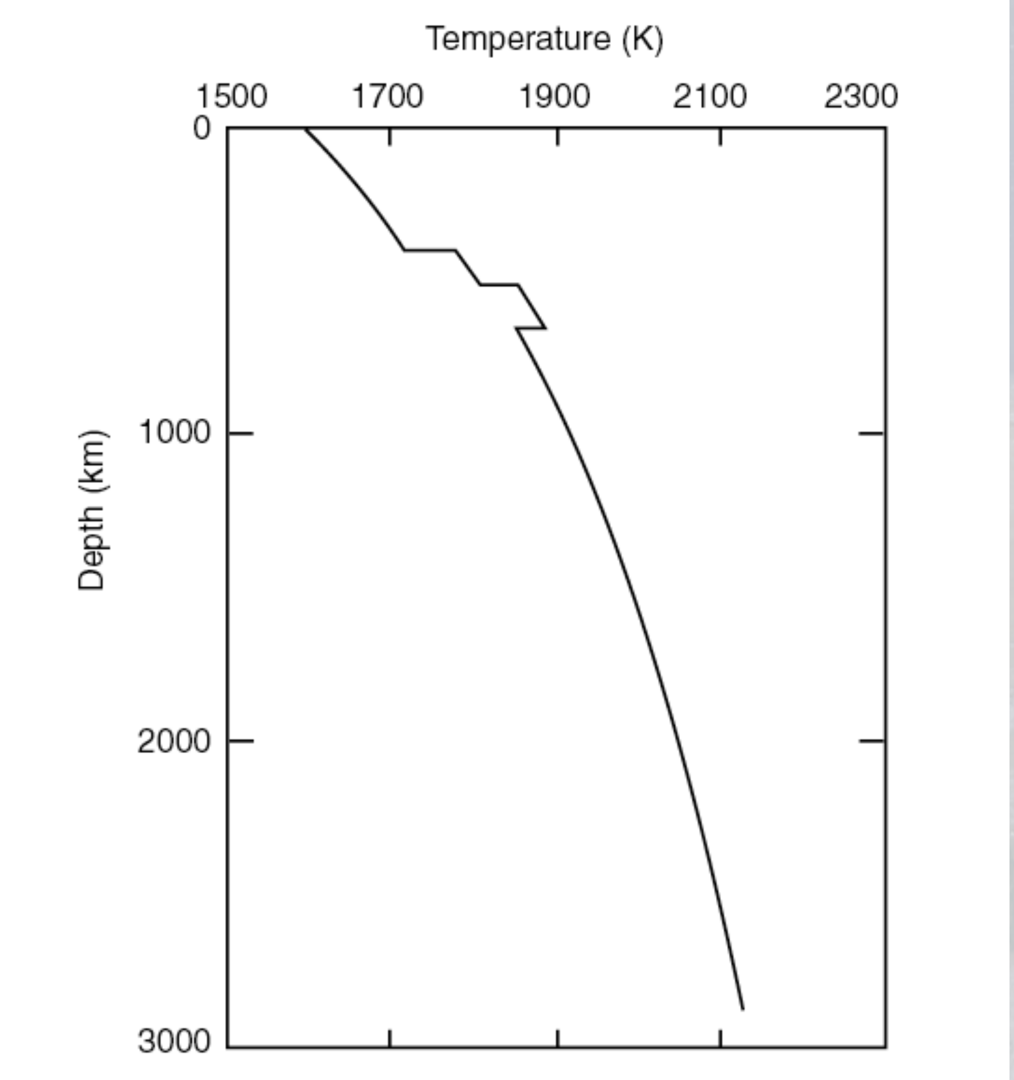
$$\frac{dU}{dt} = M\,C_p \frac{dT}{dt} = -\int q_r\, dA + \int H\, dV + \int \psi\, dV$$

= - surface heat loss
+ internal heat production
+ external energy tranfers (ex: tidal interaction)

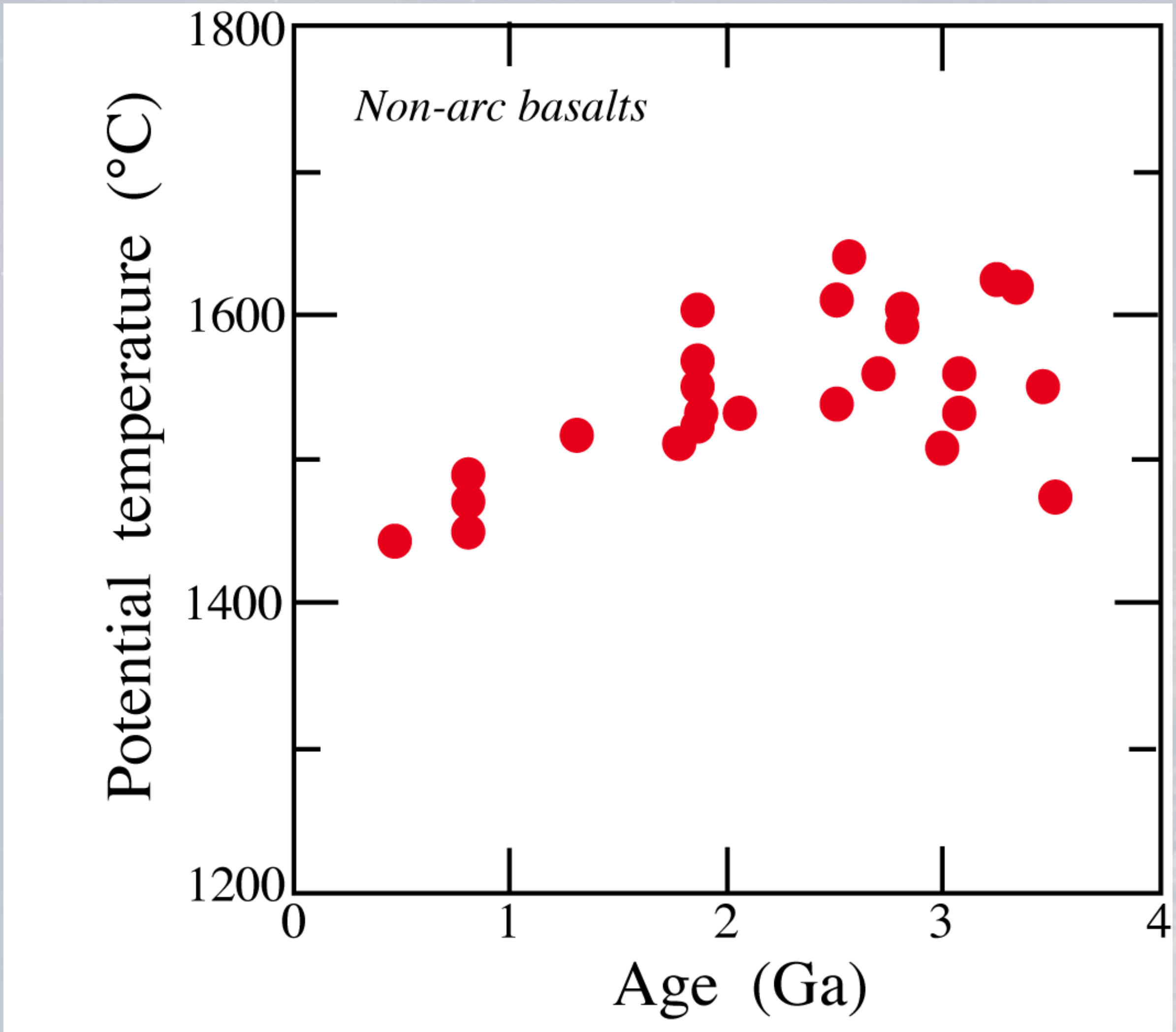
Note (1) : negligible contribution of contraction, zero contribution of dissipation

Note (2) : external energy transfers are negligible

Radial temperature profile through the Earth's mantle



Mantle temperature as a function of time T(t)



Bulk Silicate Earth heat production

Reference	H (pW kg^{-1})	H M_{BSE} (TW)
Hart & Zindler (1986)	4.9	19
McDonough & Sun (1995)	4.8 ± 0.8	19 ± 3
Palme & O' Neill (2003)	5.1 ± 0.8	20 ± 3
Lyubetskaya & Korenaga (2006)	3.9 ± 0.7	16 ± 3
Average mid-ocean ridge basalt source (Su, 2000; Langmuir et al., 2005)	2.8	**11**
Crustal + lith. mantle heat production (Jaupart & Mareschal, 2003; Rudnick & Gao, 2003)	/	**7 ± 1**

18 (sum of 11 and 7 ± 1)

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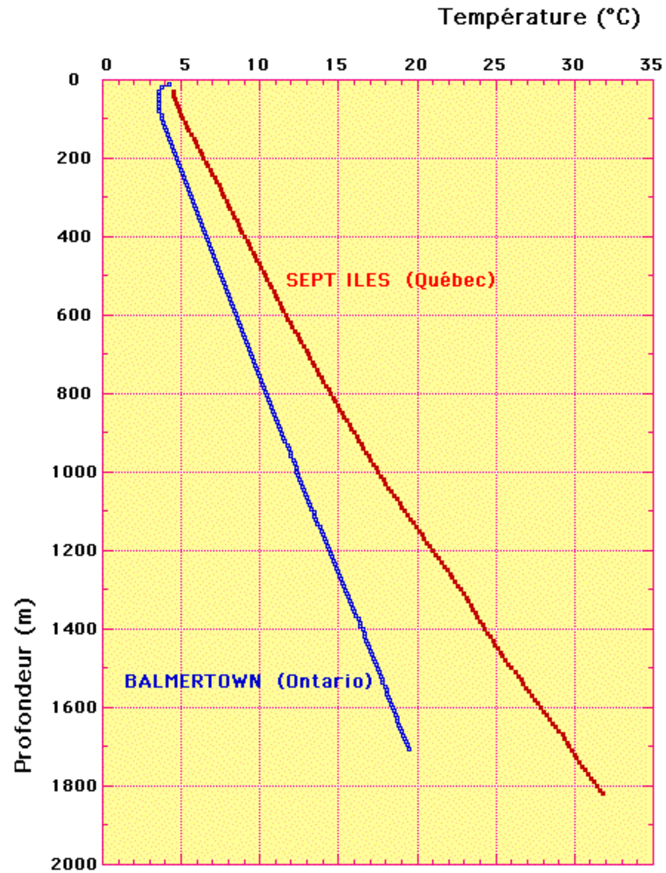

SECULAR COOLING OF THE EARTH

Secular cooling (mantle) ≈ 25 - 75 K Gy^{-1}

≈ 4 - 12 TW

Secular cooling (core) = 5 - 15 TW

Bulk Silicate Earth (BSE) radiogenic heat production

≈ 13 - 24 TW

Surface heat loss

Oceans	= 32 ± 2 TW
Continents	= 13 ± 1 TW
Total	= 45 ± 3 TW

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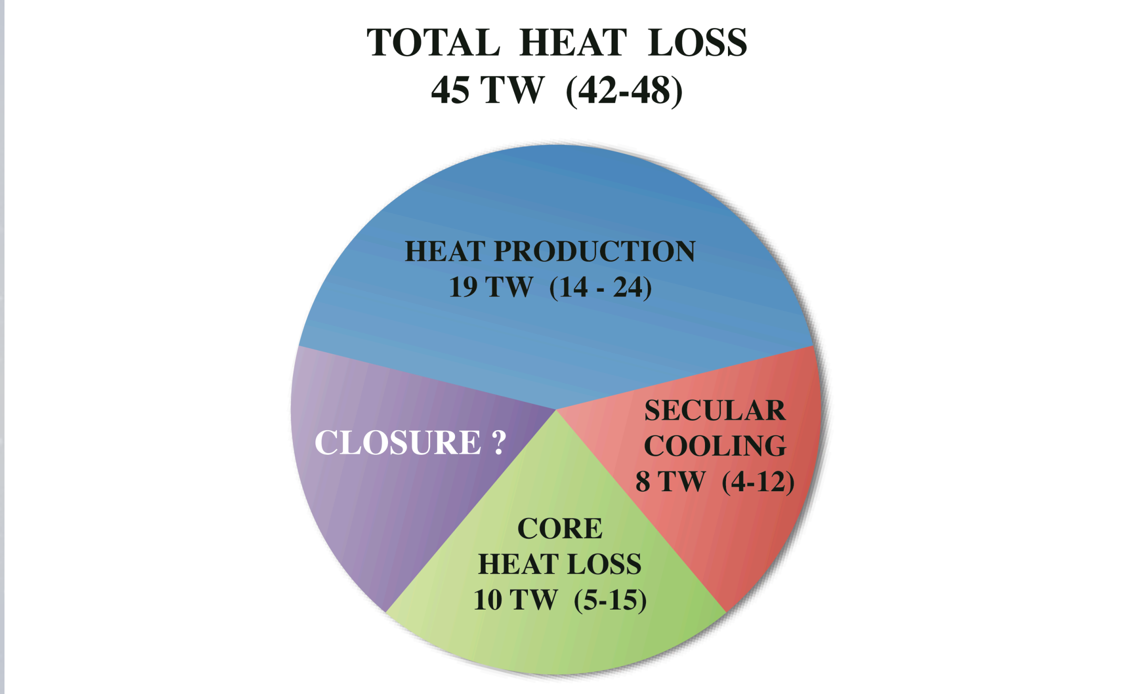

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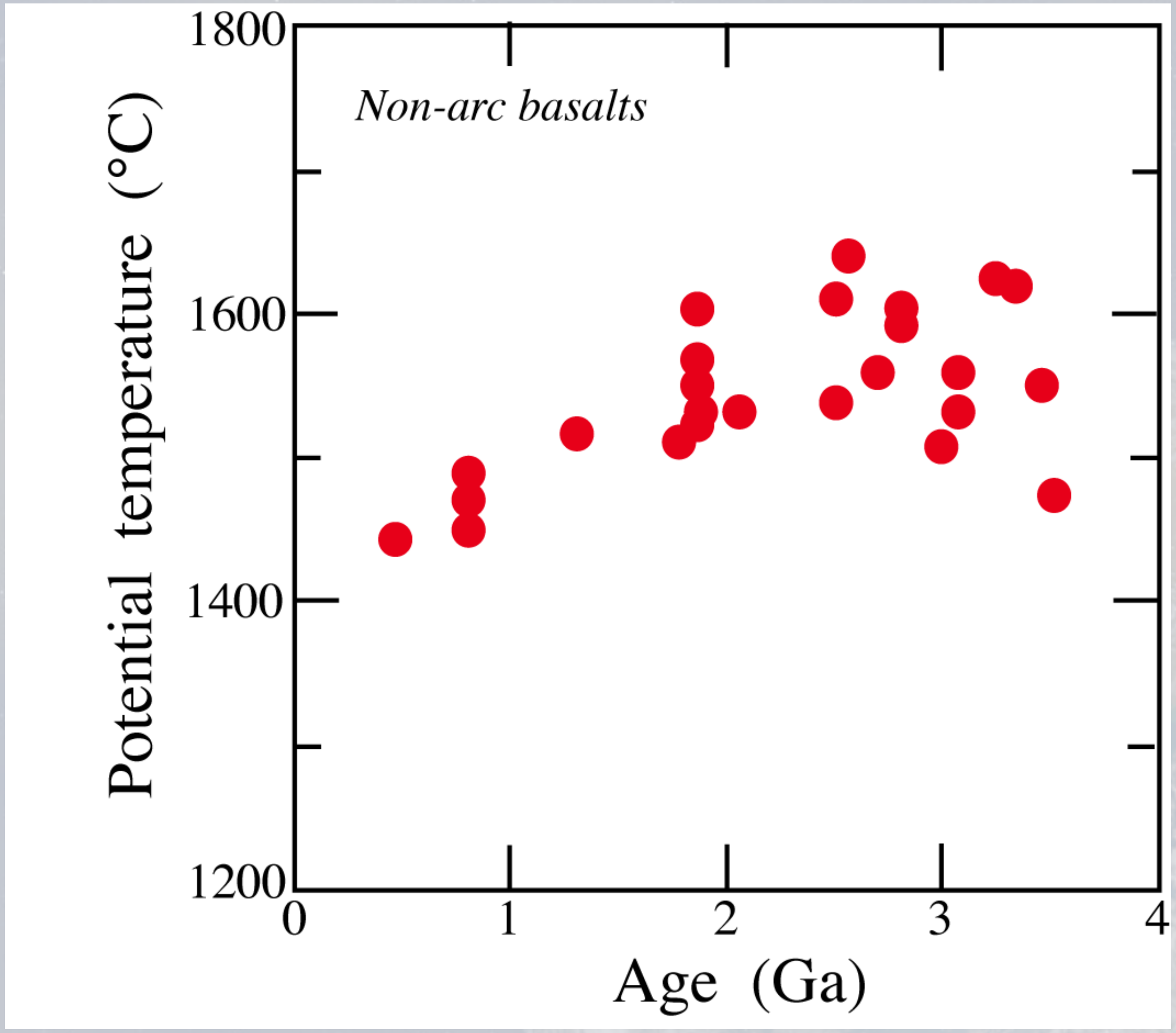
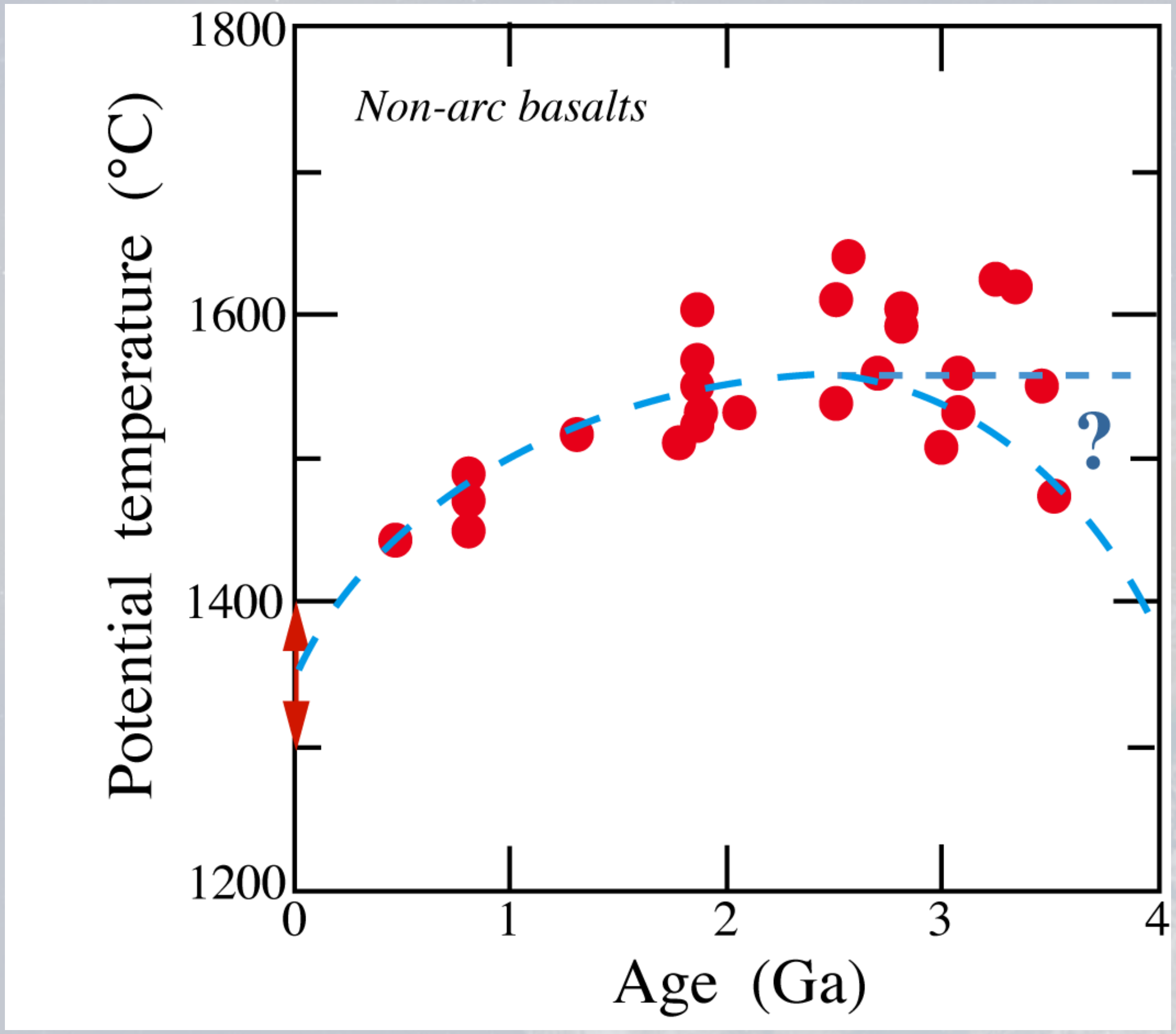


Average temperature versus age



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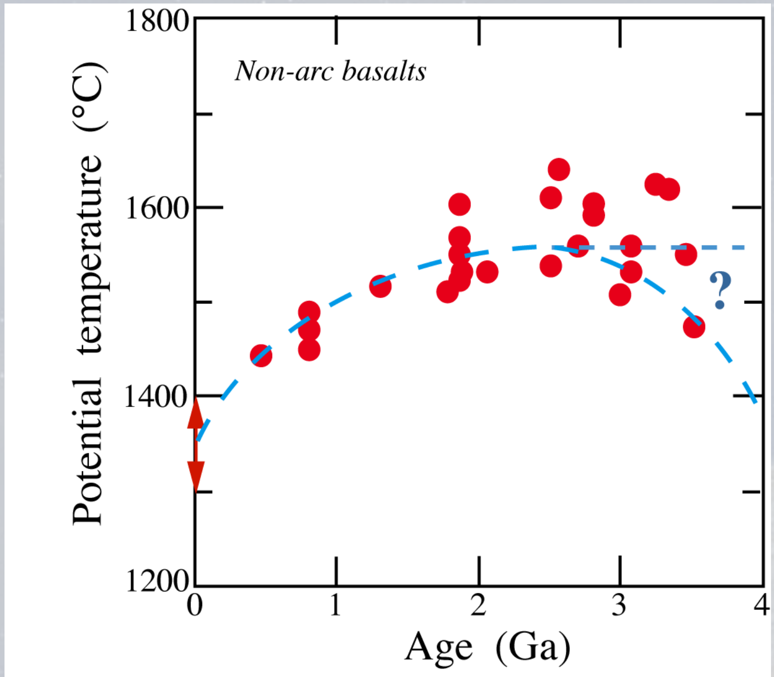

At t ≈ 2.5-3.0 Gy, T is maximum.

Implies that heat loss = heat production.

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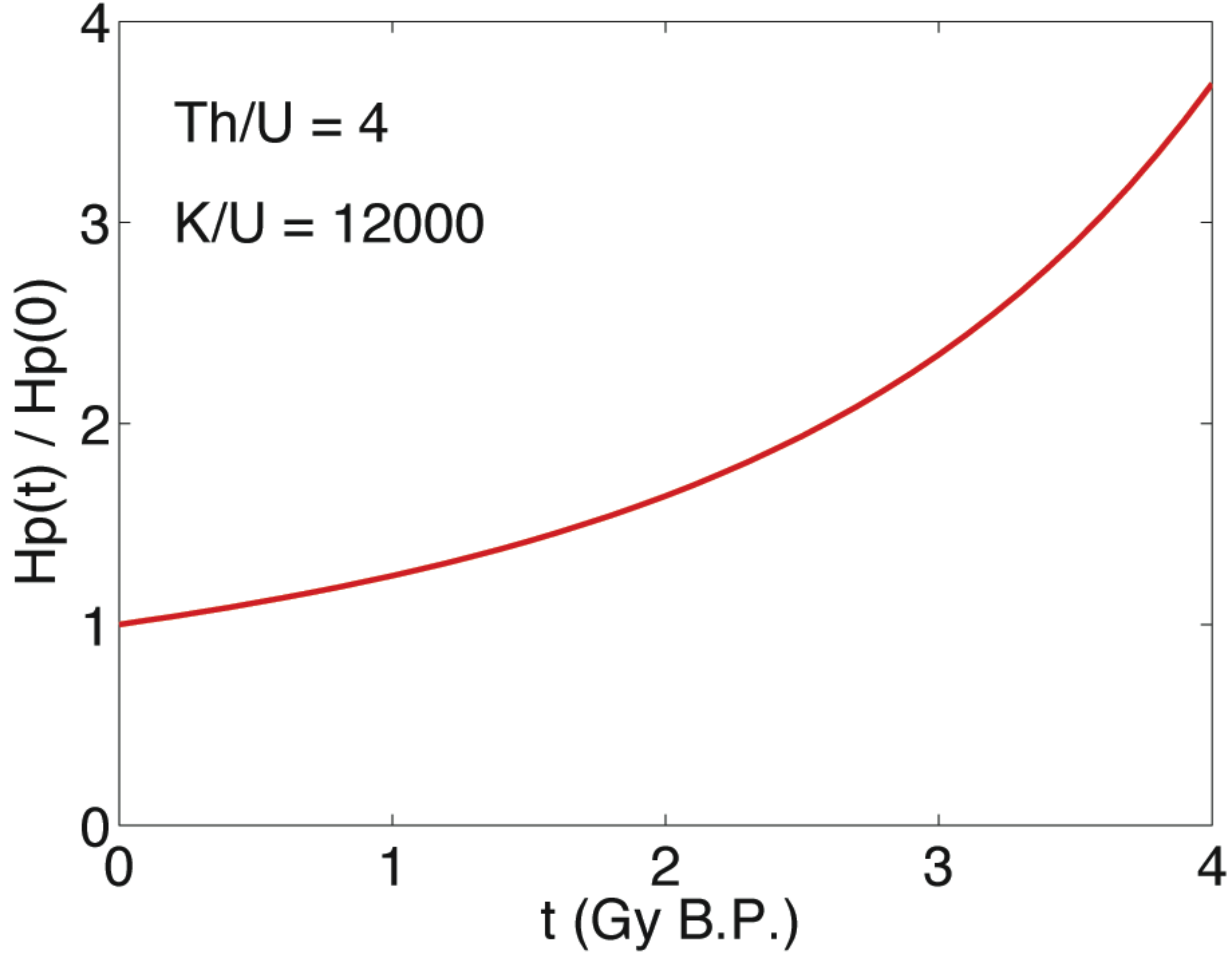

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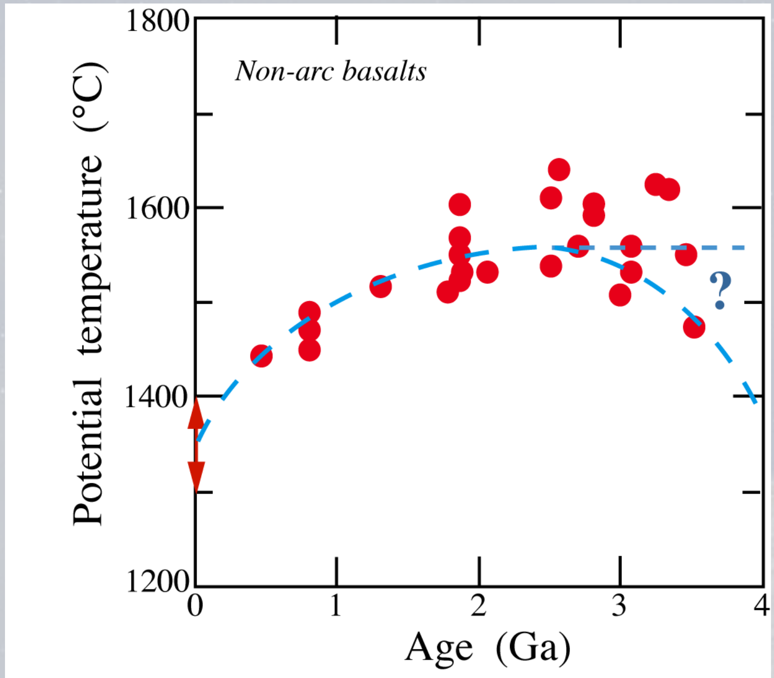

At t ≈ 2.5-3.0 Gy, T is maximum.

Heat production ≈ 40 TW

Heat loss ≈ 40 TW : not significantly different from today's value

Cooling through formation of continental crust

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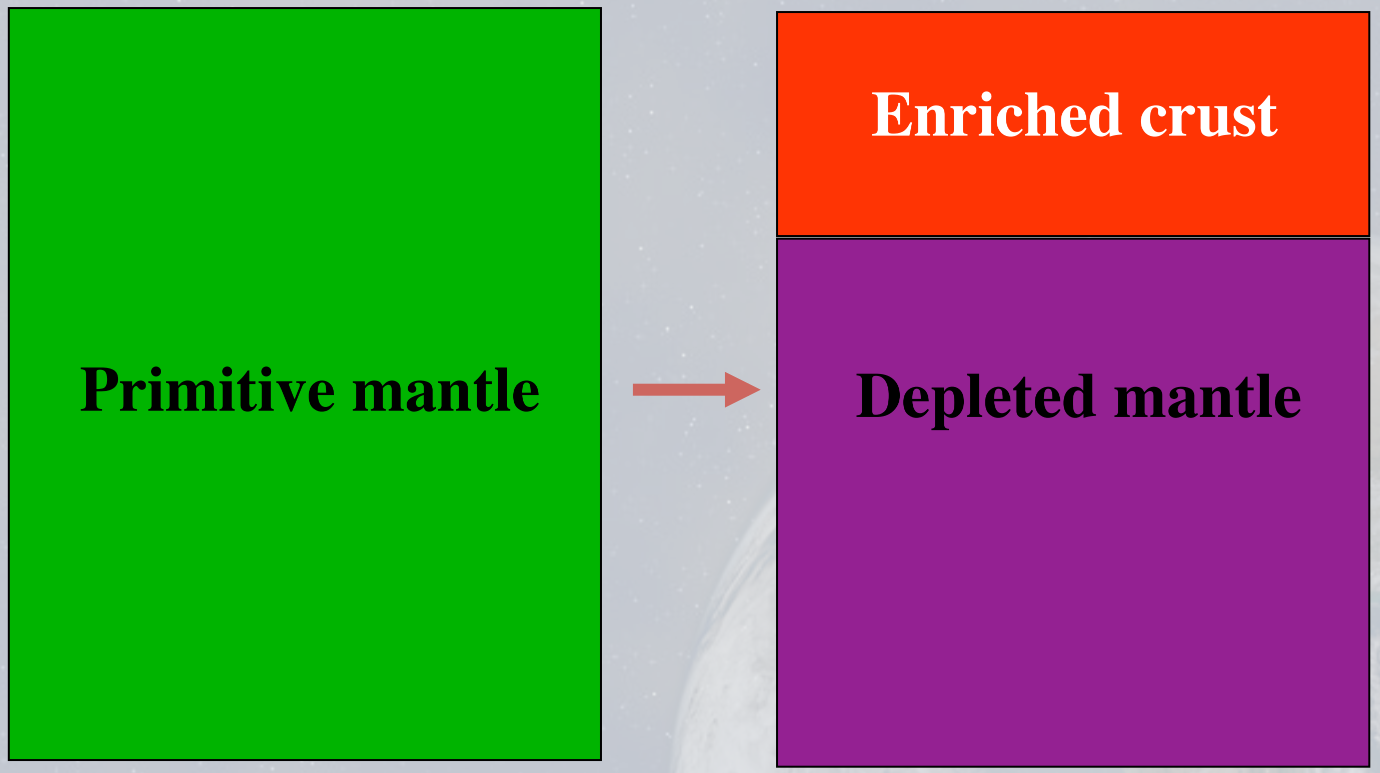

What is more "thermally" efficient for the cooling of a planet ?

(1) To segregate its heat producing elements in a rigid crust at its upper surface
(2) Or to convect vigourously ?

Compare two cases:

heat production in a thin crust
or in the convecting mantle.

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$$H_{\mathrm{conv}} h = H_{\mathrm{cond}} d_c$$

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$$\Delta T_{\mathrm{conv}} = C_Q^{-3/4} \left(\frac{H_{\mathrm{conv}} h}{\lambda} \right)^{3/4} \left(\frac{\kappa \mu}{\rho_o g \alpha} \right)^{1/4}$$

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$$\frac{\Delta T_{\mathrm{cond}}}{\Delta T_{\mathrm{conv}}} = \frac{C_Q^{3/4}}{2} \frac{d_c}{h} \left(\frac{\rho_o g \alpha H_{\mathrm{conv}} h^5}{\lambda \kappa \mu} \right)^{1/4} = \frac{C_Q^{3/4}}{2} \frac{d_c}{h} \mathrm{Ra}_H^{1/4}$$

$\ll 1$

Is the Earth working this way ?

Bulk Silicate Earth models

= 13 - 24 TW

MORB source + continental crust

≈ 17 – 19 TW

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Continental Crust (+ lithos. mantle) (40% of total area)

= 6 - 8 TW

Continental Crust over whole Earth's surface

= 15 - 20 TW

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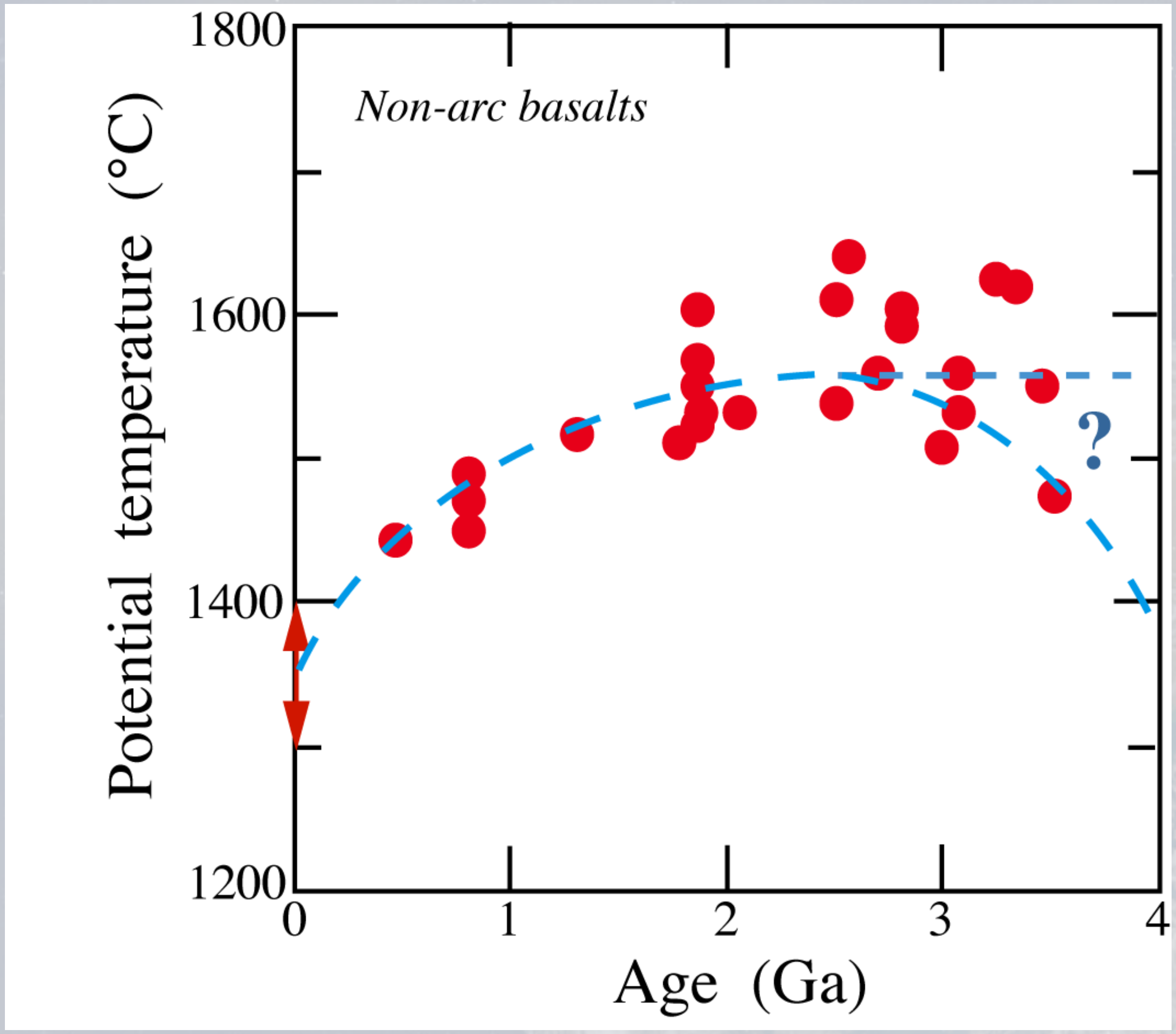
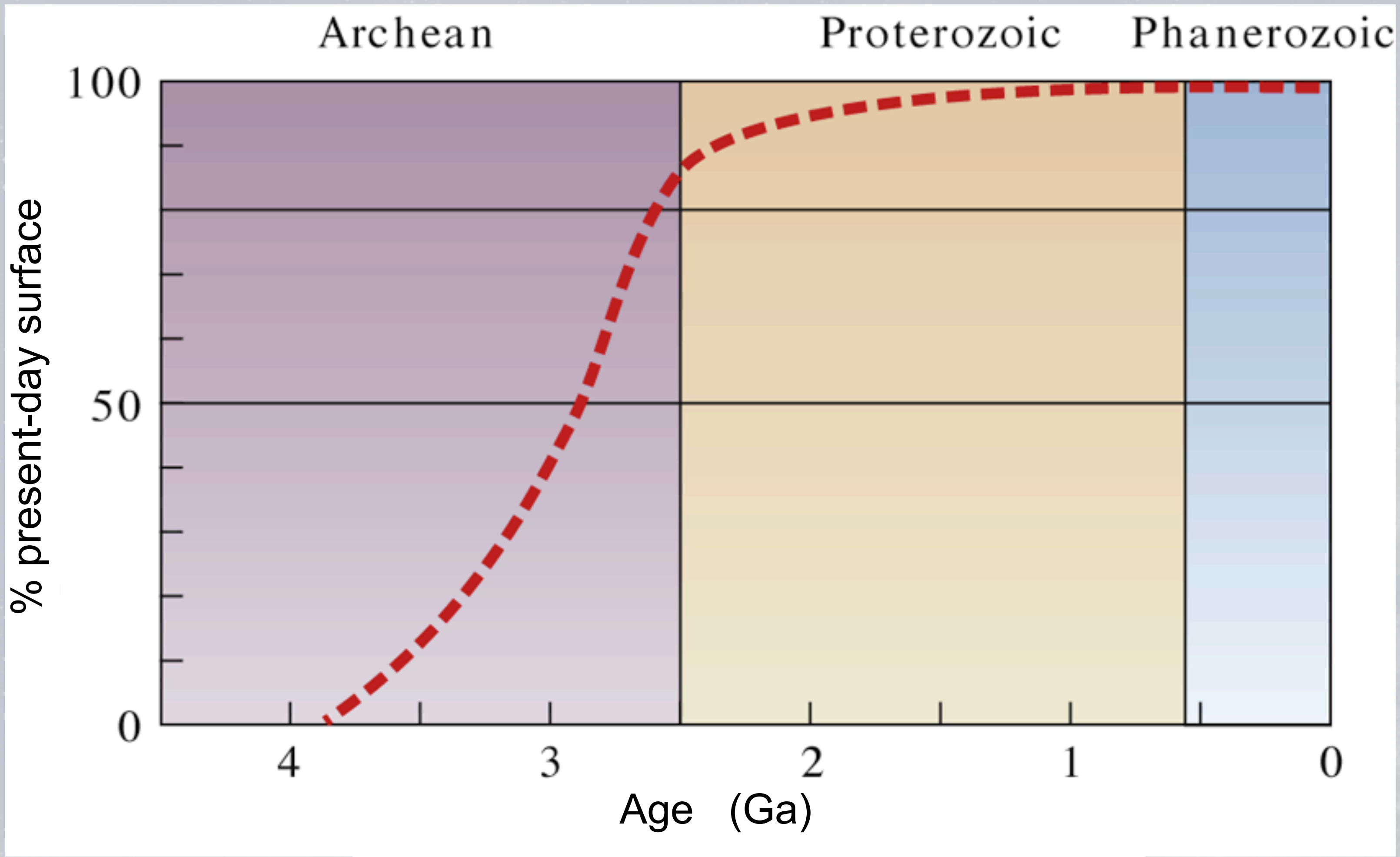


Continental Growth



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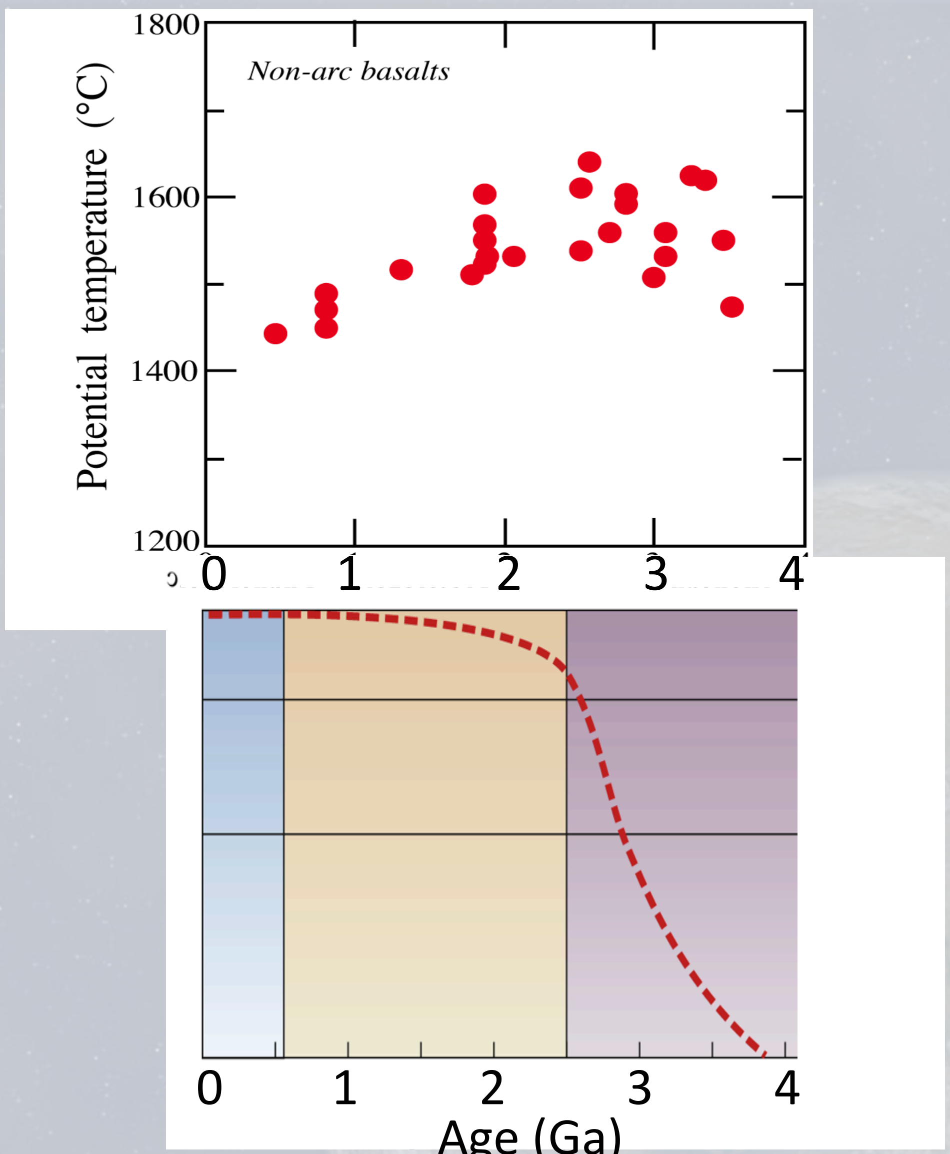

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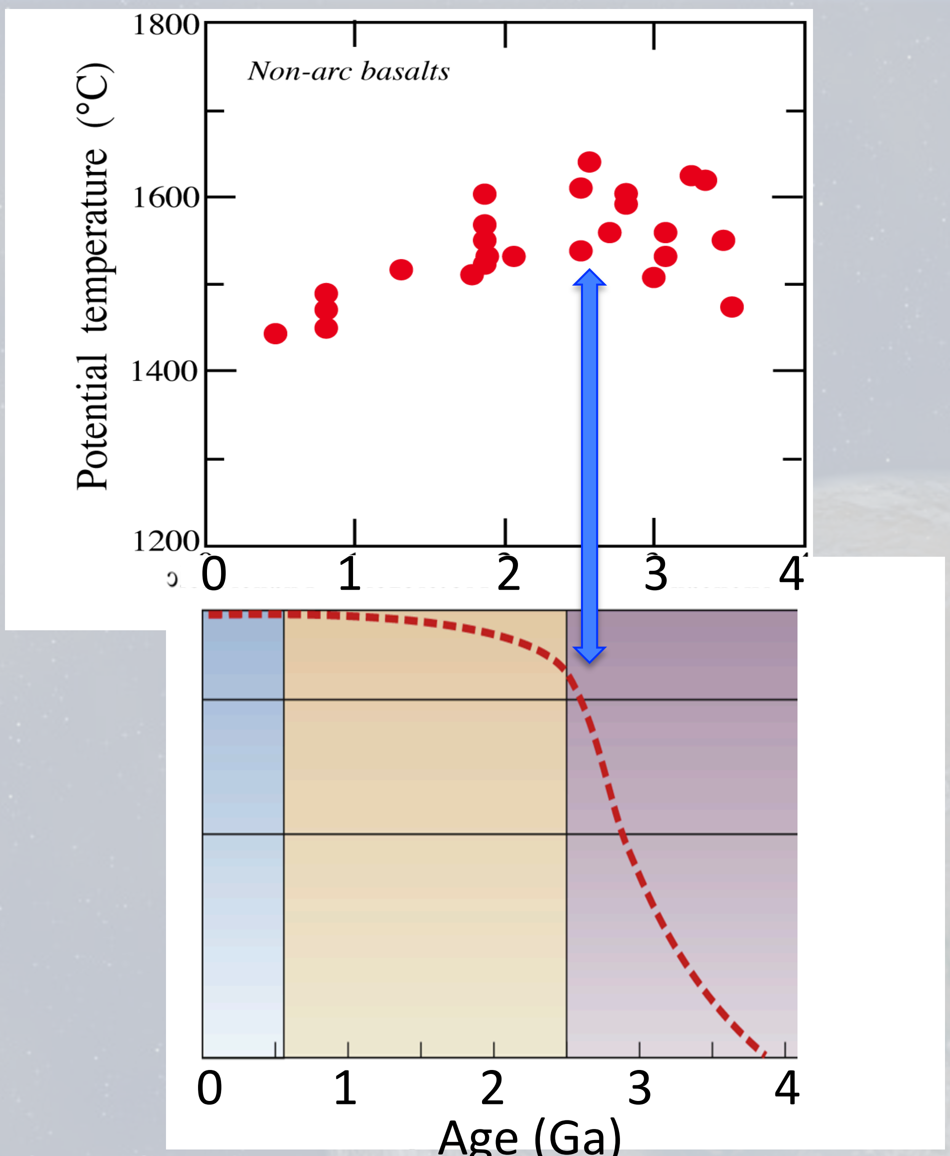

THE BUILDING OF AN ARCHEAN CONTINENT : THE SUPERIOR PROVINCE, CANADA

Raglan heat flow site 62° North

SECULAR COOLING OF THE EARTH

Questions

(1) Structure of new continental assemblage.
(2) Composition of juvenile continental material (including lower crust).
(3) Conditions for a stable continental assemblage
(melting, mechanical properties).

Answer

Lies in the thermal structure, which depends on amount
AND
distribution of radioactive elements in the crust.

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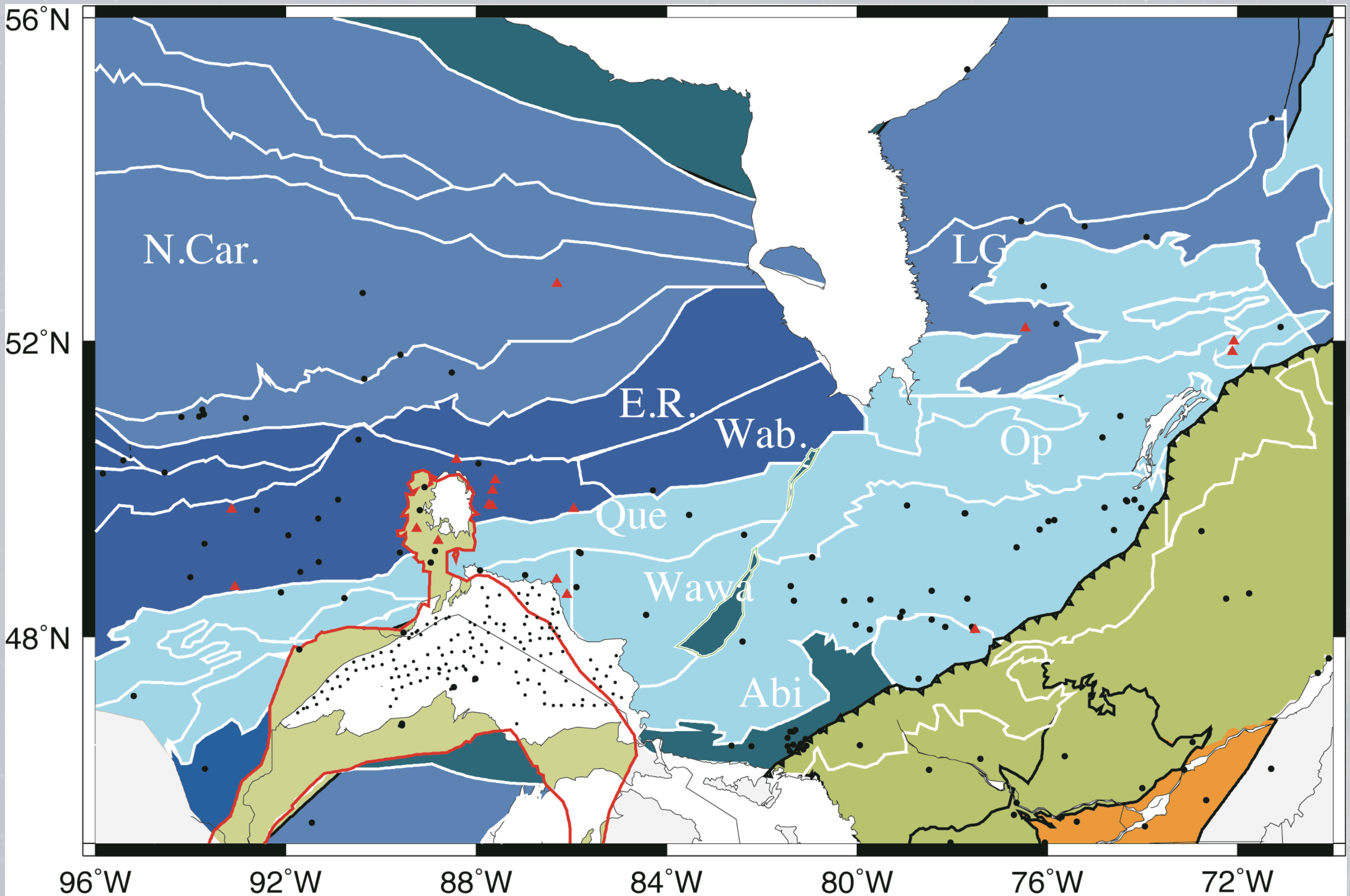

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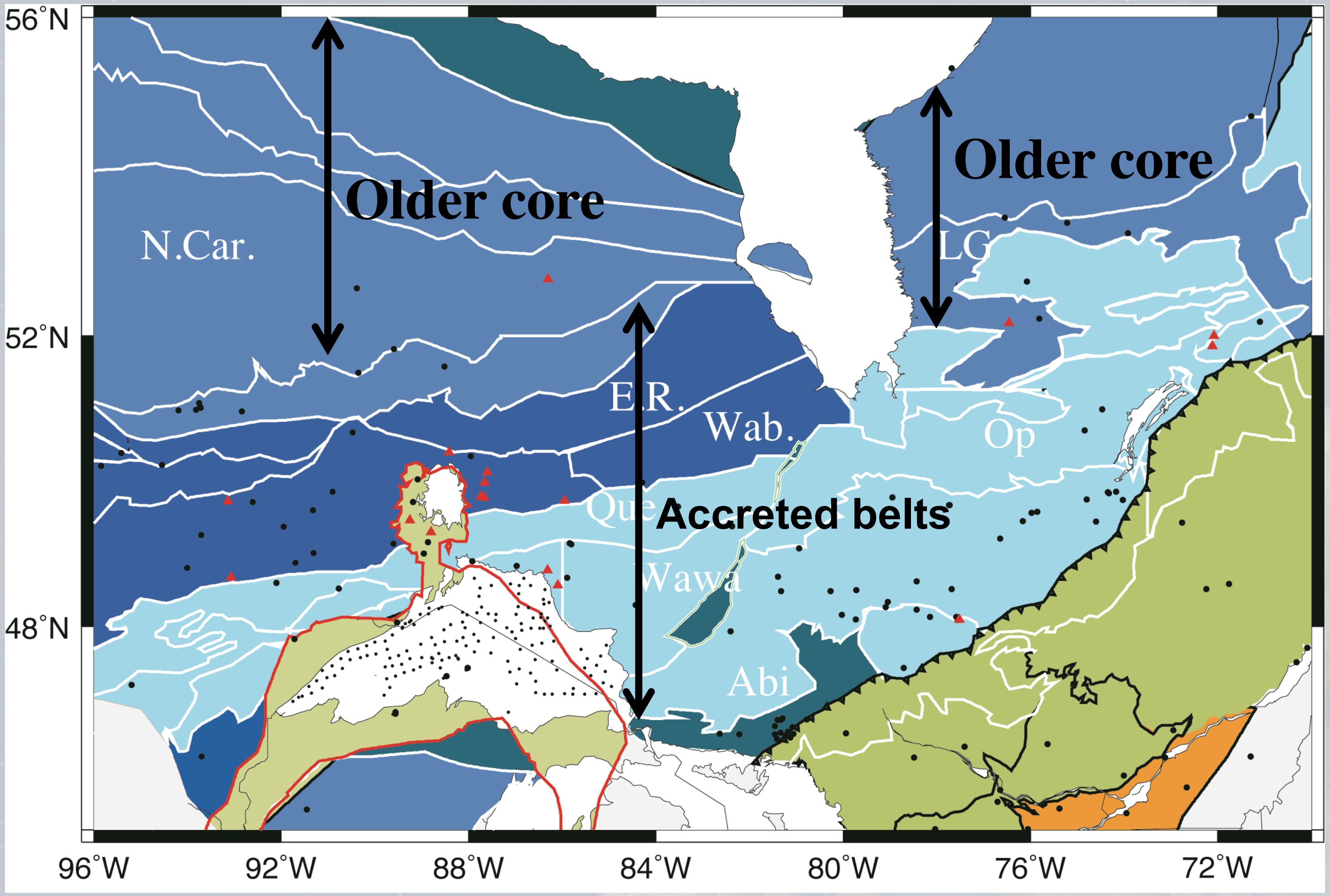
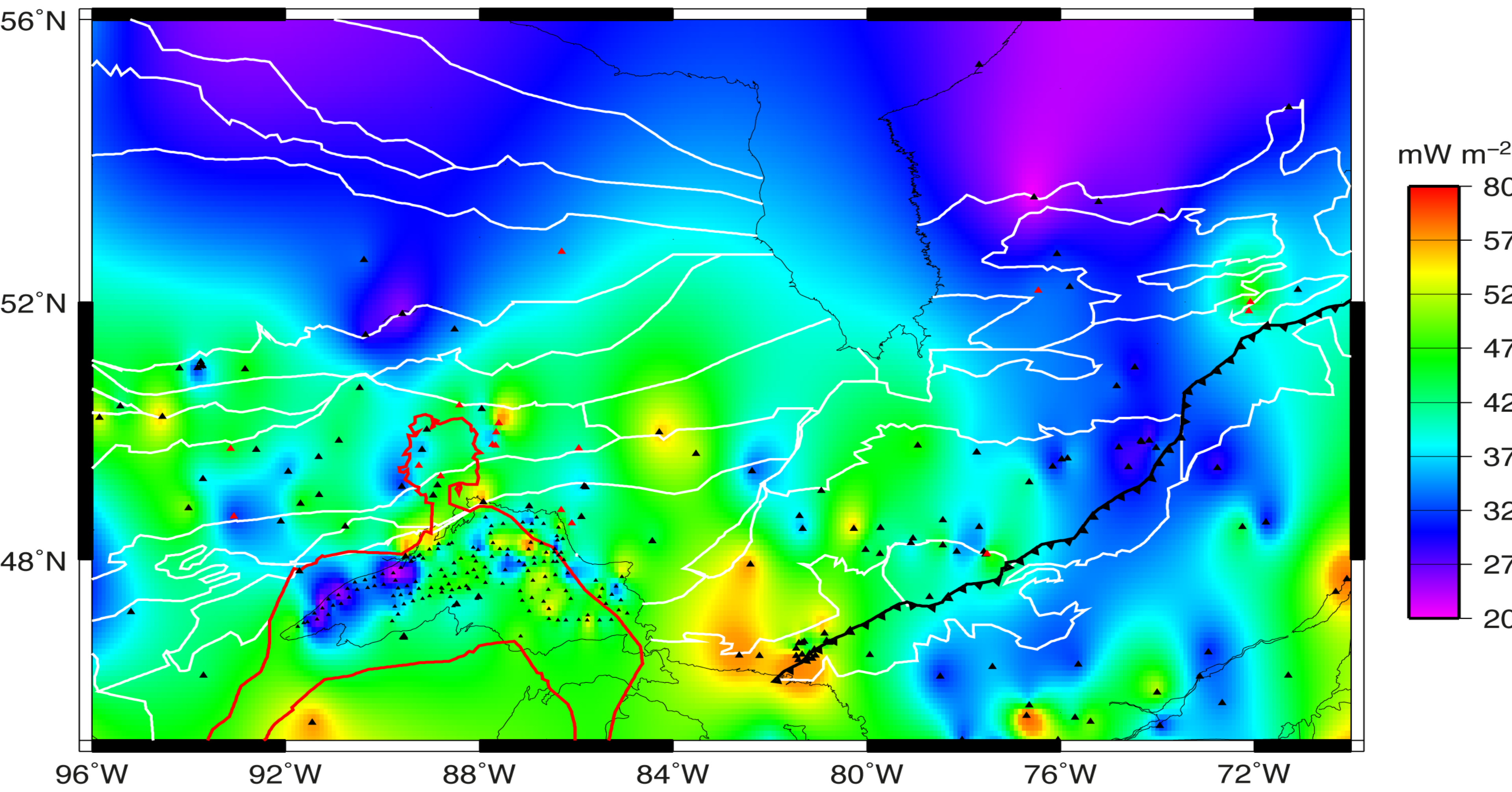


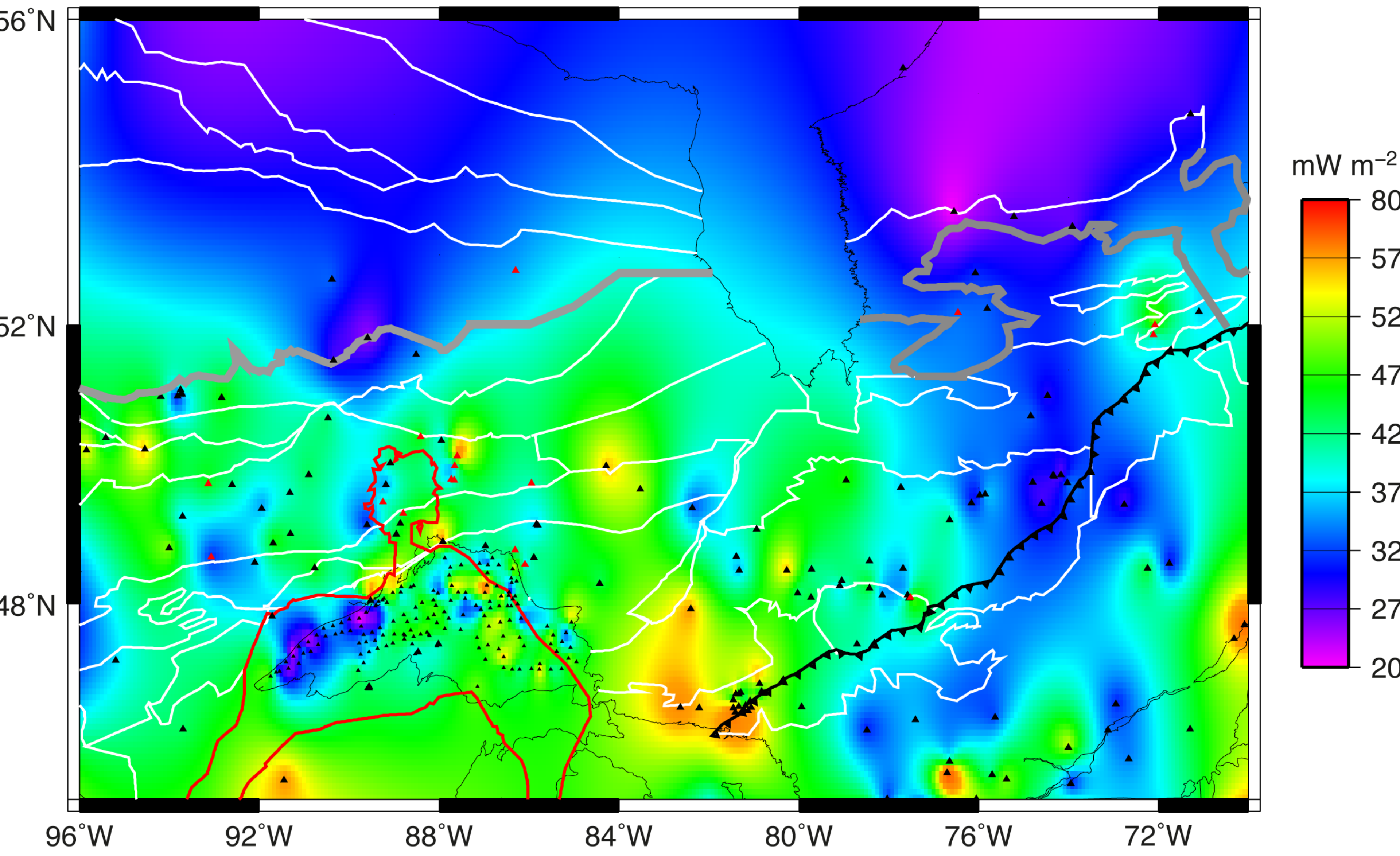
Heat flux



56°N
52°N
48°N
96°W
92°W
88°W
84°W
80°W
76°W
72°W
mW m⁻²
80
57
52
47
42
37
32
27
20

On the scale of the province, mantle heat flow is ≈ uniform.

Variations of surface heat flow
=
variations of crustal composition.



56°N
52°N
48°N
96°W
92°W
88°W
84°W
80°W
76°W
72°W
mW m^{-2}
80
57
52
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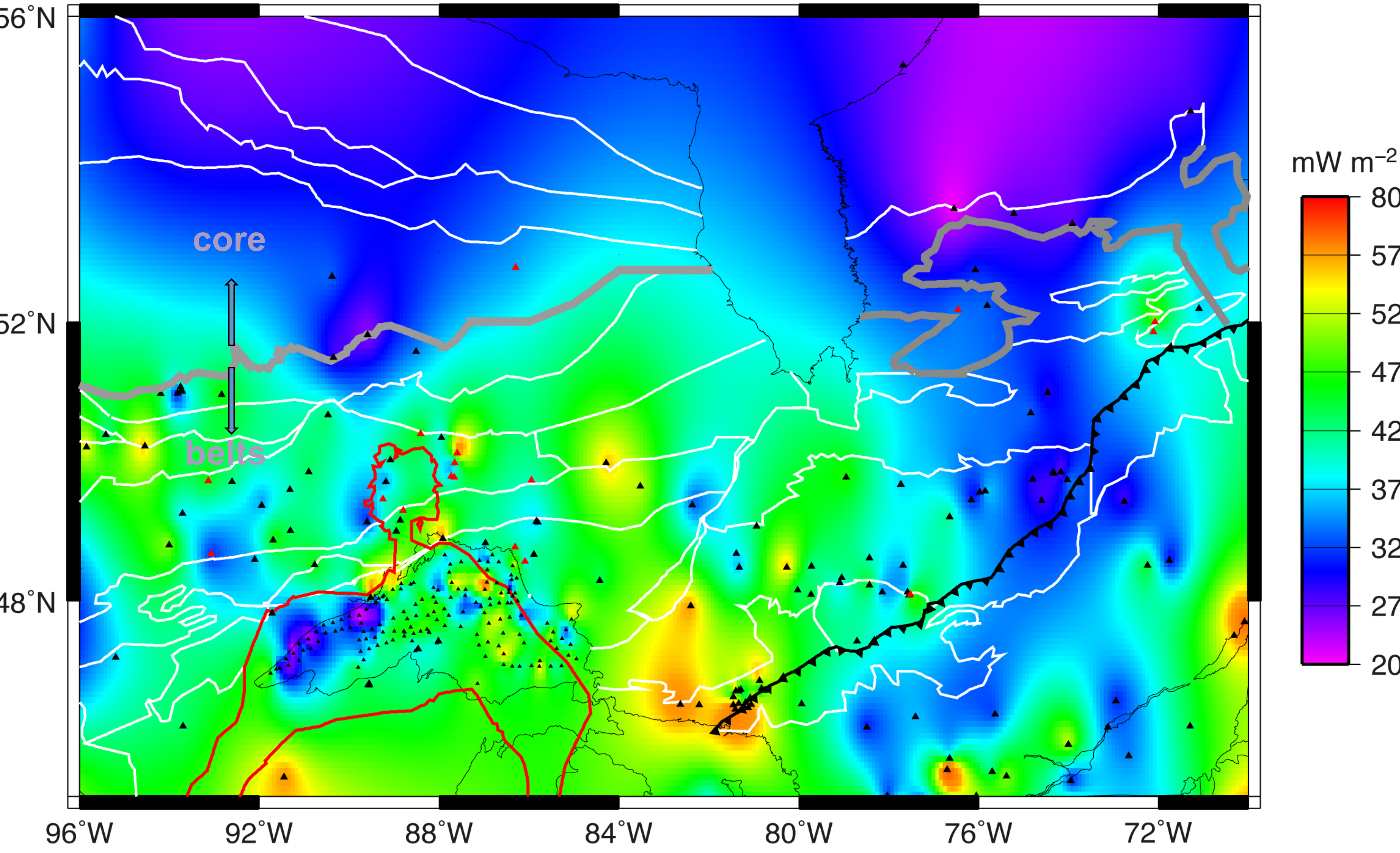
27
20


56˚N
52˚N
48˚N
96˚W
92˚W
88˚W
84˚W
80˚W
76˚W
72˚W
core
belts
mW m−2
80
57
52
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42
37
32
27
20

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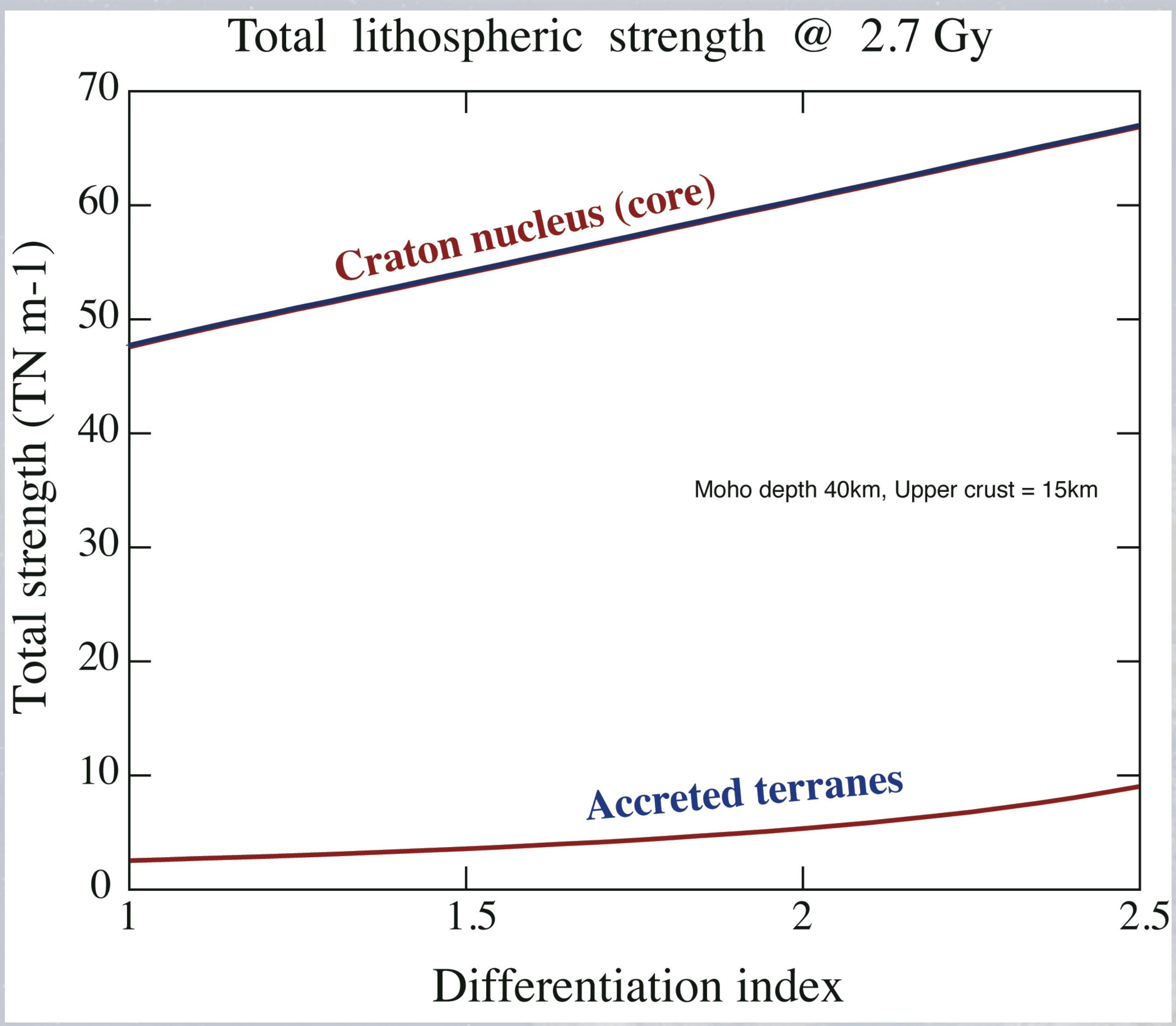

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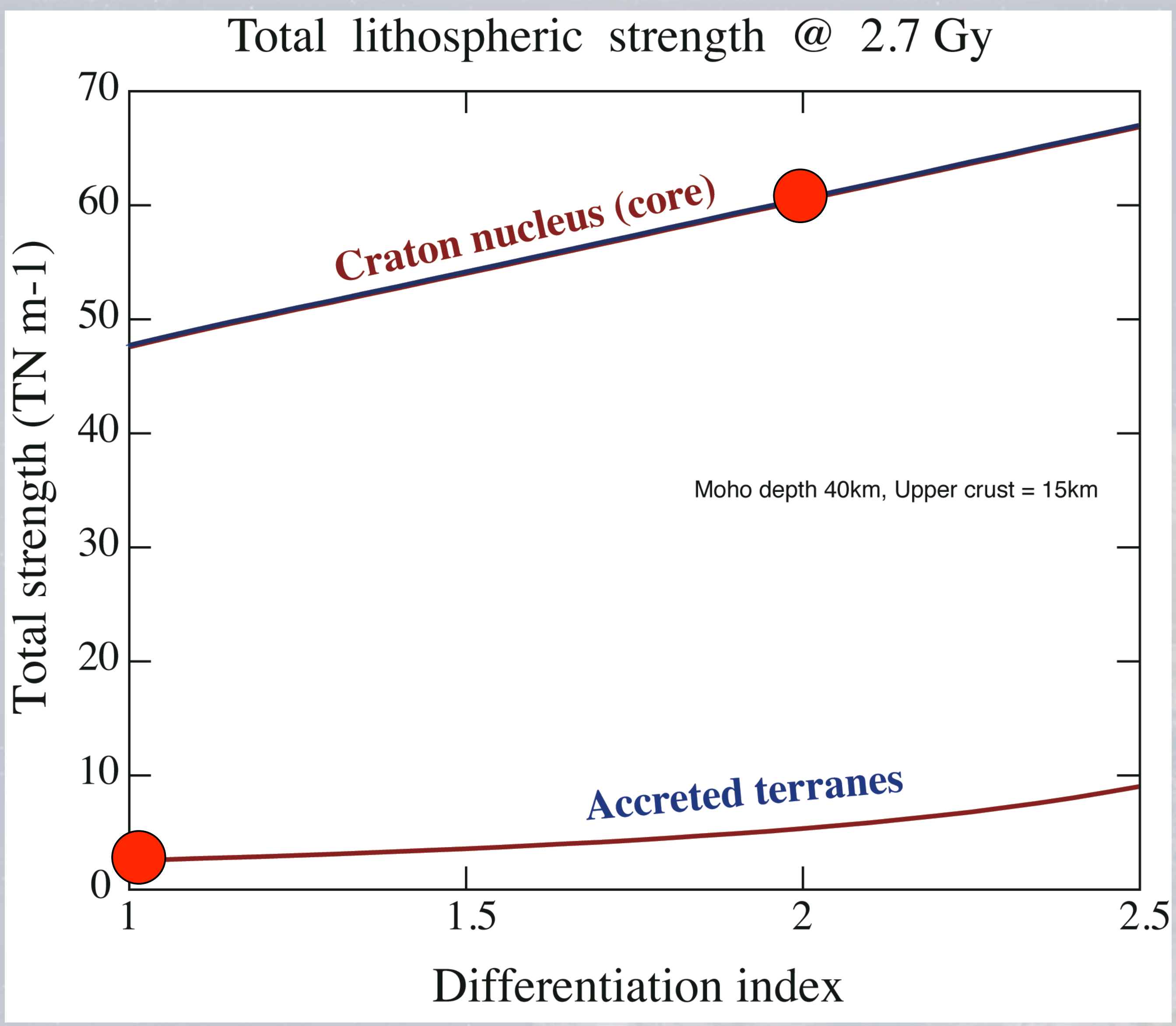

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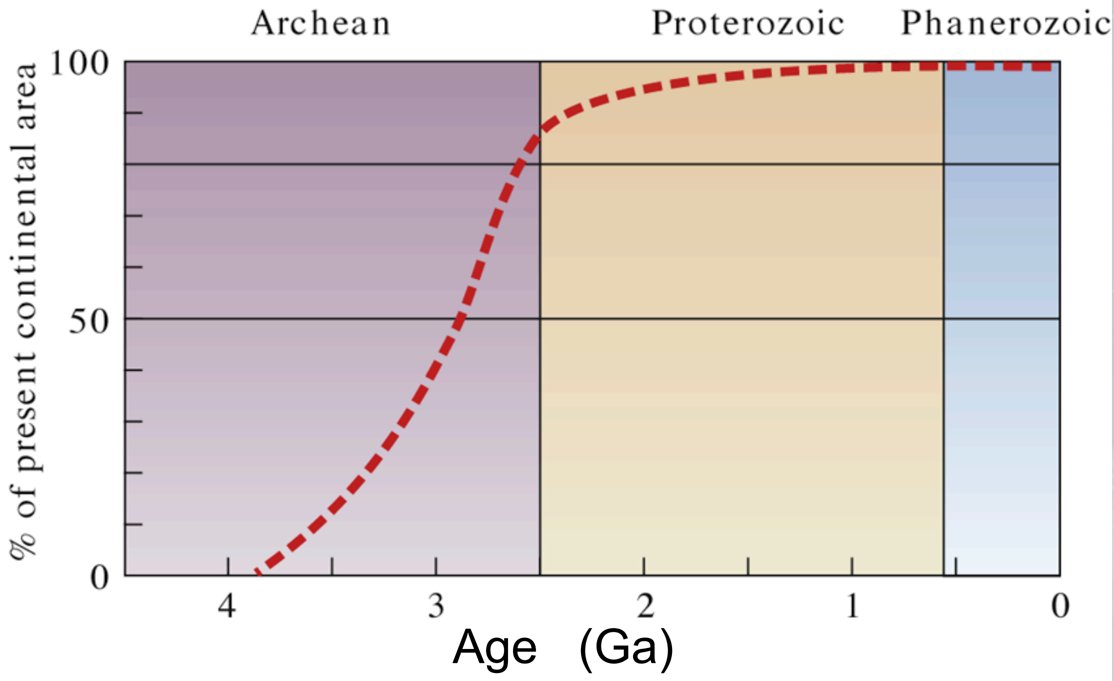

After ≈ 3 Gy
Creation of new (juvenile) continental crust ≈ balanced by destruction.
Destruction achieved in large part through collision and mountain belt formation:

area destruction (shortening)
+
volume destruction (erosion and sediment transport to the oceans).