Heat transfer: the sources

From the sun:

- $2x10^{17}$ W
- $4x10^{2}$ Wm^{-2}

Derives surface processes:

- Water cycle
- Biosphere
- Rain
- Erosion

Sun

From the Earth interior:

- $4x10^{13}$ W
- $8x10^{-2}$ Wm^{-2}

Derives deep Processes:

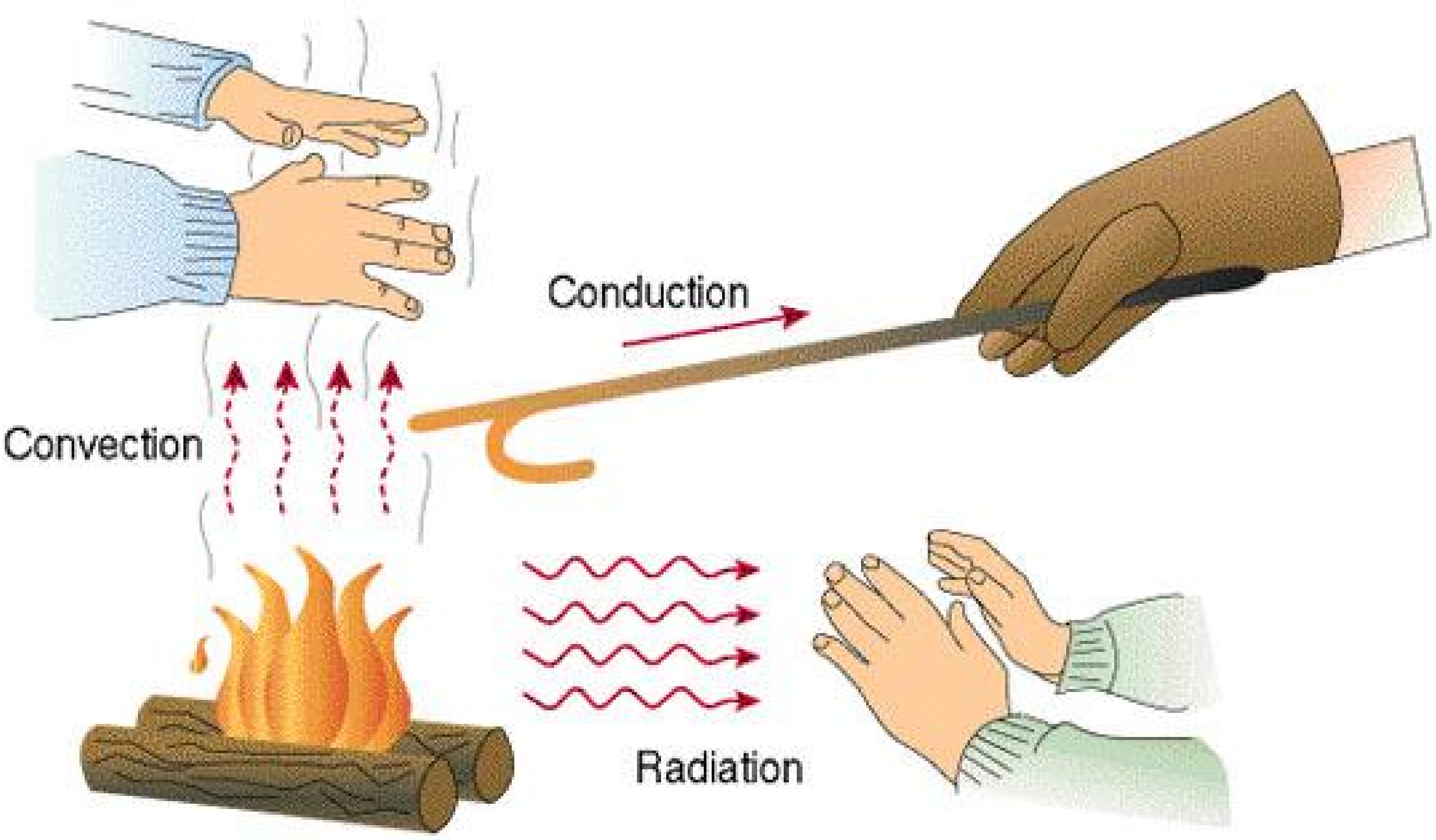
- Mantle convection
- Geodynamo
- Plate tectonics
- Metamorphism
- Volcanism

Earth

Earthquakes: 10^{11} W

Heat transfer: the mechanisms

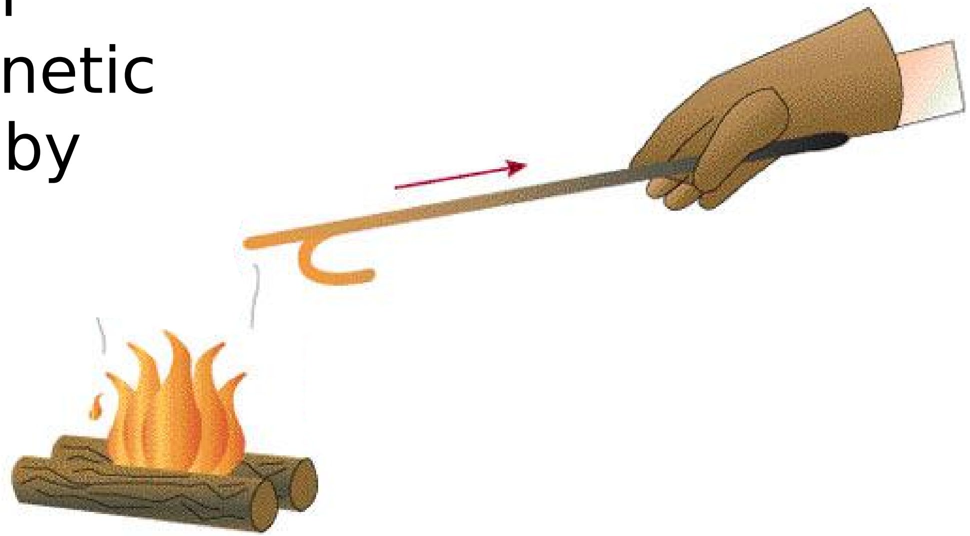
Three mechanisms for heat transfer: conduction, convection and radiation.



Heat transfer: the mechanisms

Conduction:

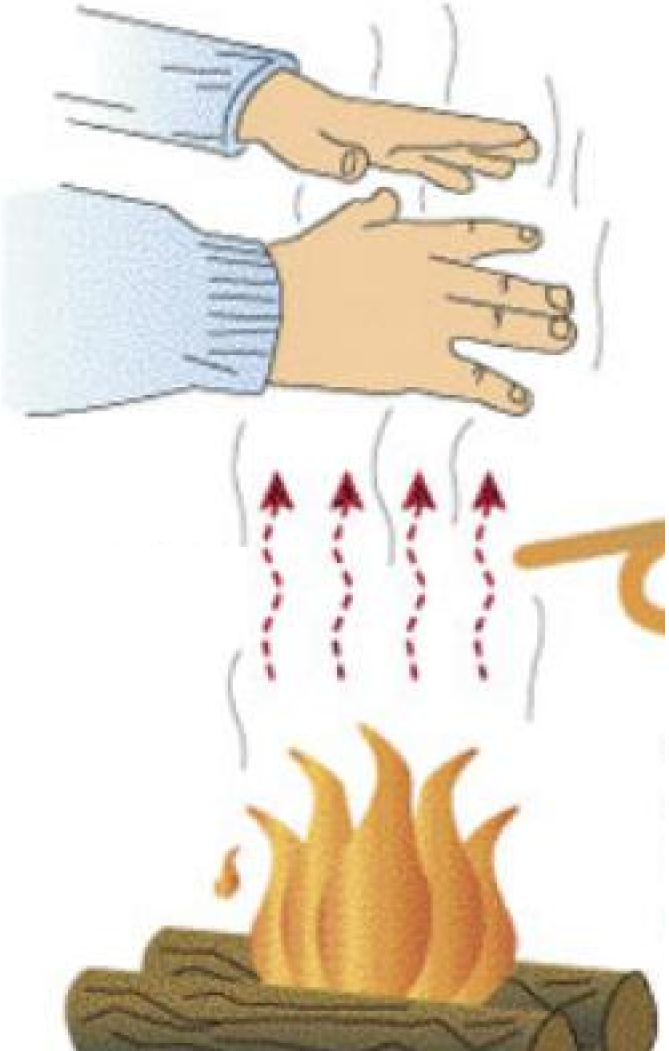
A diffusive process wherein molecules transmit their kinetic energy to other molecules by colliding with them.



Heat transfer: the mechanisms

Convection:

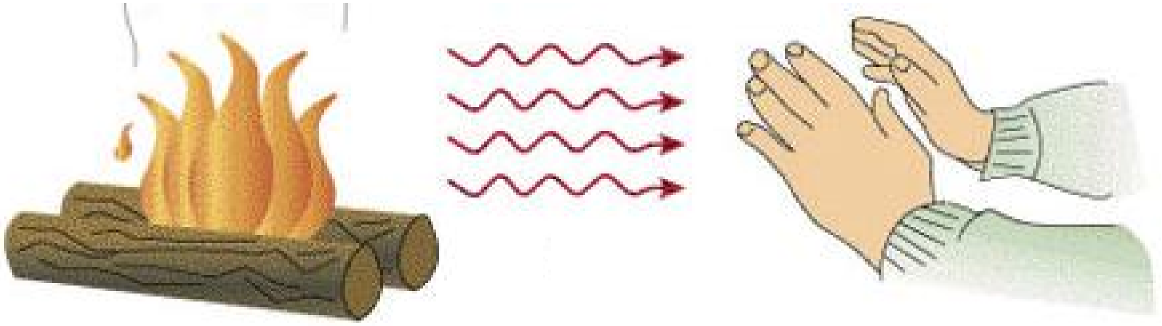
A process associated with the motion of the medium. When a hot material flows into a cold material, it will heat the region - and vise versa.



Heat transfer: the mechanisms

Radiation:

The transfer of heat via electromagnetic radiation.
Example - the Sun.



Heat transfer: the mechanisms

- In the Earth, both conduction and convection are important.

- In the lithosphere, the temperature gradient is controlled mainly by conduction.

- Convection in the lithosphere does play a role in:
    - Mid-ocean ridges in the form of hydrothermal ocean circulation.
    - Volcanism and emplacement of magmatic bodies.

Heat transfer: heat flux

Heat flux is the flow per unit area and per unit time of heat. It is directly proportional to the temperature gradient.

One dimensional Fourier's law:

where:
q is the heat flux
k is the coefficient of thermal conductivity
T is the temperature
y is a spatial coordinate

Question: why is the minus sign?

Question: is q a vector or a scalar?

Heat transfer: heat flux

Units:

- q is in [Wm^{-2}]

- k is in [$Wm^{-1}K^{-1}$]

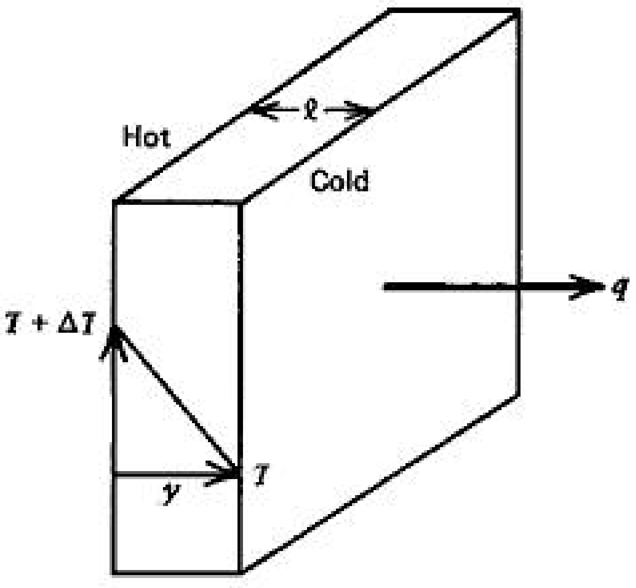
where W is read “watt”, and is equal to Joule per second.

A substance with a large value of k is a good thermal conductor, whereas a substance with a small value of k is a poor thermal conductor or a good thermal insulator.

Heat transfer: heat flux

Example 1: a slab of thickness l, and a temperature difference of ƛT:

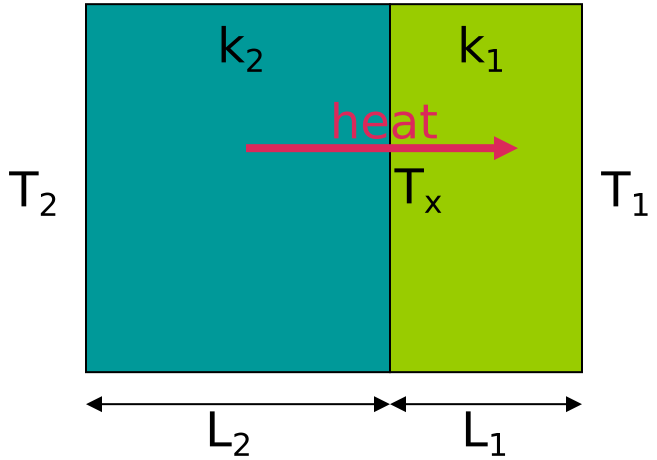
The heat flux is given by:



Heat transfer: heat flux

Example 2: a composite slab

H.F. through slab 2:



H.F. through slab 1:

In steady-state q_1=q_2, we get:

Or more generally:

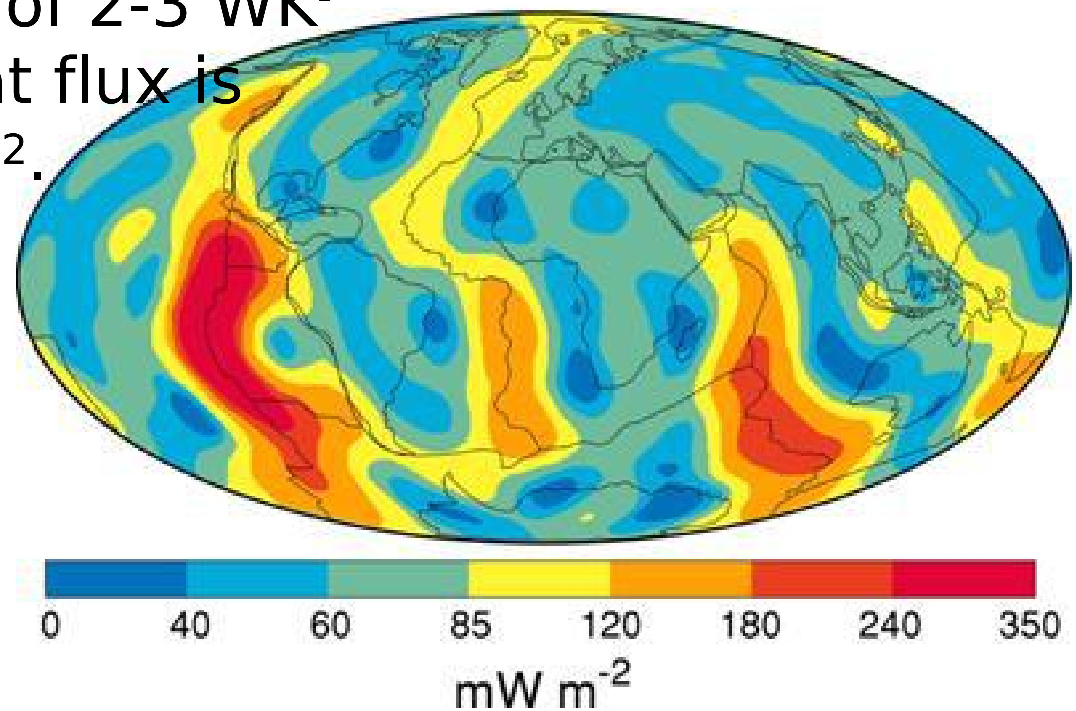
Note the trade-off between thermal conductivity, k, and the medium thickness, L. Thus, the important quantity is L/k, often referred to as thermal resistance.

Heat transfer: world-wide heat flow

- Highest heat loss at mid-ocean ridges and lowest at old oceanic crust.
- With temperature gradient of 20-30 K/km, and thermal conductivity of 2-3 $WK^{-1}m^{-1}$, the heat flux is 40-90 mWm^{-2}.

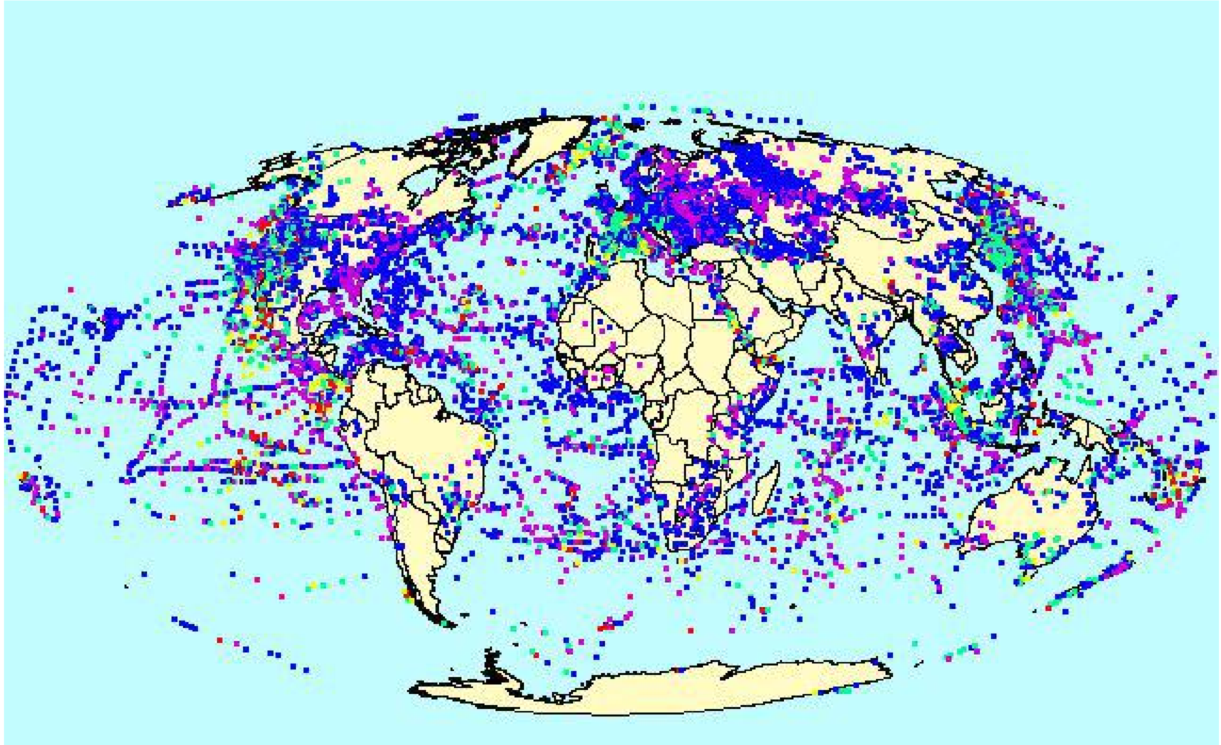
Table 7.3 *Heat loss and heat flow from the Earth*

	Area (10^6 km^2)	Mean heat flow (10^{3} $W\,m^{-2}$)	Heat loss (10^{12} W)
Continents (post-Archaean)	142	63	9.0
Archaean	13	52	0.7
Continental shelves	46	78	3.5
Total continental area	201	65 ± 1.6	13.1 ± 0.3
Oceans (including marginal basins)	309	101 ± 2.2	31.2 ± 0.7
Worldwide total	510	87 ± 2.0	44.2 ± 1.0



Heat transfer: measurements

Heat flow measurements: the global heat flow map on the previous slide is based on a compilation of individual measurements whose distribution is shown below.



Map from: www.heatflow.und.edu/

For practical reasons, the vast majority of the measurements are from continental areas.

Heat transfer: heat flow over stable continental areas

- The surface heat flow is strongly correlated with the surface concentration of the radioactive heat producing elements.

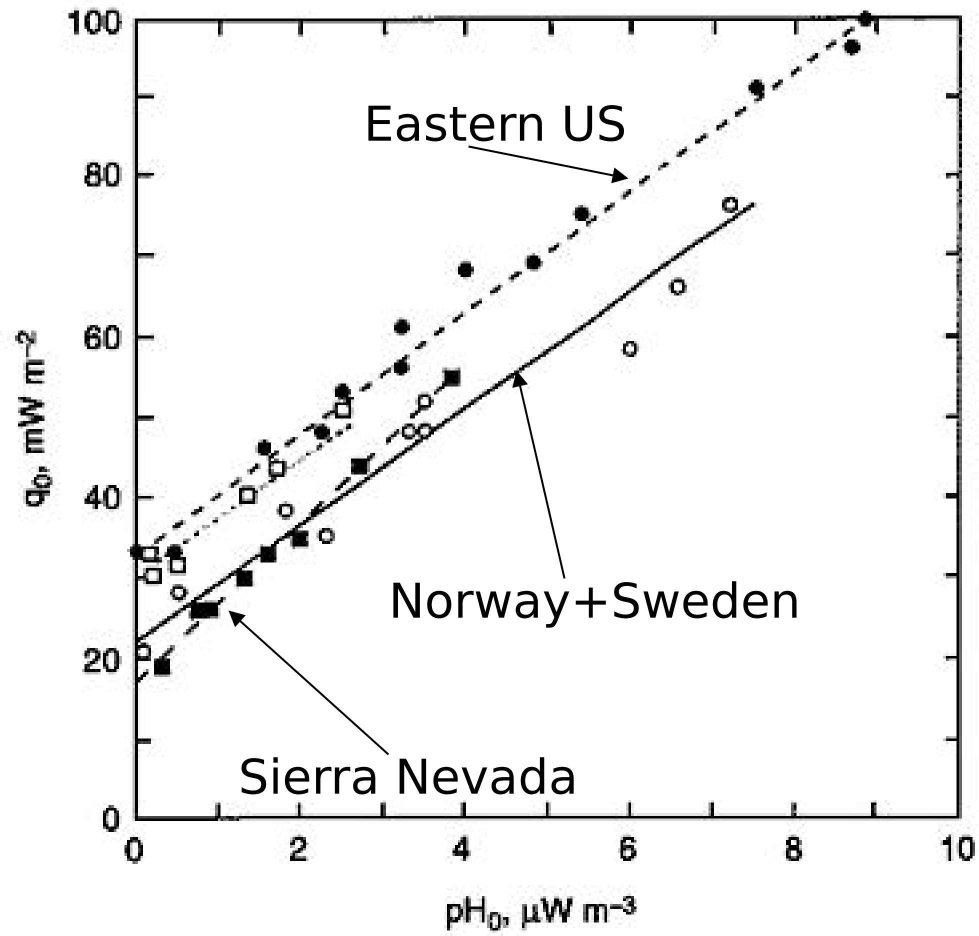


Figure from Turcotte and Schubert textb

Heat transfer: heat flow over stable continental areas

- In the stable continental areas, surface heat flow systematically decreases with the age of the surface rocks.

- Latter we will see that this effect can be attributed to the decrease in the crustal concentrations of the heat producing isotopes due to progressive erosion.

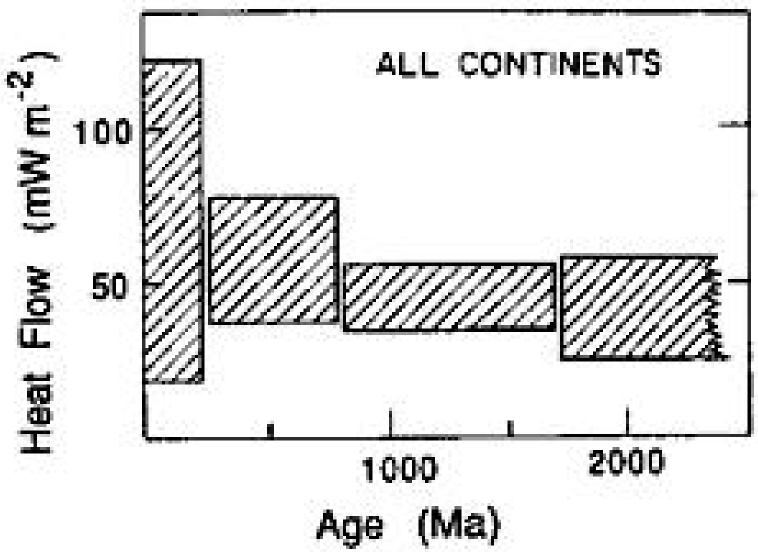


Figure 7.11 Heat flow versus age for the continents. The height of the boxes represents the scatter in heat flow, and the width represents the age range (From Sclater et al. 1981.)

Heat transfer: heat flow over oceanic crust

What is the contribution from radioactive elements in the ocean?

- The concentration of the heat producing isotopes in oceanic crust is about an order of magnitude less than in continental crust.

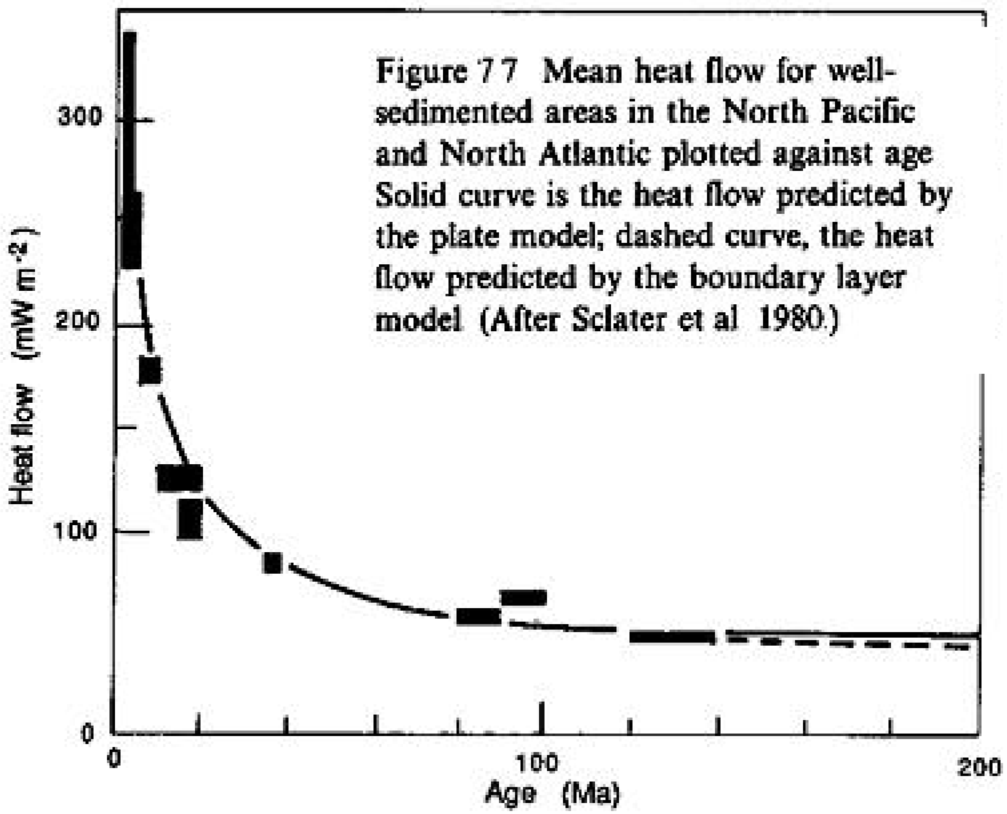
- The oceanic crust is about a factor of 5 thinner than the continental crust.

Thus, the contribution of heat producing elements is negligible!

Heat transfer: heat flow over oceanic crust

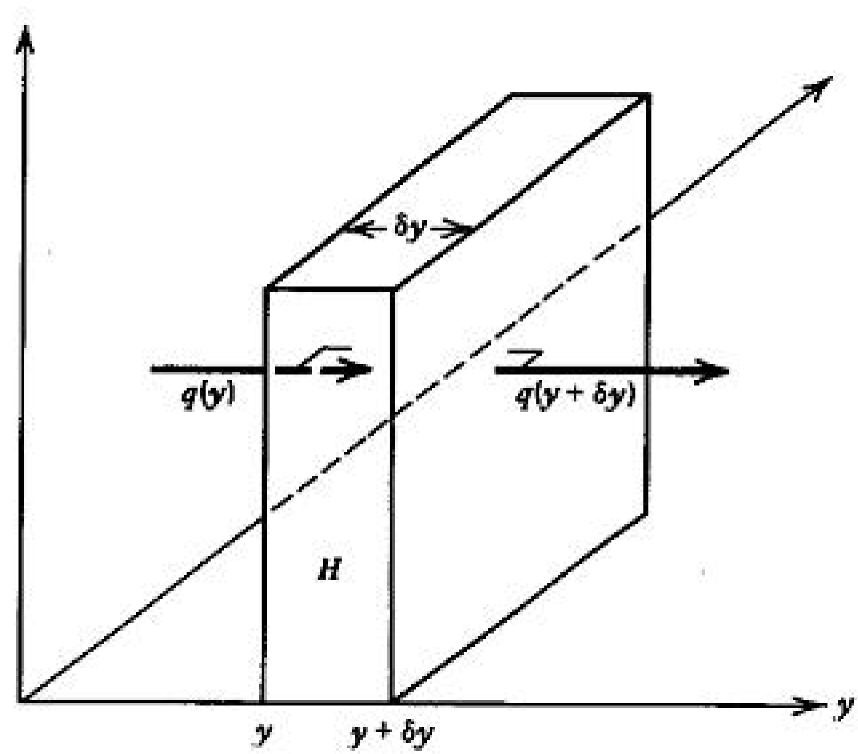
• There is a systematic dependence of the surface heat flow on the age of the sea floor.

• Later we will see that this can be understood as gradual cooling.



Heat transfer: conservation of energy in 1-dimension

Consider a slab of infinitesimal thickness ○y; the heat flux out of the slab is q(y + ○y), and the heat flux into the slab q(y).



The net heat flow out of the slab, per unit time and per unit area of the slab's face, is:

Heat transfer: conservation of energy in 1-dimension

In the absence of internal heat production, conservation of energy requires that:

Since ○y is infinitesimal, we can expand q(y+○y) in a Taylor series as:

Ignoring terms higher than the first order term, leads to:

Thus:

Heat transfer: conservation of energy in 1-dimension

Question: in the absence of internal heat production, how does the geotherm look like?

If there's nonzero net heat flow per unit area out of the slab, this heat must be generated internally in the slab. In that case:

where:

H is the heat production rate per unit mass

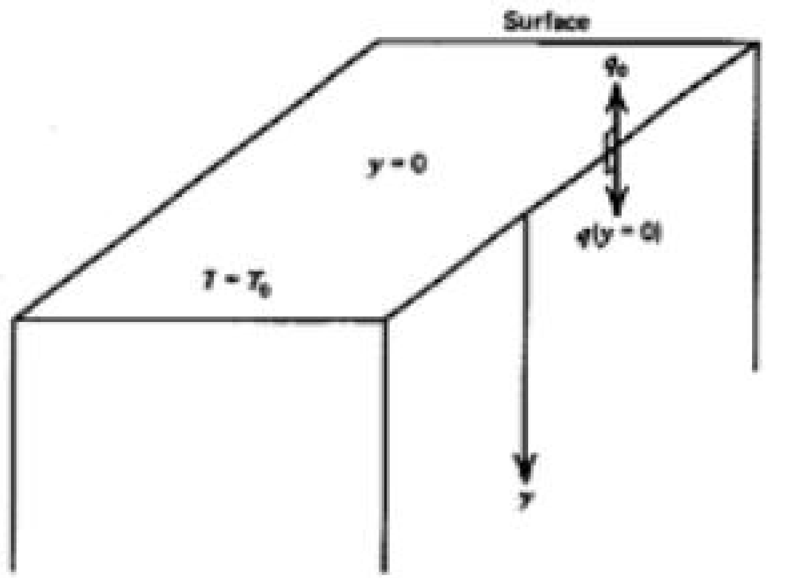
→ is the density

Question: what is the source for steady-state internal heating in the Earth lithosphere?

Heat transfer: geotherm

The previous result may be integrated to determine the geotherm, i.e. the temperature as a function of depth.

Hereafter we consider a half-space, with a surface at y=0, where y is a depth coordinate increasing downward.



Boundary conditions are:

- $q = -q_0$ at $y = 0$
- $T = T_0$ at $y = 0$

Heat transfer: geotherm

Starting with:

and integrating once gives:

The 1st b.c. requires that: $C_1=q_0$, leading to:

Additional integration gives:

The 2nd b.c. requires that $C_2=kT_0$, giving: